

# Goddard's Astrophysics Science Division Annual Report 2011

*Joan Centrella and Francis Reddy, Editors*  
*Pat Tyler, Graphical Editor*



NASA Goddard Space Flight Center  
Greenbelt, Maryland 20771

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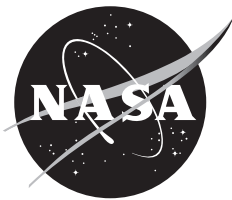
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## **Goddard's Astrophysics Science Division Annual Report 2011**

*Joan Centrella*

*NASA Goddard Space Flight Center, Greenbelt, Maryland*

*Francis Reddy*

*Syneren Technologies, Inc., Greenbelt, Maryland*

*Pat Tyler, Graphical Editor*

*Syneren Technologies, Inc., Greenbelt, Maryland*

**National Aeronautics and  
Space Administration**

**Goddard Space Flight Center  
Greenbelt, Maryland 20771**

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## 2011: Year in Review

The New Year for the Astrophysics Science Division (ASD) got off to a rousing start at the American Astronomical Society meeting in Seattle. Dr. John Mather gave the Welcome Address to start the meeting, with a talk on the exciting future that lies ahead for astrophysical discoveries, concentrating on expectations for the James Webb Space Telescope (JWST). This was followed the next day by Dr. Julie McEnery's invited talk "A New View of the High Energy Gamma-Ray Sky with the Fermi Gamma-Ray Space Telescope". The Fermi team also issued several press releases describing observations of the Crab nebula, and gamma-ray flashes from thunderstorms on Earth. At the meeting, it was announced that Dr. David Leckrone, now an emeritus scientist at GSFC, was awarded the 2011 George van Biesbroeck Prize for his long-term and excellent service as the Senior Project Scientist for the Hubble Space Telescope. The 2011 Rossi Prize went to Bill Atwood (UCSC) and Peter Michelson (Stanford) and the Fermi Large Area Telescope (LAT) team (including Julie McEnery and Dave Thompson from GSFC) for providing new insights into neutron stars, supernova remnants, cosmic rays, binary systems, active galactic nuclei, and gamma-ray bursts.

Speaking of Fermi, the mission continues to operate well and is producing new discoveries on a regular basis. The discovery of giant twin "bubbles" of gamma-ray emission surrounding the Milky Way was selected as one of the Top Ten Physics stories of the year by the American Physical Society (announced in February 2011). Fermi also released new maps of the sky at energies greater than 10 GeV and observations of gamma-ray emission from Tycho's supernova remnant.

The highlight of the year for the Swift Explorer was the unusual gamma-ray burst discovered in April 2011 (now known as Swift J1644+57). This was not a typical GRB – the object continued to flare for many months with a slowly declining flux. Follow-up observations by HST and the EVLA pinpointed the source to be the center of a galaxy. It is now thought that we have, for the first time, witnessed a tidal disruption event in which a star is disrupted and devoured by the galaxy's central black hole.

Excellent technical progress is being made in the development of JWST. Dr. Mal Niedner was added as a new Deputy Project Scientist for technical matters.

At the beginning of 2011, the House moved to cancel JWST for budgetary reasons, but eventually JWST's budget was approved for FY13 at the level requested by NASA. The new launch date is in 2018. The fact that NASA elevated JWST to one of the agency's top priorities, coupled with support by the Administration, is extremely good news. Now, we need to deliver on launching JWST on time and within the new budget.

The extended JWST development schedule caused a ripple effect on plans for future flagship missions in NASA's portfolio. The IXO and LISA Projects, as they were originally conceived, have been abandoned by ESA and NASA, and less costly concepts are now being studied in Europe and the U.S. Scientists from ASD are assisting the Physics of the Cosmos Office with these studies in the U.S. Tuck Stebbins and Nick White from Goddard are the U.S. representatives for the new ESA gravitational wave and X-ray studies, respectively. Serious development of the Wide-Field Infrared Space Telescope (WFIRST), the 2010 Decadal Survey's No. 1 large space priority, has been postponed, at least in the near-term. However, it appears that NASA will provide a contribution of Near-IR detectors to ESA's dark energy mission (Euclid) in exchange for participation in the resulting science.

There was considerable activity this year for our Explorer missions. We submitted three Explorer proposals to the "EX" class (\$200M) Explorer opportunity last year, and all three received high rankings in the competition. One of proposals, the Transiting Exoplanet Survey Satellite (TESS) with George Ricker (MIT) as PI, was selected for an 11-month Phase A study. Goddard provides project management, system engineering, and science co-investigators to the mission. Proposals not selected, but nevertheless receiving high ranking, included a proposal to perform a sky survey for highly redshifted gamma-ray bursts and other X-ray transients (Gehrels, PI) and a concept to study the polarization of the cosmic microwave background (Kogut, PI). A Mission of Opportunity proposal called the Neutron Interior Composition Explorer (NICER), with Keith Gendreau as PI, was also selected for a Phase A study. NICER is an X-ray timing experiment and is destined to fly on the International Space Station. The NICER hardware can also be used to perform interplanetary and even interstellar navigation by employing the signals from X-ray emitting pulsars as essentially celestial GPS emitters. And, as a bonus, the same instrument could provide the first

demonstration of X-ray communication; that is, sending information modulated on X-rays. The technology applications of NICER are being funded by the Office of Chief Technologist at NASA HQ. This work earned Keith and Zaven Arzoumanian the “IRAD Innovator of the Year” award for 2011.

Our Explorer missions and instruments in development made excellent progress during the year. The X-ray polarimeter instrument for the Gravity and Extreme Magnetism SMEX (GEMS) achieved a technical readiness level of TRL-6 in October 2011. GEMS is slated to complete its Preliminary Design Review in early 2012. The engineering model of the Soft X-ray Spectrometer (SXS) for the Astro-H mission was completed and is awaiting shipment to Japan for testing. We are also supplying the mirror for this calorimeter-based instrument as well as the soft X-ray mirror for a CCD-based instrument. The thousands of X-ray mirrors fabricated at Goddard by Will Zhang (GSFC) for the NuSTAR mission (Harrison, PI (Caltech)) were delivered to Columbia University, who integrated them into the mirror assembly. The mirror survived environmental testing, and was installed on the NuSTAR observatory, which is now awaiting a March 2012 launch from Kwajalein (from an air-launched Pegasus XL rocket). After a two-year PI-led program, NuSTAR will be open to guest investigators. Goddard will manage the GO program, as well as archive the NuSTAR data.

The High Energy Astrophysics Science Archive Center (HEASARC) underwent the Senior Review process in 2011, and came out tied for first place in the rankings, with a rating of “Excellent”. The overall summary stated: “HEASARC serves a valuable role in the portfolio of NASA data archives, curating a large number of past and current missions, and with plans to act as data archive for future missions. The panel recommends that NASA continue to support HEASARC at the full in-guide budget.” We were obviously pleased at the outcome!

Our vigorous program of suborbital payload development continued in 2011. The X-ray Quantum Calorimeter (XQC) sounding rocket (McCammon, PI, (Wisconsin)) had a successful launch late in 2011, and the resulting science data is awaiting analysis. XQC was designed to resolve the soft X-ray background. The detector was built at Goddard by our calorimeter group (Porter, Kilbourne, Kelley). The X-ray Advanced Concepts Testbed (XACT) is a sounding

rocket payload in development geared to testing new technologies such as modulated X-ray sources, optics and polarimeters. Keith Gendreau is the PI, and the first flight is late 2012. The Micro-X rocket payload (Figueroa, PI (MIT)) will fly the first Transition Edge Sensor (TES) device in space to obtain a spectrum of a supernova remnant. Goddard is supplying a refurbished X-ray mirror from a previous rocket payload as well as the detectors for Micro-X. The Diffuse X-rays from the Local Galaxy (DXL) rocket payload (Galeazzi, PI (Miami)) will have its first flight around December 2012, with the aim of separating out the local solar wind charge-exchange emission from the X-ray emission emanating from the Local Hot Bubble. Scott Porter and Steve Snowden are co-Is.

Turning to our balloon payloads, work continues on the Primordial Inflation Polarization Explorer (PIPER). Al Kogut (GSFC) is the PI. This experiment is designed to measure the polarization of the cosmic microwave background in search of the expected signature of primordial gravity waves excited during an inflationary epoch shortly after the Big Bang. The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII), an eight-meter baseline Michelson stellar interferometer (Rinehart, PI, GSFC) has just begun development. BETTII will attempt to answer key questions about the nature of disks in young star clusters and active galactic nuclei and the envelopes of evolved stars, as well as pioneering the concept of IR interferometry from near-space. The InFOCuS gondola (Tueller, GSFC) is in the process of being upgraded with a new pointing control system, a new hard X-ray mirror and a new detector from Washington University/St Louis, with plans to observe the polarization of hard X-rays from black holes and other energetic objects. Finally, we are members of the Trans-Iron Galactic Element Recorder (Super-TIGER) balloon experiment (Binns, PI (Washington U/StLouis)). Super-TIGER is designed to measure the abundances of ultra-heavy Galactic cosmic ray nuclei (zinc and heavier), to provide sensitive tests of the origin of cosmic-rays. John Mitchell is a co-I, and a launch from Antarctica in December 2012 is planned. All of these suborbital payloads are described in more detail in this annual report.

In the Fall of 2011, we held a celebration to honor the 50th year of civil service by Dr. Peter Serlemitsos. The celebration was attended by over 100 of Peter’s friends and colleagues. Mr. Robert Strain, the GSFC



Center Director, gave opening remarks and presented Peter with a service emblem. This was followed by talks and reminiscences by Richard Mushotzky, Rob Petre, Jean Swank, Tom Cline, and Hideo Kunieda. Frank Marshall presided over the ceremonies and read letters of congratulation from colleagues who could not attend, including Steve Holt and Jonathan Ormes. Peter has served as a world-leader in the development of instrumentation for X-ray astronomy. His development of wire proportional counters opened up the entire field of astronomical X-ray spectroscopy, and his foil X-ray mirrors have been employed on numerous space telescopes. In fact, Peter is busily working away right now on the mirrors for GEMS and Astro-H!

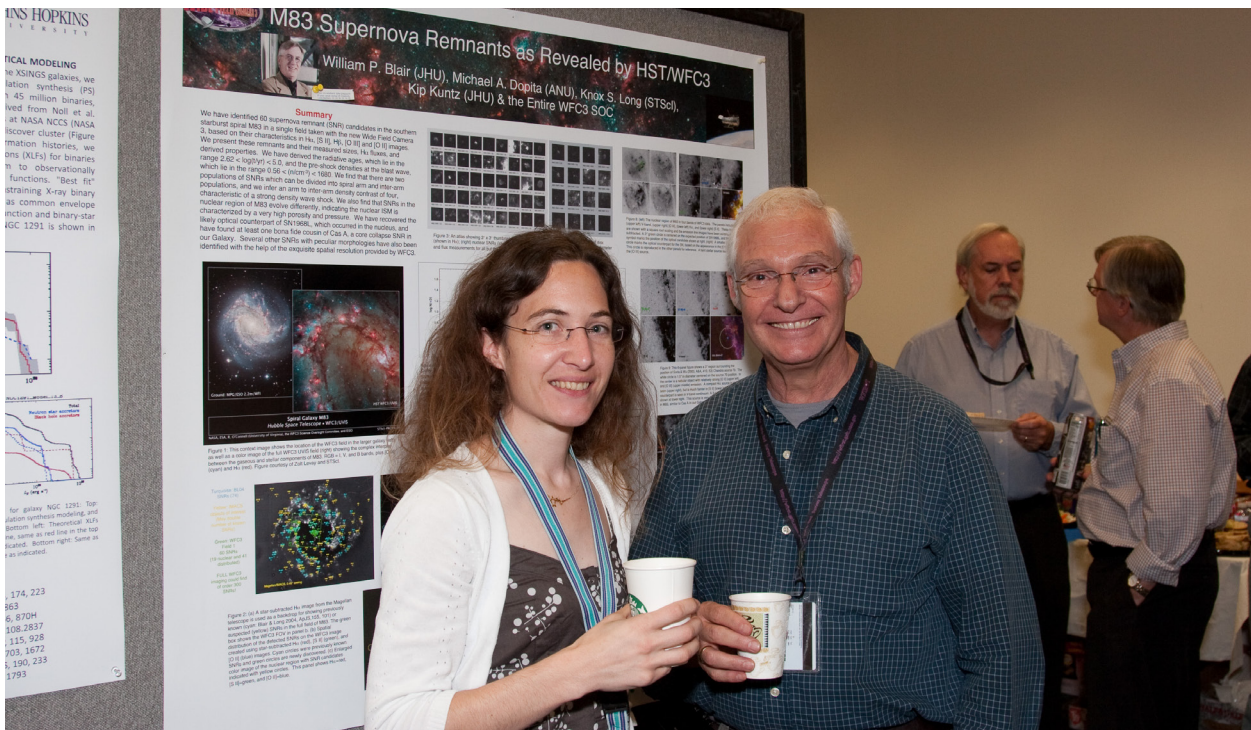


William Oegerle  
Director

2011 Events



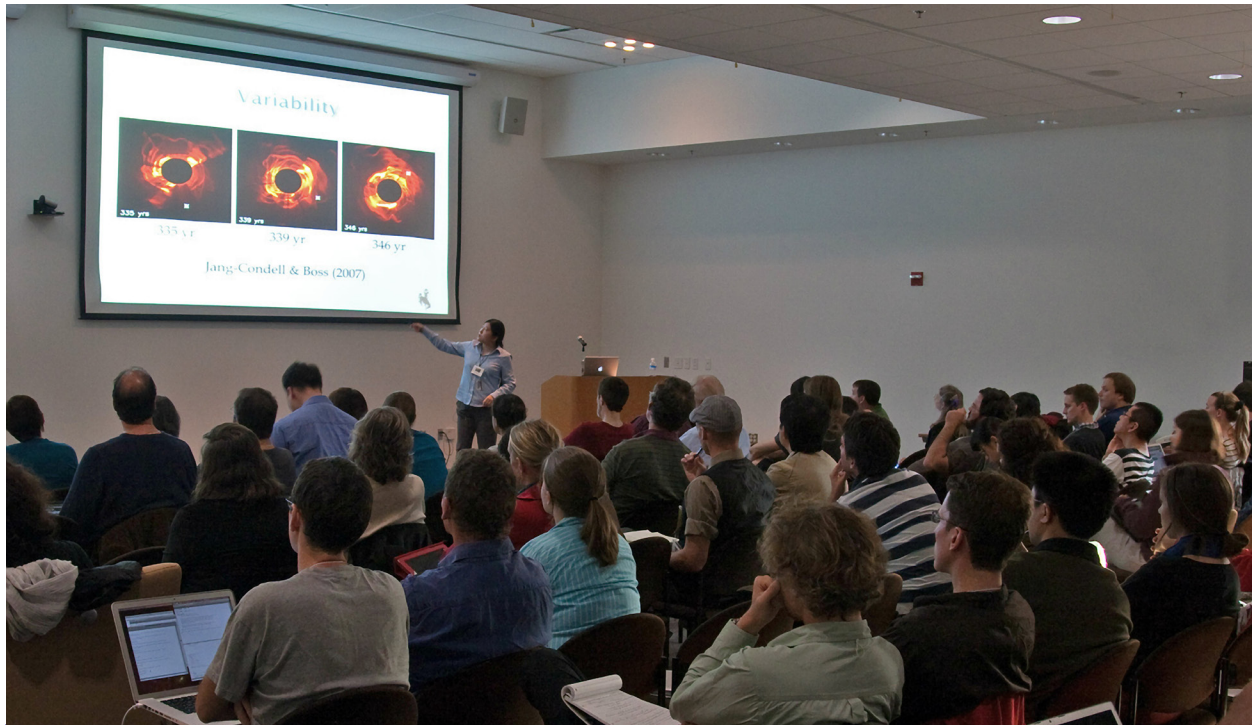
Highlights of Fall 2011 included several notable ASD-hosted events, beginning on Sept. 26 with a celebration of Dr. Peter Serlemitsos (right) and his 50 distinguished years at NASA Goddard. Peter and his wife Marigail chat with attendees before the start of the event. All photos by David Friedlander



JHU-Goddard Interaction Day, held on Oct. 11, presented an opportunity to highlight collaboration between ASD and the Department of Physics and Astronomy at Johns Hopkins University. Seen here are Drs. Eli Dwek (right) and Christa Gall, an NPP postdoc, exploring the event's poster session.



A workshop on data analysis for the European-led LISA Pathfinder mission was held Oct. 11–13. It was organized by James Ira Thorpe, GSFC's official liaison for the mission, with the goal of bringing together key members of both European and U.S. project teams. The participants, from left to right, are Bob Silverberg (GSFC), Peiman Maghami (GSFC), Curt Cutler (JPL), Charley Dunn (JPL), Michele Armano (ESA), Martin Hewitson (ESA), John Ziemer (JPL), Felipe Guzman (AEI), Paul McNamara (ESA), Guido Mueller (UF), Ira Thorpe (GSFC), Jordan Camp (GSFC), Robin Stebbins (GSFC), John Baker (GSFC), Josep SanJuan (UF), Jim O'Donnel (GSFC), Yinan Yu (UF), Alix Preston (GSFC), Kenji Numata (GSFC), and Raksha Kapil (GSFC).



The Signposts of Planets Conference, held Oct. 18–20 and organized by GSFC's Marc Kuchner, invited observers, modelers, and instrument builders to explore various aspects about the relationship between circumstellar disks and the planets they may contain. Above, former ASD scientist Hannah Jang-Condell, now at the Univ. of Wyoming, discusses the signatures of planet formation in gravitationally unstable disks.



## Awards

In 2011, several individuals and teams within the Astrophysics Science Division (ASD) were honored for their extraordinary contributions to their respective fields.

NASA's most prestigious honor awards are approved by the Administrator and presented to selected individuals and groups, both government and non-government, who have distinguished themselves by making outstanding contributions to the Agency's mission. In June, several members of ASD were so honored. Richard Mushotzky, now an ASD emeritus scientist, was awarded NASA's Distinguished Service Medal—the agency's highest honor—in recognition of his long career, his influence on the development of X-ray astronomy and the inspiration he has provided to a generation of young astrophysicists.

The agency conferred its Exceptional Achievement Medal to Harvey Moseley, “for significant sustained creativity and technical leadership in support of the James Webb Space Telescope.” NASA also honored the JWST Micro-shutter System Team with its Group Achievement Award, citing “outstanding accomplishment in development and delivery of the JWST flight micro-shutter system.” The team includes Moseley



*Richard Mushotzky*

and ASD members Robert Silverberg, Richard Arndt, Wayne Landsman, Elmer Sharp, David Rappahun, Ernest Buchanan and Alexander Kutryev.

Sara Mitchell received the Exceptional Public Service Medal “for raising the visibility of NASA's science missions by producing excellent programs and fostering collaborations within education and public outreach at NASA's GSFC.”

Julie McEnery was awarded NASA's Exceptional Scientific Achievement Medal for her key roles in the observatory's many discoveries. In addition, she was elected a Fellow of the American Physical Society—the world's second-largest organization of physicists—in recognition of “her fundamental contributions to the understanding of the gamma-ray sky through her leadership of the Fermi mission as Project Scientist and her discoveries of gamma-ray burst high energy properties.” Fermi was also recognized by the High Energy Division of the American Astronomical Society (AAS), which awarded the 2011 Rossi Prize to Bill Atwood (UCSC), Peter Michelson (Stanford) and the Fermi Large Area Telescope (LAT) team (which includes GSFC's Julie McEnery and Dave Thompson) for providing new insights into neutron stars, supernova remnants, cosmic rays, binary systems, active galactic nuclei, and gamma-ray bursts.



*Julie McEnery*



From left: Goddard Chief Technologist Peter Hughes, Zaven Arzoumanian, Keith Gendreau, and Goddard Deputy Director for Science and Technology Christyl Johnson at the awards ceremony at the annual IRAD Poster Session on Dec. 1, 2011.

The AAS George Van Biesbroeck Prize is normally awarded every two years and honors a living individual for long-term extraordinary or unselfish service to astronomy, often beyond the requirements of his or her paid position. The 2011 recipient was David Leckrone, now an emeritus scientist at GSFC, for his long-term and excellent service as the Senior Project Scientist for the Hubble Space Telescope.

Goddard's Office of the Chief Technologist named Keith Gendreau, Zaven Arzoumanian and the NICER team as the 2011 IRAD Innovators of the Year. This annual award is conferred on technologists who exemplify the best in research and development. NICER is an X-ray timing experiment and is destined to fly on the International Space Station, however the hardware also can be used to perform interplanetary and even interstellar navigation by treating signals from X-ray-emitting pulsars in much the same way as global navigation devices use GPS radio broadcasts. In addition, the same instrument could provide the first

demonstration of communication via X-rays. The selection committee chose the NICER team because of its sustained effort developing innovative solutions for navigating in deep space using pulsars, transmitting data via X-rays, and gathering first-of-a-kind measurements to better understand the interior composition of neutron stars.

The Robert H. Goddard Awards recognize outstanding individuals for accomplishments in space-flight, engineering, science, management and education. In 2011, the JWST Near-Infrared Spectrometer (NIRSpec) Instrument Detector System Team received the Exceptional Achievement Award in Engineering "for outstanding accomplishment in the development and delivery of the JWST NIRSpec flight detector system." Members of the team from ASD are Bernie Rauscher, Bob Hill Jr., Meng Chiao, Greg Delo, Don Lindler and Ori Fox.

Sarah Eyer mann received the Exceptional Achievement Award in Outreach. The selection committee

cited her for outstanding leadership and coordination of the Afterschool Universe program during its development, culminating in a successful train-the-trainer workshop and nationwide dissemination network. The Customer Service Award went to the Exploration Sciences Building Outfitting Project Team, which included ASD Curtis Odell and Larry Olsen.

John Mather received an honorary degree from the University of Notre Dame and was later elected as a Fellow of the American Association for the Advancement of Science (AAAS). Election as a Fellow of AAAS is an honor bestowed upon members by their peers. Fellows are recognized for meritorious efforts on behalf of the advancement of science or its applications.



*John Mather*





## New Faces in ASD

### Theresa Brandt

After nearly two years enjoying a post-doctoral position in Toulouse, France, Terri returned to her roots in September 2011. Her work as a civil servant in ASD expands her pursuit of the origins, acceleration, and propagation of galactic cosmic rays (CR). At Goddard, she can now combine her previous life as a direct-detection CR astrophysicist launching balloons from Antarctica, with her recent work in France on the Fermi Gamma-ray Space Telescope studying supernova remnants and other indirect CR tracers. Her ASD colleagues are an invaluable resource for both her current Fermi project—the first SNR catalog—and for her work on Super-TIGER, a nearly 10 times bigger CR balloon experiment scheduled for launch during the Antarctic summer of 2012–13. She looks forward to completing these projects, to the next interesting questions they lead us to ask, and to the subsequent experiments to answer them.



### Sarah Busch

In May 2011, Sarah completed her doctorate in physics at the University of California, Berkeley. While there, she built and developed a novel type of magnetic-resonance imaging system and studied applications to imaging cancer. Sarah came to ASD in June 2011 as a fellow in the NASA Postdoctoral Program. She brings her experience in low-temperature detectors to the X-ray Astrophysics Lab, where she works on the development of X-ray detectors.



### Christa Gall

Christa joined ASD's Observational Cosmology Lab as a NASA Postdoctoral Program Fellow to work with Eli Dwek in August 2011. She received her doctorate from the

Dark Cosmology Center at the Niels Bohr Institute, University of Copenhagen, under the supervision of Anja C. Andersen. She continued there for a short period as a Postdoctoral Fellow, collaborating with Prof. Jens Hjorth on problems related to dust production by massive stars. Her research is mainly devoted to the studies of astrophysical dust. She uses theoretical and observational methods to study its properties, composition, formation, processing and evolution in various astrophysical environments at low and high redshifts. These environments include supernova remnants, the interstellar medium, starburst galaxies and active galactic nuclei.

### Sylvain Guiriec

Sylvain joined ASD as a NASA Postdoctoral Program fellow in October 2011 and works under the supervision of Julie McEnery and Neil Gehrels. He received his doctorate from the Laboratory of Theoretical Physics and Astroparticles (LPTA) in Montpellier, France. His history with Fermi began well before its launch.



He participated to the integration of the calorimeter modules of its Large Area Telescope (LAT) and developed an algorithm to identify and reject protons based on calorimeter-only information. Following Fermi's launch, he spent three years as a postdoc at the University of Alabama in Huntsville working with the Gamma-ray Burst Monitor team. He is studying prompt emission spectroscopy and the theory of gamma-ray bursts with the Fermi group and expects to extend his results to data from other gamma-ray instruments, such as those on Swift, Konus, and Suzaku.

### Jonah Kanner

Jonah began his NASA Postdoctoral Program fellowship with the ASD's Gravitational Astrophysics Lab in October 2011. Jonah comes to Goddard from the nearby University of Maryland, where he completed his disserta-



tion work developing the first prompt optical follow-up observations to triggers from the LIGO and Virgo gravitational wave observatories. His scientific interests include time-domain astronomy and gravitational wave data analysis. Here at ASD, Jonah is looking forward to learning from the expertise in X-ray astronomy and gamma-ray burst observations. He is pursuing research themed around multi-spectral searches that combine gravitational and electromagnetic data to find astrophysical transients in the local universe as they are happening.

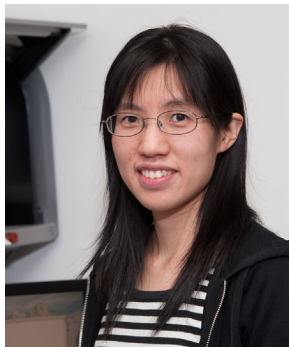
### Yong-Hamb Kim

Yong-Hamb Kim arrived at ASD in September 2011 as a visitor in X-ray Calorimeter Group. His home institute is Korea Research Institute of Standards and Science. He studied his Ph.D. and postdoctoral programs at Brown University. His major research interests lie in high resolution detector development for astroparticle physics applications. He is also a collaborator on the Advanced Molybdenum-based Rare Process Experiment (AMoRE) and on the Xenon detector for weakly interacting MASSive particles (XMASS) projects. He is excited to be interacting with many bright scientists at Goddard and to learn about NASA missions.



### Amy Lien

Amy became a NASA Postdoctoral Program Fellow working with Dr. Neil Gehrels since September 2011. She recently graduated from the University of Illinois at Urbana-Champaign, working with Prof. Brian Fields. Her Ph.D. thesis focused on forecasts of core-collapse supernova detections for upcoming large sky surveys, such as Large Synoptic Survey Telescope (optical) and the Square Kilometer Array (radio). Her research also involves exploring possibilities of studying supernova physics by combining these upcoming



surveys with other multimessenger observations, such as neutrinos and gamma rays. She is interested in extending her previous work on supernovae to gamma-ray bursts (GRBs), and exploring the connection between the two via multimessenger observations (e.g., gamma ray, X-ray, optical, radio, and neutrino). She is especially excited about the opportunities to work with researchers in the Swift and Fermi team, and to connect GRB/supernova theories to observations.

### Maxim Markevitch

Maxim joined the ASD as a civil servant in January 2011 after working for 12 years at the Chandra X-ray Center in Cambridge, Mass. After completing his doctorate in 1993 at the Space Research Institute of the Russian Academy of Sciences, he went on to postdocs at ISAS in Japan, the University of Virginia, and the Harvard-Smithsonian Center for Astrophysics. His main interest is clusters of galaxies—in particular, the physics of the intracluster medium, cluster mergers, shocks, and cold fronts (his Chandra discovery). He has worked with X-ray data from Chandra, XMM-Newton, ASCA, ROSAT and Granat; some of these observatories, he helped calibrate. With Steven Allen, J. Patrick Henry and Alexey Vikhlinin, he was co-recipient of the 2008 Rossi Prize awarded by the American Astronomical Society's High Energy Astrophysics Division. At the ASD, Maxim works with the Astro-H team and hopes to be among the first to see a cluster spectrum from an X-ray calorimeter. He is excited to come to a place with state-of-the-art lab facilities and hopes to take advantage of them to test some telescope-building ideas.



### Michael McElwain

Michael joined the ASD as a civil servant in March 2011. He arrived from Princeton University, where he was a Russell fellow and NSF fellow. His research focuses on observations and instrumentation for characteriz-



ing exoplanets. As a Ph.D. student at UCLA, Michael was part of the core instrument team for the adaptive-optics-assisted OSIRIS infrared integral-field spectrograph at the Keck Observatory. As a postdoc, he became one of the leaders of Subaru Telescope's SEEDS survey to directly image exoplanets and disks using high-contrast imaging techniques. He also designed a specialized high-contrast integral-field spectrograph for Subaru that is now funded for development through Princeton. Shortly after arriving at GSFC, Michael led an instrument proposal to build a multi-band near-infrared imager for SOFIA to characterize the atmospheres of newly discovered transiting planets and enable ultraprecise measurements of the broad spectral features for Trans-Neptunian Objects, Main Belt asteroids, brown dwarfs, and globular clusters. He is excited about the prospects for exoplanetary science and the lead role GSFC scientists and engineers will play in its pursuit.

#### Deborah Padgett

Deborah arrived at ASD in the Observational Cosmology Lab as a civil servant in September 2011, coming from the Infrared Processing and Analysis Center at Caltech in Pasadena, Calif. She has spent the last 15 years working on space astronomy missions, including WIRE, the Spitzer Space Telescope, and the Wide-field Infrared Survey Explorer (WISE). Deborah's primary research interest is the study of circumstellar disks, found using wide-field infrared surveys and investigated at high-resolution with Hubble and various ground-based telescopes.



#### Jan-Patrick "JP" Porst

JP joined the microcalorimeter group at ASD in April 2011 from Heidelberg, Germany, where he completed his dissertation work on the development of metallic magnetic calorimeters (MMCs) for applications such as beta



spectroscopy. He visited GSFC for five months in 2008, working on high-resolution position-resolved X-ray detectors. Currently, he is a postdoctoral research associate with Brown University, R.I. Now, he continues working with MMCs as well as with a fairly new and promising low-temperature detector technology—magnetic penetration thermometers (MPTs). JP is also looking forward to working with and contributing to the further development of Transition Edge Sensor (TES) technology, for which he finds vast expertise at Goddard. He is further excited to learn about the science and technology of space-based missions.

#### Christina Richey

Christina Richey came to ASD in August 2011 as a NASA Postdoctoral Program fellow working with Stephen Rinehart, where she is studying optical properties of carbonaceous and silicate dust grain analogs in the near-infrared to submillimeter as a function of wavelength, temperature, and composition as part of the OPASI-T program. This data will be used for interpretation of observations from Spitzer and Herschel, and will be critical for understanding the data from future facilities such as SOFIA, JWST, and ALMA. She completed her graduate doctorate work on the near-infrared spectroscopy of ices under conditions relevant to interstellar and planetary environments at the University of Alabama at Birmingham in May 2011, under the direction of Perry Gerakines. Christina is also a member of the Division of Planetary Science's Federal Relations Subcommittee and tries to include educational outreach and public policy activities into her busy schedule.



#### Kenichi Sakai

Kenichi Sakai joined the ASD's High-Energy Cosmic Radiations Group in June 2011 after finishing his Ph.D. at the University of Tokyo. His dissertation was based on precise measurements of the



low-energy antiproton spectrum in a long-duration balloon flight over Antarctica by the BESS-Polar II instrument. Since coming to Goddard, he has been the principal scientist in the antiproton analysis, which was recently accepted for publication in *Physical Review Letters*. In addition, he is now a part of the Super-TIGER experiment to measure the abundances of ultra-heavy cosmic-ray nuclei. His research interests focus on cosmic-ray origin studied with Super-TIGER and cosmic-ray transport using BESS results. It is necessary to engage in both experiments to achieve overall understanding of galactic cosmic rays.

### Athena Stacy

Athena Stacy arrived in September of 2011 after completing her doctorate at the University of Texas in Austin. Her main interest has been theoretical studies of the nature of Population III stars using numerical simulations. At ASD she looks forward to continuing research on the earliest luminous objects in the universe, studying the nature of the first galaxies, and relating this to future observations by JWST.



### Karl Stapelfeldt

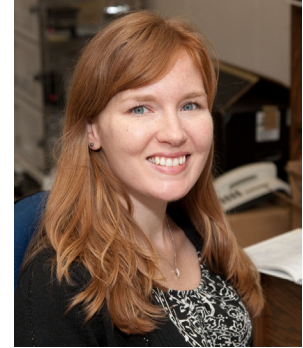
Karl Stapelfeldt came to ASD in August 2011 as the new Chief of the Exoplanets and Stellar Astrophysics Laboratory. He spent the previous 18 years at the Jet Propulsion Laboratory as a member of the Hubble WFC2 Science Team, the Spitzer Space Telescope Project Science Office, and the Terrestrial Planet Finder Coronagraph mission study. Over his career he has worked on topics ranging from star formation to circumstellar disks to exoplanets and high-contrast imaging. His current observational projects include Herschel studies of debris disks, Hubble imaging of protoplanetary and debris disks, Hubble and Spitzer imaging of Her-



big-Haro flows, and adaptive-optics imaging searches for exoplanets in young disk systems. At Goddard, he seeks to “untangle the Gordian knot of terrestrial exoplanet space mission concepts” and build toward the goal of a joint exoplanet /general astrophysics mission as the next large community telescope after Hubble and JWST.

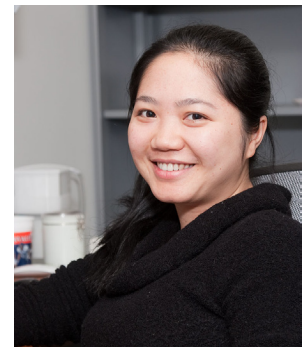
### Amber Straughn

Amber Straughn joined ASD as a civil servant in March 2011 after 2.5 years as an NPP Fellow at Goddard. Before that, she was at Arizona State University, where she obtained her Ph.D. in 2008. Amber’s research focuses on interacting and star-forming galaxies within the context of galaxy assembly, using mostly data from Hubble; she most recently has been working on infrared spectroscopic grism data from Hubble’s WFC3. Amber is the Deputy Project Scientist for JWST EPO, where she serves as the scientific liaison for EPO, public affairs, and legislative affairs. She is also the Civil Servant Lead for ASD EPO, and is on the WFIRST science team. Amber is excited about not only the excellent scientific research going on at Goddard, but also communicating that science to the public.



### Stacy Teng

Stacy joined the Observational Cosmology Lab in August 2011 as an NPP fellow working with Jane Rigby. She completed her Ph.D. at the University of Maryland where she also had a short stint as a postdoc. Her primary research is in galaxy evolution, with particular interest in the formation and growth of active nuclei in merging galaxies. Stacy mainly uses data from X-ray telescopes, but also dabbles in radio observations for her research. At Goddard, she looks forward to working with the



NuSTAR team to understand the nature of active galaxies using the very first hard X-ray focusing telescope.

### Andrey Timokhin

Andrey arrived at ADS in December 2011 as a Senior Fellow in the NASA Postdoctoral Program. He is a theorist with research interests in physics of compact objects and plasma- and high-energy astrophysics. At Goddard, he is planning to work on modeling of pulsar magnetospheres and trying to unravel the mystery of the pulsar emission mechanism, a problem eluding solution for more than 40 years. He also plans to work closely with the Fermi team, using pulsar observations for checking theoretical models. He is a staff scientist at Moscow State University in Russia, currently on unpaid leave. Before coming to ADS, he spent four years as a research scientist at the University of California, Berkeley, working on the physics of radio pulsars.



### John ZuHone

John arrived at ASD in March of 2011 after finishing his first postdoctoral appointment at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass. He is now a NASA Postdoctoral Program fellow working with Maxim Markevitch on galaxy cluster mergers. He is using numerical simulations with the FLASH and Enzo codes to principally study the dynamics of the intracluster medium and what effects may arise due to merging activity that would be observable using X-ray observatories such as Chandra and XMM-Newton, as well as future missions. Chief among these are cold fronts, whose properties can be used to constrain the microphysics of the cluster gas, e.g., its viscosity, magnetic field strength and orientation. If he ever gets around to it, he would like to use his time at ASD to learn more about interesting problems in solar system formation.



### Tonia Venters

Tonia joined ASD in September 2009 as a NASA Postdoctoral Program fellow and became a civil servant in January 2011. She received her doctorate from the University of Chicago, where she worked with the Pierre Auger Observatory searching for the sources of ultra-high-energy cosmic rays (UHECRs). Her research interests include (but are not limited to) theoretical studies of the origins of gamma rays and UHECRs from extragalactic astrophysical objects and their propagation through the cosmological photon backgrounds and extragalactic magnetic fields. She is also an affiliated scientist with the Fermi Large Area Telescope. She is excited to be working with a team whose research interests are as broad and as diverse as the ASD's.





## Research Highlights

### *Resolving and Characterizing the Massive Winds of Eta Carinae*

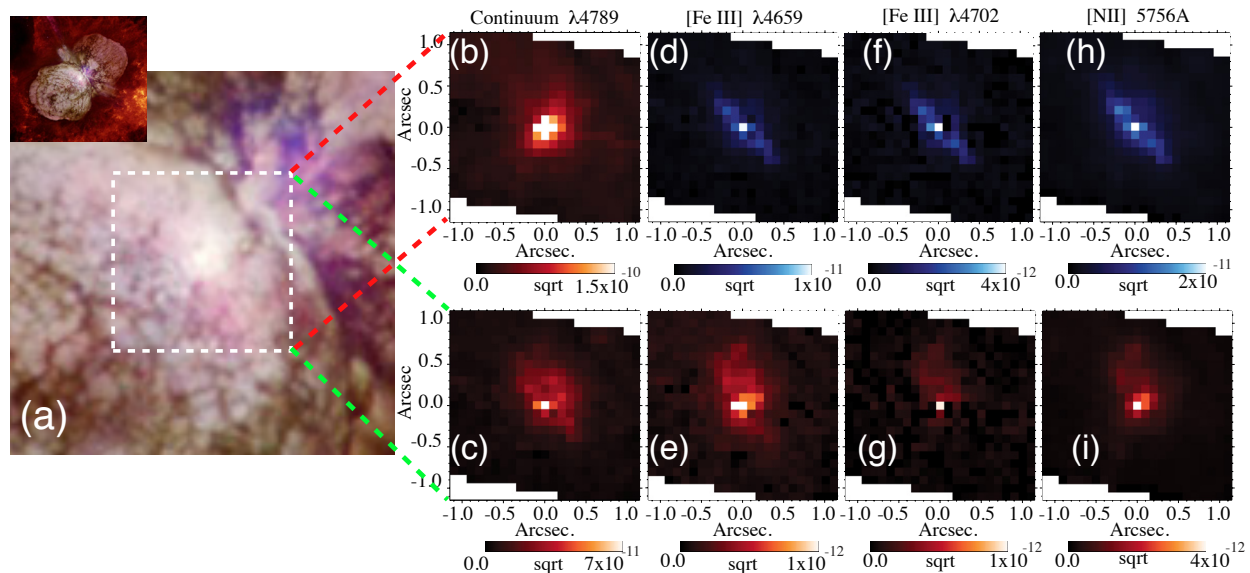
For a decade in the 1840s, Eta Carinae brightened enough to rival Sirius, the brightest star in the night sky. It then gradually faded, only to brighten again in the 1890s, after which it faded to below naked-eye visibility. Today, an expanding bipolar nebula surrounds Eta Carinae, which now is slowly brightening again.

Astronomers eventually realized that Eta Carinae is a massive binary system still obscured by massive interacting winds. Its total radiation of 5 million solar luminosities suggests that the combined stellar mass must be at least 120 solar masses, divided between two components with an orbital period of 5.5 years. Both stars are sufficiently massive that eventually each will explode as supernovae. The 1840s event was likely a preliminary explosion that precedes the more energetic supernova event. The Homunculus, a dusty hour-glass-shaped nebula containing at least 12 solar masses, was ejected with energy that almost rivals known supernova events. Yet the two stars survived. How? Astronomers doing supernova searches have identified multiple near-supernovae that appear to have similar

behaviors. Studies of Eta Carinae in its current stage will lead to new insights on this near-supernovae class.

Ted Gull realized that the high resolution achieved by Hubble Space Telescope and the spectral dispersing properties of the Space Telescope Imaging Spectrograph could reveal the interacting winds of these massive stars. Long-slit spectra obtained by HST/STIS revealed forbidden-line emissions that extended in specific directions from the central stellar source. At the distance of Eta Carinae, HST/STIS reveals spatial features down to about 200 astronomical units (where 1 AU equals mean Earth-Sun distance). These forbidden-emission-line structures trace the boundaries of a cavity carved out by an outflowing wind from the secondary star that also ionizes the cavity edges. Recorded at various orientations across the star and sampled at selected times, these structures change in synchrony with the binary period. He and colleagues suggested that modeling the behavior of these structures would lead to understanding of interacting stellar winds and in turn would provide much new information on the properties of the two stars.

Tom Madura, as a NASA Graduate Student Research Fellow at University of Delaware, modified a three-dimensional (3D) model of interacting binary winds to replicate the interacting massive winds of Eta Carinae. From the model, he calculated synthetic



Upper left: HST image of Eta Carinae and the Homunculus. The central structure is shown in (a). Images (b) through (i) are maps of selected spectral emissions from this central structure: (b) continuum; (c) [Fe III] emission at 4659Å; (d), (f), and (h) are blueshifted (approaching) maps of three forbidden emission lines; and (e), (g) and (i) are redshifted (receding) maps of the same lines.

spectra to compare to multiple observations recorded by HST/STIS. The fruit of his thesis led to constraining the orientation of the binary orbit on the sky. From the nearly dozen observations recorded by HST/STIS between early 1998 and mid-2004, the axis defined by the orbital plane is closely aligned to the axis of the Homunculus hourglass. Hence the geometry of the material thrown out in the 1840s event appears to be related to the orbit of the binary system. This provides an important clue to how stars in massive binary systems eject massive amounts of material and may provide insight to the long-period gamma-ray bursters, which are thought to originate from rapidly rotating stars at cosmological distances that have been spun up by massive binary interactions.

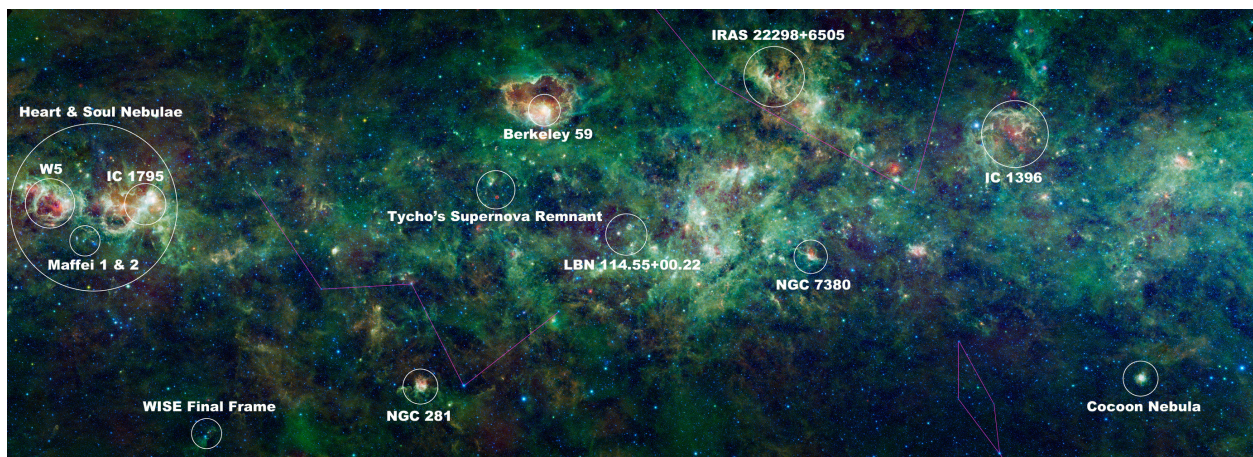
A single observation with the HST/STIS slit positioned on Eta Carinae provides a slice of information about the interacting winds. Stepping the HST/STIS slit across the wind structure provides a map of the wind interactions, and mapping at selected intervals across the 5.5-year period will measure changes of the wind structure, leading to limits on the constancy of the winds, the amount of ultraviolet radiation that ionizes the winds and improved measures of the properties of the individual stars, both of which are completely obscured by the interacting winds. The binary system has a very eccentric orbit and the two stars spend most of the orbit near apastron, where the wind structures are highly excited. But during the several months centered on periastron, the hot secondary

star plunges close to the primary's wind, escapes its own cavity, and then begins carving a new cavity from scratch.

During the final servicing mission to Hubble in May 2009, a failed computer board within the STIS was successfully replaced. The early release observation, designed to demonstrate that the HST/STIS was fully operational, was the first mapping of the winds of Eta Carinae just as it recovered from the periastron event in early 2009. Ted Gull, Tom Madura, with Jose Groh (MPIR), and Mike Corcoran (USRA/GSFC) and colleagues, successfully proposed to continue these mappings in coordination with Chandra X-ray observations, sampling at specific times when the interacting wind structures were predicted to change. With four mappings in hand leading from periastron to apastron in late 2011, they are refining the 3-D models to predict the behavior of the wind structure as the 2014.5 periastron event approaches, then recedes. Contingent upon the HST/STIS being operational through early 2015, they will be testing and refining the interacting wind models by planned HST/STIS mappings.

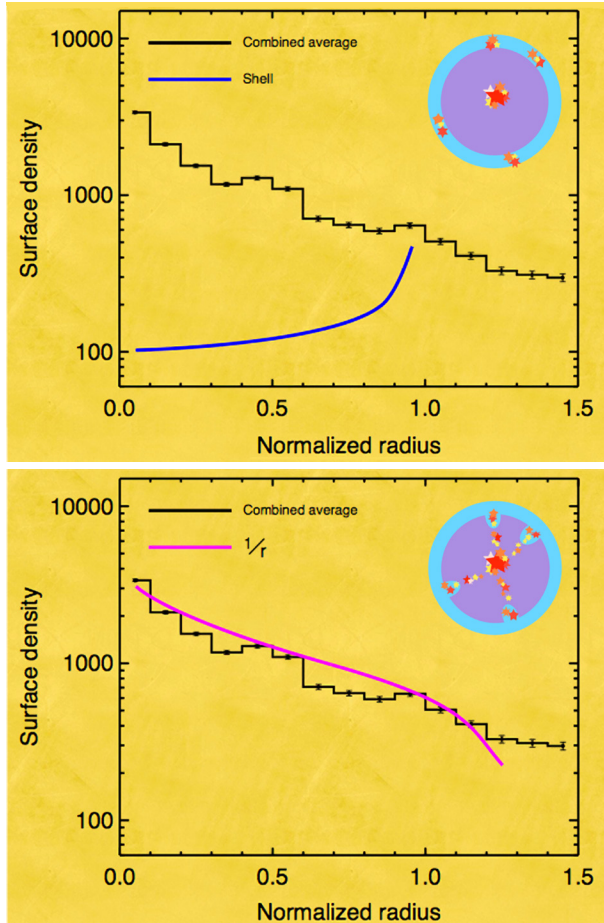
### *Testing Models of Triggered Star Formation*

The vast majority of stars are born in massive star-forming regions. That makes these stellar factories extremely important to study, since the Sun itself was likely born in a large cluster of stars, perhaps in a long-



*This enormous section of the Milky Way is a mosaic of images from WISE was released at the Jan. 2012 AAS meeting to accompany the announcement of these results. Covering 1000 square degrees of the Galactic plane, the mosaic highlights numerous features—including some of the regions studied in this work—and demonstrates the beauty of the Galaxy as seen in infrared light. NASA/JPL-Caltech/UCLA*





These graphs show the averaged spatial distribution of young stars in the regions surveyed (black line), scaling all to a radius of 1. Colored lines represent simple models of expected stellar distributions for (top) the collect and collapse model and (bottom) the squeeze model.

since vanished massive star-forming region. But the details of how huge clusters of thousands of stars are born from giant molecular clouds and then disperse their birth environment remain unclear to scientists.

In particular, it has been thought for almost 60 years that the first stellar generation's most massive, hottest stars—O-type stars 20 to 100 times the Sun's mass—would promote further star formation in the cold molecular gas around them even as their radiation and winds disrupted and blew this gas away. Just how this triggered star formation happens, or if it happens at all, remains undetermined. Does gas gathered up by an ionization shock front then collapse into new stars, or does the hot ionized bubble of gas made by O stars radiation squeeze already overdense portions of the molecular gas into forming new stars?

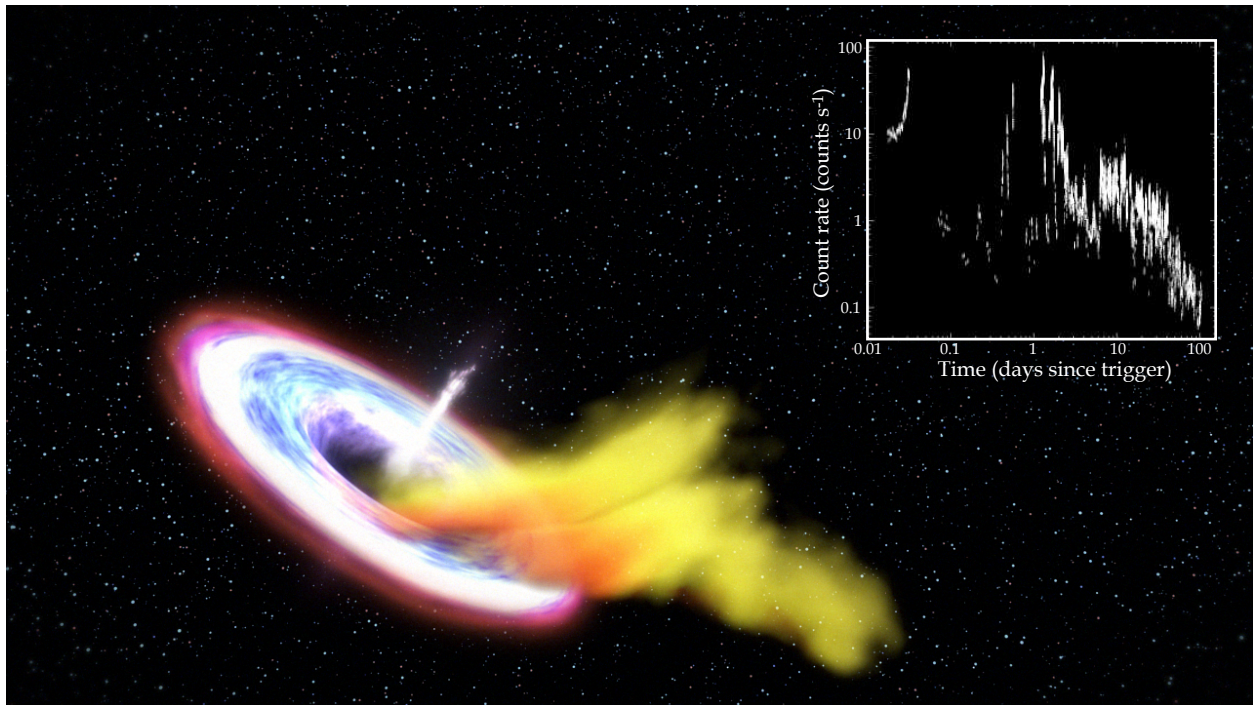
Xavier Koenig and his colleagues have used data from the recently launched Wide-field Infrared Survey Explorer (WISE) telescope to study 11 such massive star-forming regions to answer these questions. They used photometry from 2MASS and WISE to find young stars in these regions by their excess of infrared emission between 1 and 22 microns and then look at their distributions across each region. The fact that 2MASS and WISE are both all-sky surveys now makes the task of mapping young stars across many square degrees of the sky quite straightforward.

The simplest picture is that the “collect and collapse” model of triggering would lead to a deficit of stars around the first generation, whereas the “squeeze” model would produce a continuous distribution of stars that would, on average, extend away from the center. Koenig and his co-workers found a smooth distribution of young stellar objects in these regions, thus supporting a “squeeze” origin in a radiatively driven implosion that triggered star formation in pre-existing dense structures.

### *Tidal Disruption of a Star by a Black Hole*

Given the massive black holes that are known to reside at the centers of most galaxies, an unavoidable consequence will be the occasional errant star wandering into the galactic center. If the stellar orbit lies within a certain range, the star can become disrupted and its shredded remains gobbled up by the central black hole. Furthermore, if our line-of-sight for such an event is roughly along the spin axis of the black hole, the jet produced by the sudden burst of accretion will boost the power output, making the event observable out to a large distance.

The BAT instrument on Swift discovered the first such jetted tidal disruption event (TDE) on 28 March 2011 coming from the center of a galaxy 1.4 gigaparsecs distant. Originally thought to be a gamma-ray burst and designated GRB 110328A, it is now known as Sw 1644+57. Evidence connecting the X-ray/gamma-ray source with a galactic nucleus was confirmed by precise HST, Chandra and radio localizations. The strong circumstantial evidence associating the X-ray emission with the center of a dwarf galaxy strongly suggests a jetted tidal disruption event. There are several Swift team papers on the discovery and follow-



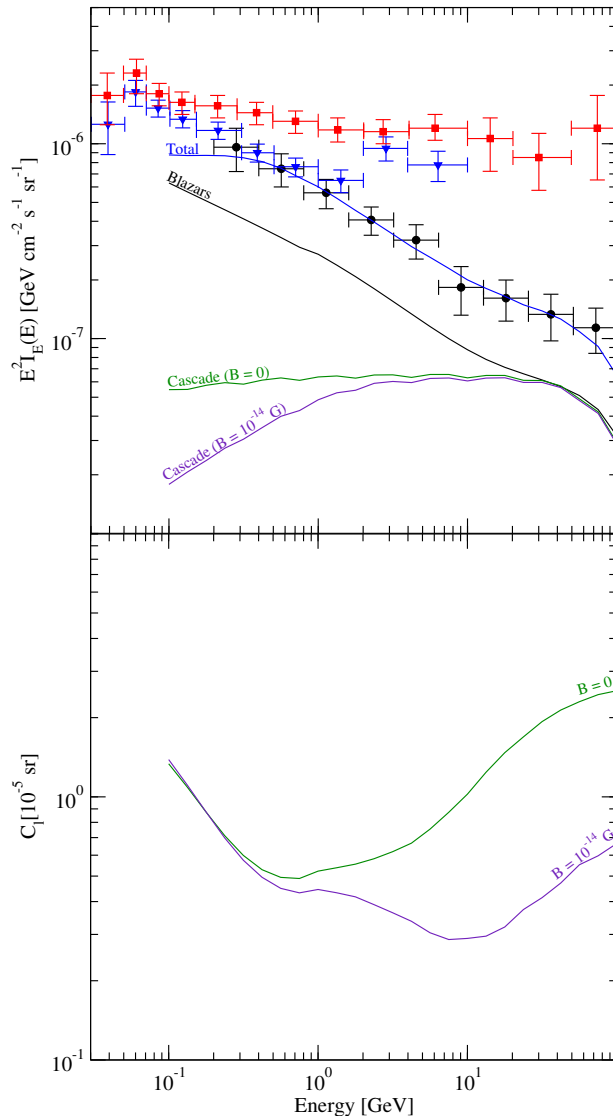
On March 28, 2011, NASA's Swift detected intense X-ray flares thought to be caused by a black hole devouring a star. In one model, illustrated in this frame from an animation produced for a press release about the finding, a sun-like star on an eccentric orbit plunges too close to its galaxy's central black hole. About half of the star's mass feeds an accretion disk around the black hole, which in turn powers a particle jet that beams radiation toward Earth. Inset: The long, slow decline of X-ray output is one characteristic that distinguishes Sw 1644+57 from a gamma-ray burst.

up observations, including two in *Science* and one in *Nature*.

John Cannizzo and Nora Troja, in collaboration with Giuseppe Lodato at the University of Milan, performed calculations to follow up on the idea of a tidal disruption event. Their work shows that, to explain the observations, the event needed to occur close to the event horizon of the black hole. This would result in a more violent stellar disruption than has been traditionally considered, hence they proposed the acronym TOE (tidal obliteration event) rather than TDE. An animation illustrating the event (<http://www.youtube.com/watch?v=azLDH9ZPbVs>) became the most watched video on Goddard's YouTube channel in just four days; in three weeks, it exceeded a million views. The X-ray light curve of Sw 1644+57's prompt phase is quite different from a gamma-ray burst's. It is surprising that such events have not been identified earlier, but now that we have some experience to guide us, a second such event has already been tentatively identified.

### **Probing the Intergalactic Magnetic Field with Fermi Measurements of the Extragalactic Gamma-ray Background**

Cosmic magnetic fields are expected to play a fundamental role in the physics of a large variety of astrophysical systems. The acceleration of charged cosmic rays to ultra-high energies in astrophysical objects and the fate of such particles as they traverse the Universe from their sources to us hinges, in large part, on magnetic fields both within these systems and without. Large-scale magnetic fields such as those found in galaxies and clusters of galaxies have been a mystery for the past several decades. While they are generally thought to be the result of the amplification of weak seed fields, the origins of these seed fields, whether they be cosmological or astrophysical in nature, are largely unknown. A definitive measurement of the intergalactic magnetic field (IGMF) could provide a fundamental step in resolving the questions of the origins of cosmic magnetic fields and their impact on



Top: The spectra of the modeled contributions of the EGB arising from blazars, which includes both flat-spectrum radio quasars and BL Lacertae-type objects (black) and electromagnetic cascades for two models of the IGMF (green and indigo). The curve labeled “Total” (blue) refers to the total contribution of blazars plus one of the cascade models plus an assumed component with very little anisotropy (e.g., normal galaxies). For reference, the spectra of the EGB based on both Fermi (black data points) and EGRET (red and blue data points) are also plotted. Bottom: The anisotropy energy spectrum of the modeled contributions to the EGB. The green line is the total model assuming zero IGMF. The indigo is the total model assuming nonzero IGMF.

the evolution of the systems in which they reside, but sufficiently constraining observations have thus far remained elusive. As such, for many areas of astrophysics, achieving a deeper understanding of the physics of

the cosmos is hindered by our lack of understanding of the IGMF.

Ongoing theoretical investigations conducted by Tonia Venters and her colleague Vasiliki Pavlidou of the Max-Planck Institute for Radio Astronomy in Bonn, Germany and the University of Crete in Greece have examined whether the extragalactic gamma-ray background (EGB) as measured by Fermi’s Large Area Telescope at GeV energies can shed light onto the nature of the IGMF. As its name implies, the EGB is a diffuse background of, presumably, extragalactic gamma-ray radiation. While the exact amount of each of the postulated contributions to the EGB remains an open question, unresolved astrophysical sources of gamma rays such as active galactic nuclei and star-forming galaxies could comprise a large fraction. Additionally, there could be a contribution from truly diffuse radiation arising from the interactions of TeV gamma rays originating from some of these same sources: as TeV gamma rays traverse the cosmos, they interact with the photons of the cosmic microwave background (CMB) and the background of infrared, optical, and ultraviolet radiation from direct and dust-reprocessed starlight. Pairs of electrons and positrons are created during these interactions, which will, in turn, Inverse Compton scatter CMB photons to high energies, thereby initiating an electromagnetic cascade. In the presence of a magnetic field, the charged particles of the cascade are deflected away from the direction of propagation resulting in several observational consequences. First, the charged particles can upscatter soft photons towards the observer but they will appear to be coming from a different direction, resulting in the formation of a halo of gamma rays around the source. Since many photons are deflected out of the observer’s line-of-sight, the spectrum of diffuse radiation arising from cascades is suppressed, particularly at lower energies. Finally, the small-scale anisotropy in the EGB arising from rare but bright sources will be suppressed at energies where the cascade contribution is significant.

In studying the development of electromagnetic cascades in the intergalactic magnetic fields, Venters and Pavlidou have determined the impact on the small-scale anisotropy of the EGB as a function of energy (the anisotropy energy spectrum) for a variety of EGB models and source spectra. The anisotropy energy spectrum is a potentially powerful tool for studying the components of the EGB since even source classes

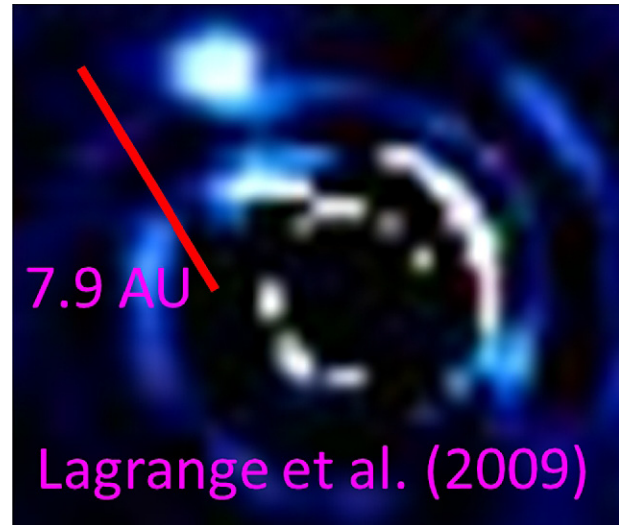
for which the contribution to the EGB is subdominant with respect to other contributions can still have a profound impact on the anisotropy of the EGB, especially if the fractional contribution of such source classes changes with energy. Since the contribution of a given source class to the anisotropy for a given angular scale,  $C_p$ , at a given energy is given by the square of its fractional contribution to the intensity of the EGB multiplied by its anisotropy (determined from the source count distribution), even a relatively small contribution to the total EGB intensity can result in a significant impact on the anisotropy.

The plot shows the impact of electromagnetic cascades on the anisotropy energy spectrum for two assumptions of the magnitude of the intergalactic magnetic field. Notably, there is a distinct difference between the zero magnetic field and the nonzero magnetic field cases due to the increasing isotropization of the EGB at high energies in the nonzero magnetic field case. Venters and Pavlidou have found that current Fermi data can already constrain the strength of the IGMF. With several more years of data and the continuing theoretical work of Venters and Pavlidou, Fermi will be able to more strongly constrain the IGMF, reaching limits that have thus far been unobtainable.

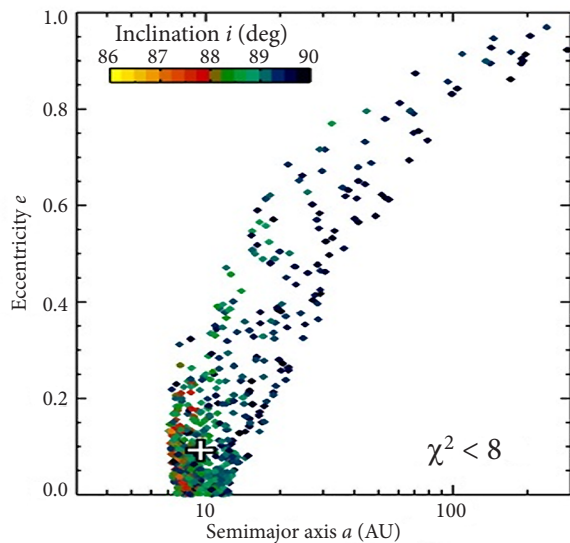
### *A 5 $\mu$ Image of Beta Pictoris b at a Sub-Jupiter Projected Separation*

The nearby, 12-Myr-old A-type star Beta Pictoris was long suspected to harbor a young planetary system, and recently a  $\sim 9$  Jupiter-mass planet (Beta Pictoris b) was discovered orbiting this star (Lagrange et al. 2009a, 2010). In these studies, the planet was detected at a projected separation of 8 AU ( $\sim 0.4$  arcsecond) from data taken in 2003 and at  $\sim 6$ – $7$  AU but on the other side of the star from 2009–2010 data, suggesting that the planet completed a substantial fraction of its orbit over the course of 7 years.

Thus, not only is Beta Pic b one of the few known directly imaged planets, but it also may provide a better comparison to the solar system's gas giants than other directly imaged planets (HR 8799bcde; Fomalhaut b), which orbit farther away from their host stars. Data taken between 2004 and 2008, when the planet was at a smaller projected separation, would better constrain its orbit. However, previous studies observing Beta Pic



*Images of Beta Pic b. Top: An L-band image from Nov. 2003 data (Lagrange et al. 2009). Middle: M-band image from Nov. 2008 data (Currie et al. 2011). Bottom: A rereduced L-band image from Dec. 2009 data (Currie et al. 2011).*



Orbital analysis results for Beta Pic data from Currie et al. (2011) for orbits whose fits to the Beta Pic b astrometry are good to within a  $\chi^2$  of 1 per degree of freedom. The family of solutions in semimajor axis, eccentricity, and inclination space.

during this time only report nondetections (Lagrange et al. 2009b; Fitzgerald et al. 2009).

Thayne Currie from NASA's Goddard Space Flight Center reexamined data from which previous studies reported non-detections of Beta Pic b, using a new state-of-the-art image-processing pipeline to better extract faint planet signals from the glare of the host star. He detected Beta Pic b from archival M'-band/5-micron VLT data taken in 2008, when the planet was at a projected separation of  $\sim 4$  AU, and obtained a much sharper image of the planet from data where the planet was previously detected.

Combining these with other data where Beta Pic b was detected constrained the orbital properties and atmosphere of the planet. The planet likely has thicker clouds than do other substellar objects (e.g., brown dwarfs) of the same temperature, though the evidence for this is weaker than for planet around HR 8799. The planet's orbit is viewed almost perfectly edge on, and the planet has a Saturn-like semimajor axis of  $\sim 9.5$  AU.

Intriguingly, Beta Pic b appears to have a longitude of ascending node of  $\sim 31^\circ$ , which would put it in the plane of the main disk but misaligned with the warp/inclined disk at  $\sim 80$  AU (offset by  $\sim 5^\circ$ ) that was discovered with Hubble Space Telescope observa-

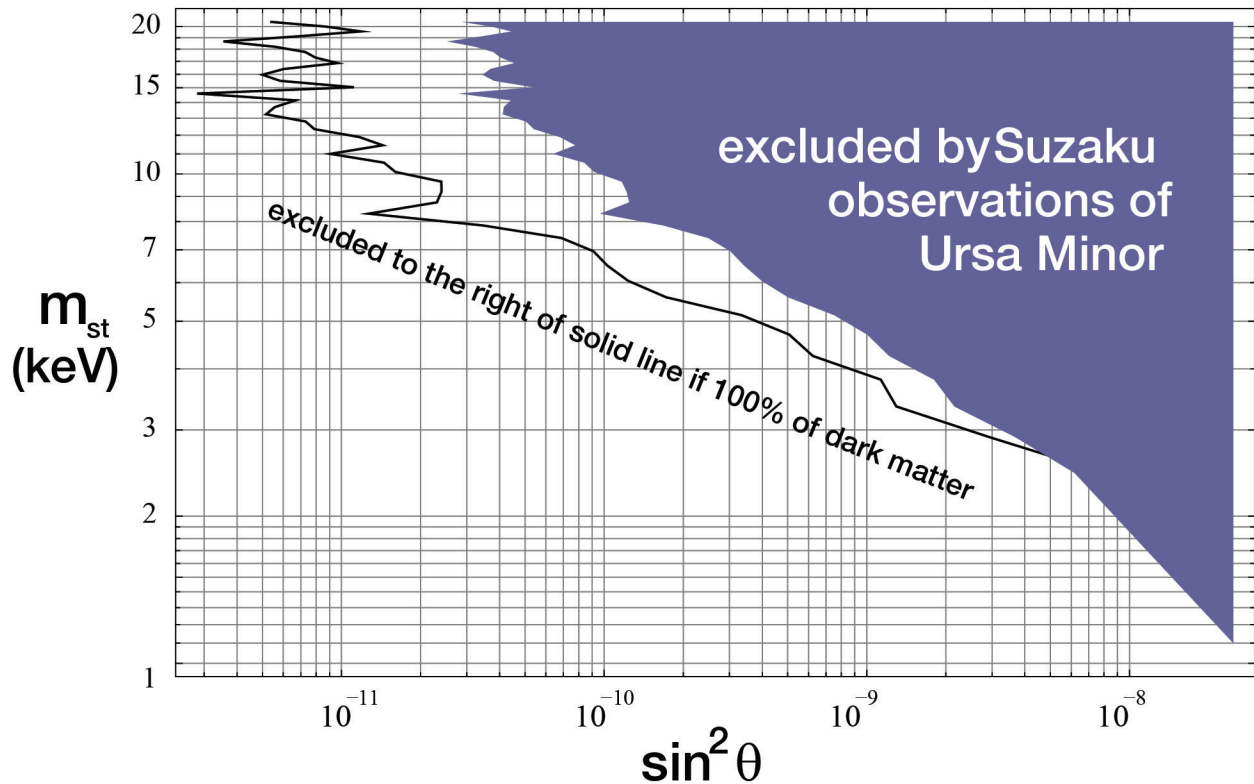
tions. Previously, models for explaining the disk warp, and for estimating the planet's mass, assumed that the planet was misaligned with the main disk and aligned with the warp. These new results motivate new observations to better clarify exactly how Beta Pic b's orbital plane is related to the main and warped disk components, new dynamical modeling of the disk warp, and searches for other planets in the system that could induce dynamical structures in the disk.

### Search for Dark Matter Using X-ray Observations of Dwarf Spheroidal Galaxies

The nature of dark matter is one of the outstanding unsolved problems in particle physics and astrophysics, and new physics will emerge with the identification of the dark matter particle. Searches for weakly interacting massive particle (WIMP) dark matter are, as yet, unsuccessful, and a number of observations of structure in the universe conflict with the Cold Dark Matter (CDM) paradigm. Therefore, consideration of alternative dark matter candidates is scientifically imperative.

There are several such candidates at the keV-mass range with observational signatures in the form of discrete X-ray radiative decay features emitted from regions of high dark matter concentration. Search for these emission lines does not require a dedicated experiment, as with direct detection efforts, but does merit a dedicated search that employs a careful and uniform analysis of well-chosen targets observed with the full fleet of current X-ray observatories, which have complementary capabilities for conducting imaging spectroscopy. This must be supported by thorough and careful theoretical consideration of the physical plausibility of such dark matter candidates and, at the same time, an open-minded approach to exploring candidates that are implicit in various proposals beyond the Standard Model of particle physics.

The research program led by Michael Loewenstein (University of Maryland at College Park, Center for Research and Exploration in Space Science and Technology, and NASA/Goddard Space Flight Center) and Alexander Kusenko (University of California at Los Angeles, Institute for the Physics and Mathematics at the University of Tokyo) focuses on two particularly compelling keV dark matter candidates, although the results may be more generically applied. An ongoing

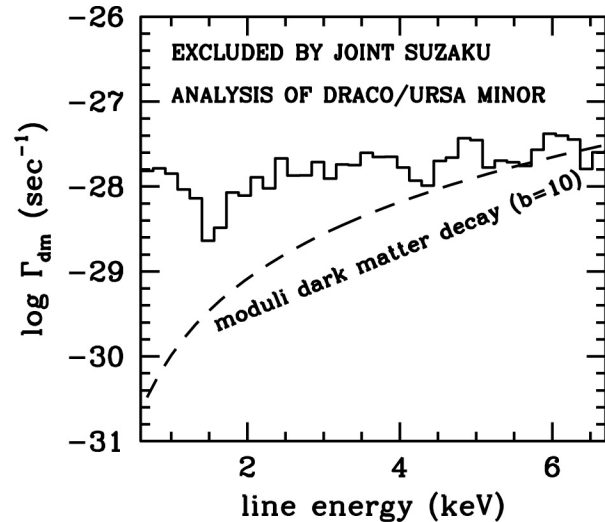


Sterile neutrino parameter space to the right of the solid curve is excluded by the Suzaku observation of Ursa Minor if dark matter is solely composed of sterile neutrinos produced by some (unspecified) mechanism. The solid exclusion region is model-independent, based only on the assumption of the standard cosmological history below the temperature of a few hundred MeV, when the production by neutrino oscillations takes place.

study focuses on the keV-mass sterile neutrino. The existence of sterile neutrinos is predicted in most extensions of the Standard Model that explain the mass of the active neutrino. If their mass lies in the 1–30 keV range, they are a plausible (warm) dark matter candidate that may resolve some of the discrepancies in CDM models while explaining pulsar kicks and facilitating primordial star formation. Moduli dark matter, a novel and equally promising candidate, is the focus of their most recent effort. These fields are generically predicted in a large class of theories for physics beyond the Standard Model, and account for dark matter if the ratio of the scale of the new physics to the Planck scale falls in the range determined by anthropic selection.

Loewenstein and Kusenko initiated the first dedicated search for dark matter using X-ray telescopes to observe dwarf spheroidal galaxies, which are ideal targets by virtue of their proximity, high dark matter density, and absence of competing X-ray sources. Working with Peter Biermann (Max-Planck-Institut für Radioastronomie, University of Karlsruhe, University of

Alabama), they placed new limits on sterile neutrino mass and mixing angle from Suzaku XIS spectra of



Constraints on the string moduli  $b$  parameter, which may be interpreted as the effective moduli scale in units of the reduced Planck scale, from joint analysis of Suzaku spectra of the Ursa Minor and Draco dwarf spheroidal galaxies. The 99% joint confidence line flux limit rules out  $b > 10$ .

the Ursa Minor dwarf spheroidal galaxy. These limits compare to the best previous results over the entire 1–20 keV mass range yet do not rule out sterile neutrinos as a viable dark matter candidate.

Loewenstein and Kusenko continued the search with Chandra observation of the ultra-faint dwarf spheroidal Willman 1. They found evidence for an emission line from the radiative decay of a 5-keV sterile neutrino with a mixing angle in the narrow range where oscillations produce all of the dark matter and for which sterile neutrino emission from cooling neutron stars can explain pulsar kicks. This tentative detection is best confirmed (or refuted) by utilizing the large effective area of the XMM-Newton EPIC detectors, and a team led by Loewenstein was awarded XMM-Newton time to observe Willman 1 for this purpose. Rigorous analysis of these data using novel techniques excludes the best-fit estimate of the Chandra 2.5-keV line flux at > 90% confidence. Having developed the methodology on this dataset, the team plans to apply it more widely in order to conduct the most sensitive search for sterile neutrinos to date.

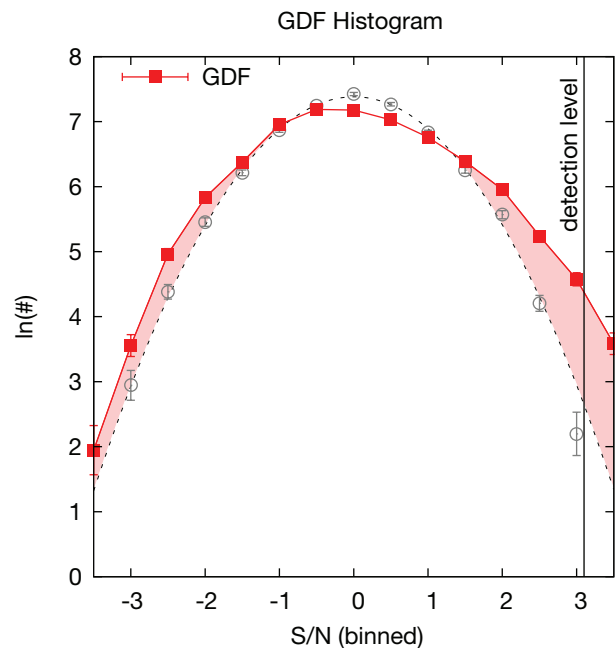
Many of these same considerations apply to moduli dark matter. Working with Tsutomu Yanagida of IPMU, Loewenstein and Kusenko derive limits on the effective moduli scale in units of the reduced Planck scale from Suzaku analysis of XIS spectra of the Ursa Minor and Draco dwarf spheroidals, thus providing constraints on the relevant new physics, such as string theory compactification or supersymmetry breaking.

### *The GISMO 2-millimeter Deep Field in GOODS-N*

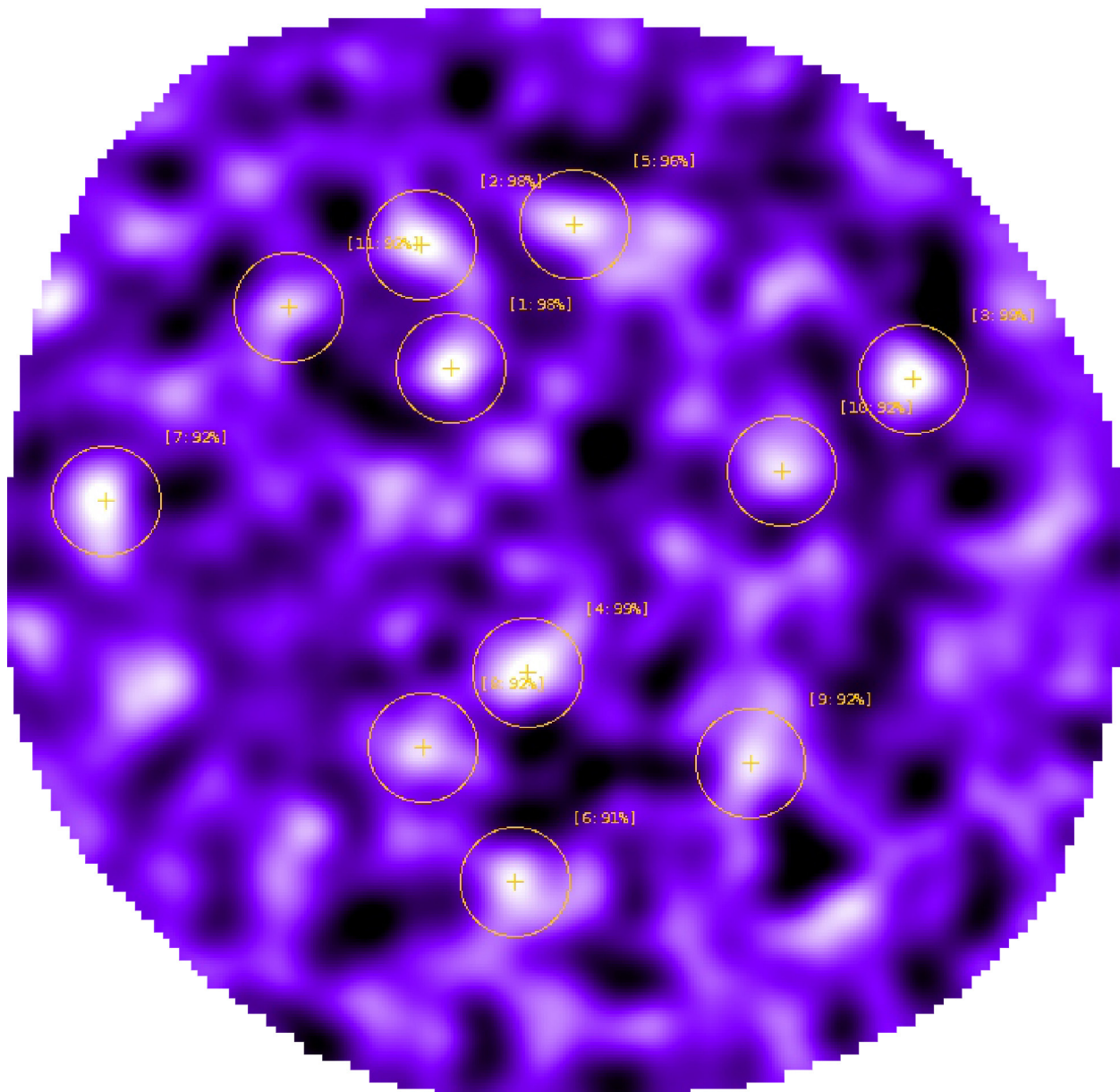
Extreme starburst galaxies are among the most luminous galaxies in the Universe, and the number density of these objects has gone through a significant evolution, peaking at redshifts  $z > 1$ . The most massive objects of this class are predicted to be at the center of galaxy clusters that reside in dark matter halos and therefore can be used to trace high-density regions in the early Universe. Rest-frame far-infrared continuum observations of luminous, dusty galaxies are well suited to determine the star-formation rate and the total energy output in these objects because virtually all of the stellar ultraviolet and optical radiation is being absorbed by interstellar dust and reradiated in the far-infrared. For large redshifts, the peak of the Spectral Energy Distribution (SED) of these galaxies is being

shifted into the (sub-)millimeter regime. The first instrument that detected ultraluminous galaxies at high redshifts was SCUBA on the JCMT, which obtained the famous SCUBA-Deep Field in the HDF-N.

The 2-mm atmospheric window has not been astronomically explored from the ground to the same degree as shorter wavelengths (1.3 mm or less). The reason is predominantly of technical nature, namely the very demanding requirements on the noise performance of a background-limited camera, operating in this low opacity atmospheric window. For many years, ASD Observational Cosmology Lab members Moseley, Benford, Staguhn, and Sharp, in collaboration with Jhabvala, Miller, and Chervenak from Goddard's Detector System Branch, have been working on the development of low-noise superconducting Transition Edge Sensor (TES) bolometer technologies for the far-infrared (FIR). These efforts have yielded devices with sensitivities that exceed those required for the 2-mm ground-based observations. Consequently, Staguhn and other members of this group, plus Fixsen from the Observational Cosmology Lab, have built a 2-mm wavelength bolometer camera, the Goddard-IRAM Superconducting 2 Millimeter Observer (GISMO), for astronomical observations at the IRAM 30m telescope on Pico Veleta, Spain. Observations and data



*Histogram of signal/noise in GDF data (red symbols). Superimposed is the histogram of the jackknifed GDF signal-to-noise data (grey symbols), which closely follows a Gaussian distribution (dashed grey line).*



The GISMO Deep Field (GDF) which is centered on the Hubble Deep Field-North. Circles mark 11 sources identified in the field, with labels indicating the confidence for detection. With an rms of  $\sim 134$  mJy in the central few arcminutes, the GDF is the deepest (sub-)millimeter field ever observed.

interpretation were additionally supported by Dwek, Arendt, and Maher from the Observational Cosmology Lab.

GISMO uses an  $8 \times 16$  array of close-packed, high-sensitivity TES bolometers with a pixel size of  $2 \times 2$  mm<sup>2</sup> that was under the lead of Jhabvala. SQUID time domain multiplexers from NIST/Boulder read out the superconducting bolometers. The array architecture we use is based on the Backshort Under Grid (BUG) design.

GISMO observed an area around the HDF at 2 mm wavelength with a total integration time of 25 hours. The rms near the center of this map is about 134 mJy, which is a factor of 3 lower than in any other (sub-)millimeter field (the deepest of those being the SCUBA “Supermap” with a depth of  $\sim 400$  mJy rms). In this field, we extracted 11 sources with the expectation that one of them is a spurious false detection. The corresponding area for the source extraction is 0.00562 square degree, i.e., it contains  $\sim 210$  telescope beams.



The measured source fluxes range from 450 mJy to 750 mJy. Our models predict that all but one of these galaxies are at a redshift of  $z > 4$ , and that about 25% of those are at a redshift of  $z > 6.5$ . Indeed, seven of these sources (one of them being SCUBA 850.1) have counterparts in 1.2 mm (Mambo-2/AzTEC) and/or 0.85 mm (SCUBA) maps, with colors consistent with redshifts between 4 and 6. We speculate that the remaining four sources that turn out not to be false detections are at redshifts of about 6 and beyond. SED models predict the bolometric luminosities for the detected sources to be around  $10^{12}$  solar masses.

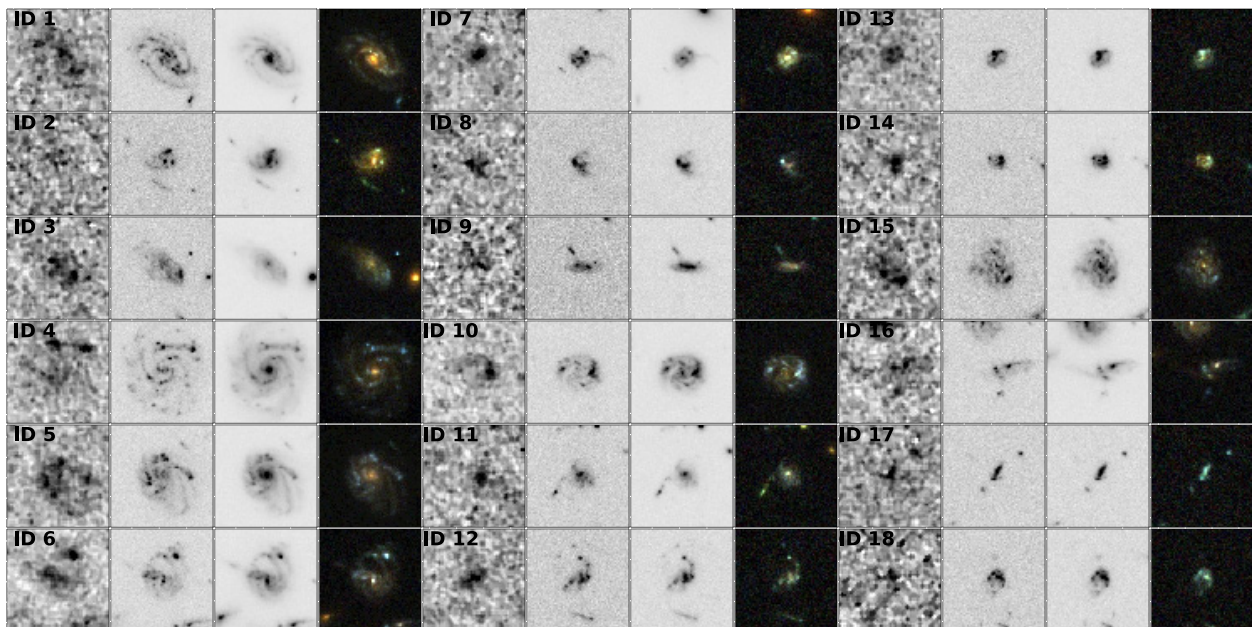
The statistics in our GDF data, superimposed over the jackknifed (a statistical method to cancel out any source emission in the map) version of the same data, follows an extremely close Gaussian distribution, illustrating the high quality of the data. The source excess for positive S/N values is clearly visible in the histogram. There is a good probability that there is also an excess for negative values, but our analysis of this aspect of the statistics in the data is still ongoing.

### *Rest-Frame Ultraviolet Star-Forming Galaxies at Intermediate Redshift Epochs*

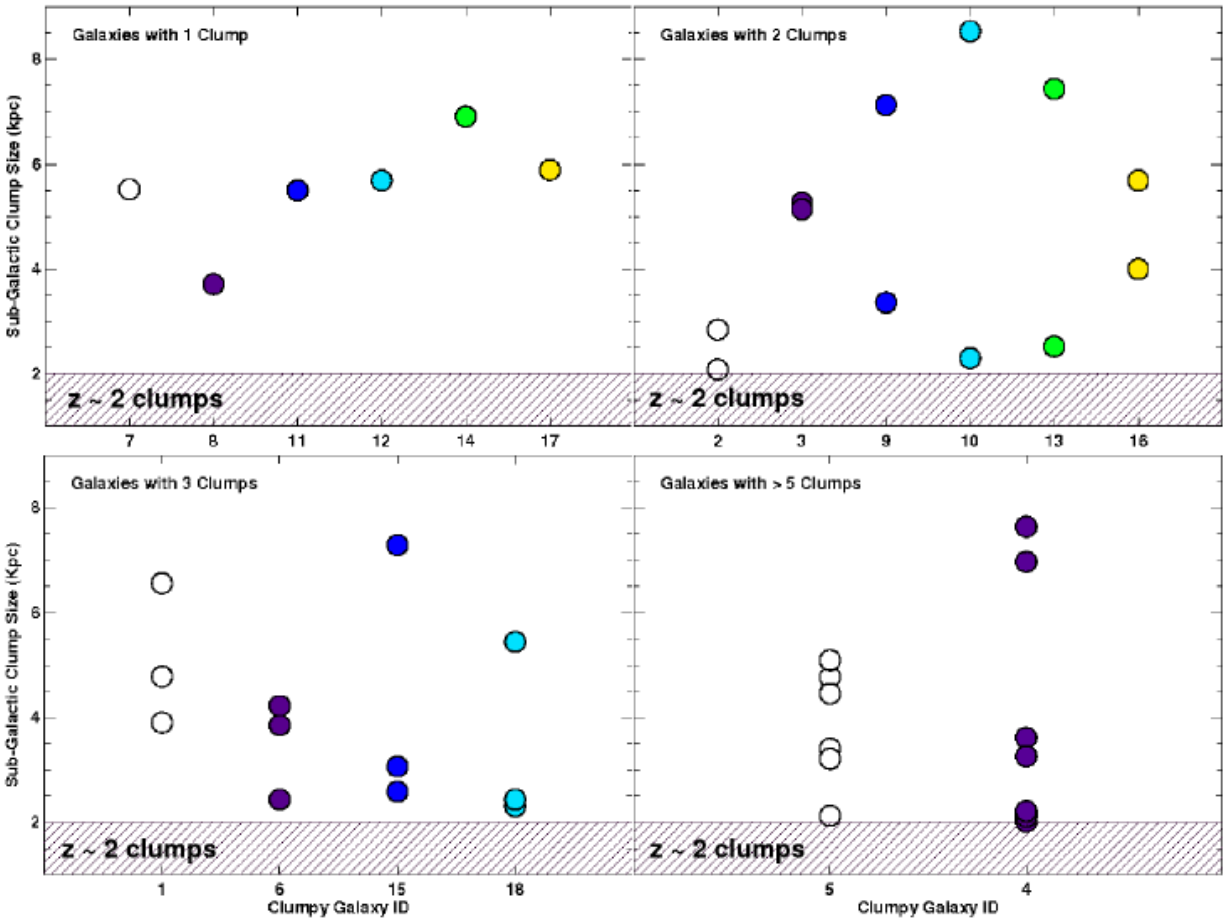
In order to explore the processes of galaxy evolution over cosmic time, it is vital to study its primary physi-

cal drivers, including the formation of stars within galaxies. Numerous data of distant ( $z > 2$ ) and local ( $z = 0$ ) galaxies have been analyzed by astronomers (e.g., Connolly et al. 1997, Madau 1998, Dahlen et al. 2005, Bouwens et al. 2006, Wadadekar et al. 2006) in order to calculate the cosmic star-formation history of the Universe which reveals a sudden decline in star-formation rate (SFR) density at  $z \sim 1$ . The main processes that caused the drop in the SFR density are still unclear, and this remains a key open question in observational cosmology. Paralleling the decline of star-formation in galaxies is the emergence of Hubble-type galaxy morphologies (i.e., elliptical, spiral, barred spiral, irregular) that dominate the local Universe. In the distant Universe, most galaxies do not have these standard morphologies; instead, they are very irregular and can be interacting, live in groups and clusters, and have tidal tails and extended halos. Some of the defining questions of modern astronomy: When did galaxies obtain their Hubble morphologies? What physical mechanisms evolved galaxies into these well-defined morphologies?

Motivated by these broad questions, former NASA Goddard GSRP fellow Elysse Voyer, Observational Cosmology Lab scientists Drs. Duilia de Mello and Jonathan Gardner, and their collaborators at NASA/IPAC and UC Riverside have been conducting several studies on distant rest-frame ultraviolet star-forming



*A multiwavelength gallery of 18 selected clumpy galaxies. In each column, from left to right, the images are WFPC2 U-band, ACS B-band, ACS i-band, and ACS BViz color combined. All cutouts are  $5 \times 5$  arcseconds in size.*

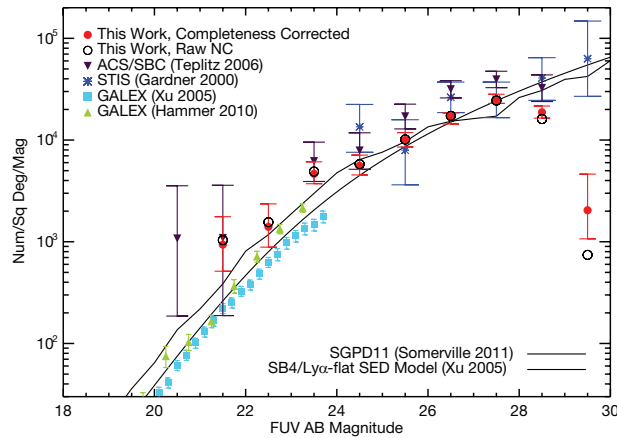


The kiloparsec sizes of individual rest-UV sub-galactic clumps in the HUDF are presented for each of the 18 clumpy galaxies measured. Galaxies are separated amongst the four plots as a function of the total number of sub-galactic clumps they contain. For comparison, the  $z \sim 2$  rest-UV sub-galactic clump size range measured by Elmegreen & Elmegreen (2005) is drawn on each plot.

galaxies that populated the universe  $\sim 4.5$ -9 billion years after the Big Bang, during the universal decline of the SFR density ( $0.4 < z < 1.4$ , i.e., intermediate- $z$ ). Emission from star-forming galaxies is dominated by the UV light from short-lived, massive O- and B-type stars. Thus, the UV spectrum detects the most recent star-formation activity in these galaxies. Because only HST has the unique capabilities to resolve rest-frame UV morphological structures during this redshift epoch, the team uses broadband HST imaging data observed through FUV and U-band filters as the foundation for their work.

In 2009 Voyer, de Mello, Gardner, and collaborators published a catalog of galaxies from the first targeted space-based U-band image of the Hubble Ultra Deep Field (HUDF) taken with HST's WFPC2. The analysis of these 96 star-forming sources revealed that the majority of this population has visual morpholo-

gies of spiral-type galaxies but are split between the SED-based morphological spectral types (STs) of late-type spirals and starburst galaxies. Measurements of the half-light-radii brightness profiles of all the sources revealed no strong evolution in the rest-frame UV sizes of star-forming galaxies over this epoch. Currently, several theoretical groups have been simulating the secular evolution of disk galaxies and predict that, during formation, sub-galactic scale "clumps" of material coalesce to form galaxy bulges if they are gravitationally supported, or dissipate into the disk if not gravitationally supported, on timescales as short as  $\sim 500$  Myr (Elmegreen et al. 2008, Krumholz & Dekel 2010, Agertz et al. 2011, Ceverino et al. 2011). This motivated the team to investigate the physical sizes of a sub-sample of 18 clumpy star-forming galaxies from the U-band catalog. Their preliminary findings show that intermediate- $z$  sub-galactic star-forming clumps



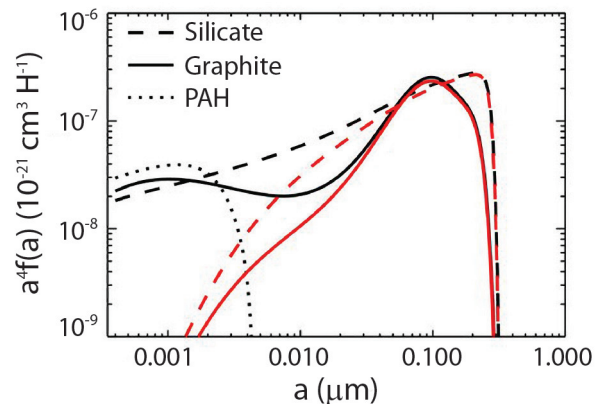
*FUV number counts of field galaxies from this work, shown with FUV number counts from previous studies and compared to semi-analytic models. Error bars are Poissonian from Gehrels (1986). The caps of the error bars do not reflect an error in magnitude, but have been manually varied in length to better distinguish among them.*

range between 1.6–10.9 kpc in physical size and their host galaxies contain between 1–5 clumps each. At higher redshifts,  $z \sim 2$ –3, these sub-galactic clumps measured at the same UV rest-frame wavelengths have smaller sizes—between 1–2 kpc—and are more numerous, with  $\sim 5$ –10 clumps per galaxy (Elmegreen & Elmegreen 2005). Thus, a potential size and number evolution has been detected, lending observational support to the current theoretical studies of disk formation.

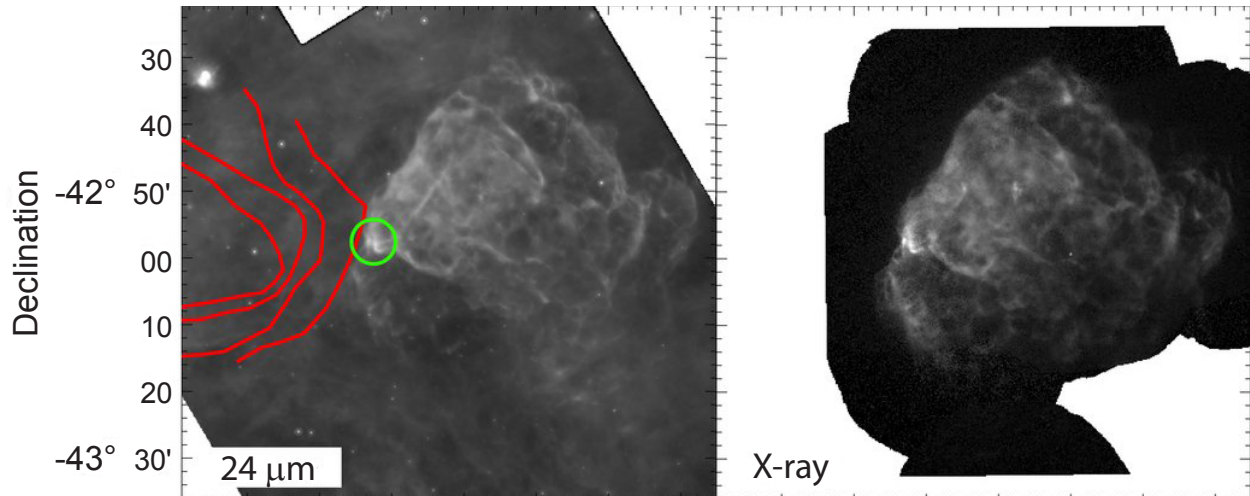
Expanding on this initial work, the team facilitated a larger statistical study of the intermediate- $z$  star-forming population from several deep ( $< 28.5$  magnitudes) FUV observations taken with the HST ACS Solar Blind Channel in the Great Observatories Origins Deep Survey-North and -South fields, including the HUDF and the Hubble Deep Field North. Using a sample of 333 FUV-detected galaxies, the team calculated and published the latest measurement of the FUV number counts of field galaxies. Number counts of star-forming galaxies provide a constraint on the evolution of the SFR density of the Universe. This new study covers an area about four times larger than the most recent HST FUV study (Teplitz et al. 2006) over multiple sight-lines, thus reducing the effects of cosmic variance in the measurements compared to previous studies. The counts are also in good agreement with results of the most recent semi-analytic models of galaxy evolution by R.S. Somerville and col-

laborators that are based on dark matter “merger trees” and WMAP5 cosmology. With these data, Voyer et al. have also determined a new measurement of the FUV-resolved extragalactic background light (EBL) from galaxies, finding a contribution between  $65.9 \pm 8$  and  $82.6 \pm 12$  photons  $s^{-1} cm^{-2} sr^{-1} \text{ \AA}^{-1}$  to the total UV background light. The new EBL measurement can be interpreted as an average of the SFR density over cosmological time, providing a lower limit for future measurements of the total UV background.

Utilizing a statistically large sub-sample of FUV-detected sources, this group is currently investigating the quantitative optical morphologies of star-forming galaxies over the intermediate epoch. This work emphasizes the importance of studying galaxy evolution from a multiwavelength perspective in order to achieve a more complete picture of the evolutionary scenario. They have made measurements of the light profiles as a function of radius (Sérsic index) in the optical rest-frame V-band images of 230 FUV-detected sources that also have SED-based STs from publicly available optical catalogs. Their initial analysis comparing these two morphological indicators shows that star formation is primarily occurring in disk or merger optical morphologies over  $0.1 < z < 1.2$ . Galaxies with Magellanic irregular STs have the best correlation with Sérsic index, with 45% having Sérsic indices indicating mergers and  $\sim 50\%$  indicating disks. Analysis of the Sbc spiral STs demonstrate that the rest-frame optical light profiles of disks span a wide range of Sérsic indices without much variation in their SEDs throughout the intermediate- $z$  epoch.



*The dashed lines depict the size distribution of the different grain types in the molecular cloud, whereas the solid lines depict their size distribution in the shocked gas (green circle in the infrared image).*



Images of Puppis A in the infrared and X-ray are essentially identical. Left: Spitzer 24 micron infrared view. Red lines mark the contours of CO emission from a molecular cloud that is being hit by the expanding remnant; the green circle marks an area of shocked gas. Right: Chandra X-ray image.

### *The Destruction of Interstellar Dust by Supernova Blast Waves*

The presence of dust in the interstellar medium manifests itself by the extinction, reddening and polarization of starlight, its infrared emission, and by depleting the gas of important refractory elements such as carbon, magnesium, silicon, iron, titanium, and calcium. In spite of abundant observations, the cycle of dust is still poorly understood. Dust is created in the quiescent outflows of red giant stars during the AGB phase of their evolution and in the explosive ejecta of massive stars that end their lives in powerful supernova explosions. Dust is also destroyed in the interstellar medium as it encounters the blast waves generated by these explosions. Quantifying the total amount of dust created in stellar ejecta and destroyed by interstellar shocks is extremely important for understanding the origin and evolution of dust in the Milky Way as well as in external galaxies.

The supernova remnant (SNR) Puppis A offers a great opportunity to study the destruction of dust by a supernova blast wave. Comparing images of the remnant in the infrared and X-ray, it's clear that Puppis A is one of the rare astronomical sites in which the infrared emission arises from dust that is collisionally heated by the X-ray emitting gas. In most other astrophysical environments, dust is heated by and reradiating the energy it absorbs from ambient starlight.

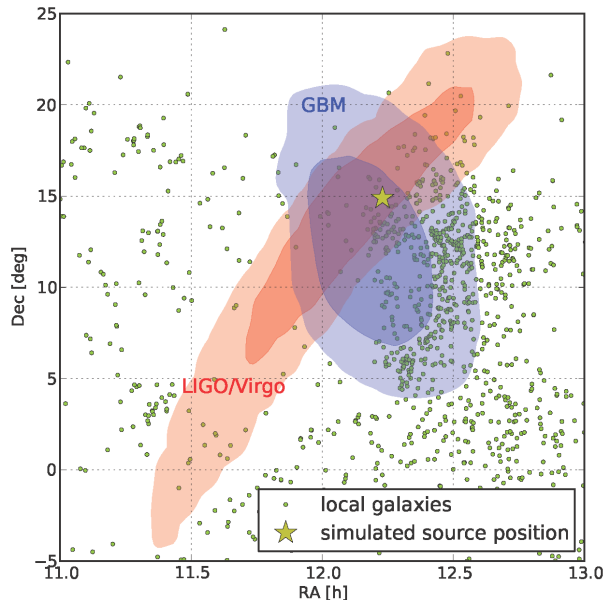
The same gas that heats the dust also destroys it by thermal sputtering. In a paper published in *The Astro-*

*physical Journal*, Arendt, Dwek, and coworkers analyzed the dust properties, abundances, composition, and size distribution before and after the encounter with the SNR blast wave. The results show that the polycyclic aromatic hydrocarbon (PAH) macromolecules that constitute about 10 percent of the total interstellar carbon abundance are totally destroyed by the shock, as is about 25 percent of the graphite and silicate dust.

The X-ray models of the interaction region suggest that the shock velocity is about 5,000 km/s. By comparing these results to model simulations, scientists can calculate the total mass of dust destroyed by a single supernova remnant during its lifetime. To account for the total mass of dust seen in the interstellar medium, this mass must be balanced by dust formation in the different stellar sources. The multi-wavelength analysis of the interaction of dust grains with supernova shock waves has put scientists one step closer to understanding the origin and evolution of dust in the interstellar medium.

### *Searching for Electromagnetic Counterparts to Gravitational-Wave Events*

The next decade should mark the opening of the gravitational-wave sky as the Advanced LIGO gravitational-wave detectors come online with sufficient sensitivity to see tens of binary neutron-star (NS) coalescence events per year. As the principle progenitor



Position reconstruction of a simulated typical NS/NS binary merger as seen by the initial LIGO/Virgo gravitational-wave detectors and a simulated weak coincident GRB detected by Fermi GBM. The one- and two-sigma error regions overlap a background of possible nearby host galaxies out to 30 Mpc, consistent with the gravitational-wave amplitude. Their locations are searched using RXTE ASM for an X-ray afterglow up to several hours after coalescence.

model for short gamma-ray bursts (sGRBs), these are of particular interest to multi-messenger astronomy. Dr. Jordan Camp and NPP postdoc Dr. Lindy Blackburn are helping to prepare for this era by designing coordinated searches between existing ground-based gravitational-wave detectors and NASA high-energy photon instruments.

The current search in development uses available science data from the first generation Initial LIGO and Virgo detectors collected during 2005–2010. The instruments operated near or in some cases beyond their design sensitivity (depending on frequency), and were able to detect an optimally oriented NS/NS coalescence out to  $\sim 30$  Mpc. The limited reach, almost a factor of ten from the advanced detector target, makes it possible though unlikely that an event occurred close enough to detect. Indeed, existing searches have so far not seen any events loud enough to claim detection from gravitational-wave data alone. However, by requiring time and sky location consistency with an electromagnetic counterpart, the background of these searches can be dramatically reduced, which will al-

low a weaker event to stand out above transient noise sources.

The two instruments chosen for this coincidence study include the soft X-ray All-Sky Monitor (ASM) on RXTE and the Gamma-ray Burst Monitor (GBM) aboard Fermi. Both are particularly well suited for following up on gravitational-wave events because of their large, regular coverage of the entire sky and because the relative closeness of detectable gravitational-wave sources means the EM counterparts should be fairly bright. ASM, with a sensitivity of 20 mCrab over a standard 90-second dwell, would be able to detect a typical sGRB afterglow at the LIGO horizon of 30 Mpc for days after the initial burst for the most luminous sGRBs.

The gravitational-wave data brings timing information as well as rough sky localization (to tens of square degrees); for a modeled source such as compact binary coalescence, it can also bring information about possible progenitor masses, distance, and orbital characteristics. The information is used to perform a detailed targeted search of archival EM data. GBM saves counts information from each of its fourteen detectors at quarter-second resolution. Along with an appropriate spectral model and understanding of the instrumental response, the rates are used to check location consistency with the gravitational-wave trigger. The known location and response also define an optimal coherent sum of the detector data, increasing the signal-to-noise of any gamma-ray excess, and allowing a search below the nominal thresholds used for onboard GBM triggering. These effects fold naturally into a likelihood-ratio statistic, which can be directly applied in prompt coincidence with triggers from a gravitational-wave search.

If we miss the prompt gamma-ray emission from an sGRB due to incomplete coverage or beaming effects, it may still be possible to pick up the X-ray afterglow. A preceding gravitational-wave merger signal would provide compelling evidence to confirm such an orphan afterglow signal, and a population of such events will eventually give us important information about sGRB beaming angles and jet characteristics. ASM uses a set of three shadow-mask X-ray cameras to scan the 1–10 keV sky, taking 90-second images of a patch in the sky as often as once every 90 minutes. Although we don't yet know empirically what an off-axis afterglow looks like, measurements of on-axis



*BESS-Polar II prepares for launch from Williams Field near McMurdo Station, Antarctica, in Dec. 2007. BESS-Polar II flew for 24.5 days with the superconducting magnet energized and measured over 4.7 billion cosmic ray events.*

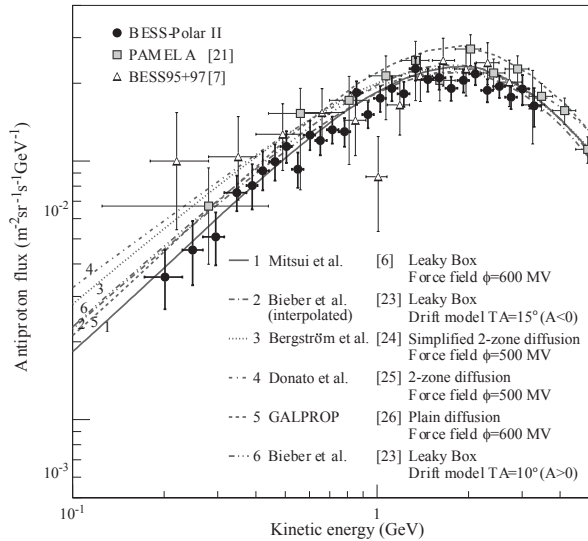
X-ray afterglows from Swift XRT indicate that ASM should be able to detect such events within the LIGO NS/NS merger horizon for at least several hours. The shadow-mask cameras are able to image down to  $\sim 0.1$  degrees, which in many cases provides a unique galaxy identification at these close distances. Using a catalog of known nearby galaxies, the data are sensitively searched specifically at the locations of galaxies with distances consistent with the gravitational-wave event. Similar to the prompt analysis with GBM, the X-ray signal-to-noise, galaxy mass (assumed to be proportional to merger rate), and location and distance overlap are folded into a joint likelihood-based statistic for detection of coincident gravitational-wave/X-ray events.

The last year has seen the development of two fully-automated follow-up pipelines for a targeted analysis of archival data from both NASA instruments, done in close coordination with mission scientists. On the gravitational-wave side, the joint analysis provides an important first large-scale application of recently available Bayesian parameter estimation methods which use nested sampling on the gravitational-wave data to provide estimates of sky location and distance

for binary mergers. Validation of the events from the Bayesian follow-up—running the EM pipelines on them will occur over the next several months—provide estimates of joint search backgrounds and sensitivities. The direct detection of gravitational waves will ultimately be an exciting first look at the innermost dynamics of the most extreme events in our universe, and associating the gravitational-wave signal with EM observations will be central to answering the two most relevant questions about the source: what are we looking at, and where is it?

### ***BESS-Polar Long-Duration Flights***

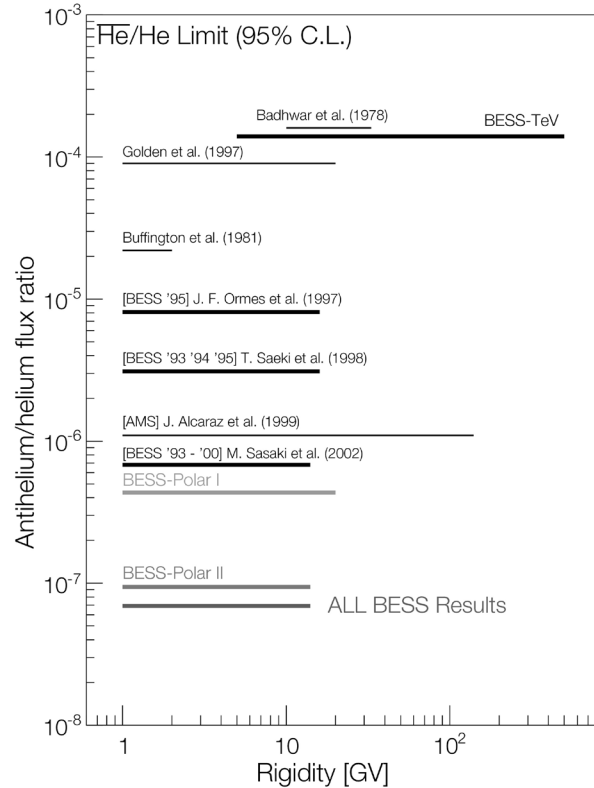
Among the most compelling questions in cosmology and astrophysics are the nature of the ubiquitous dark matter and the apparent dominance of matter over antimatter. The BESS-Polar (Balloon-borne Experiment with a Superconducting Spectrometer – Polar) instrument was developed by a collaboration co-led by GSFC (Dr. John W. Mitchell) and KEK (High Energy Accelerator Research Organization – Dr. Akira Yamamoto) for sensitive investigations of these questions in long-duration balloon flights over Antarctica.



The high-precision BESS-Polar II spectrum compared with contemporary measurements with lower statistics from the PAMELA (Payload for Antimatter and Matter Exploration and Light-nuclei Astrophysics) satellite instrument, which uses a permanent magnet, the BESS 1995/1997 results, and predictions of secondary antiproton production and transport models.

Mitchell, Makoto Sasaki, and Thomas Ham are long-term members of the BESS-Polar team at GSFC and Kenichi Sakai has recently joined after completing his Ph.D. using BESS-Polar II data. BESS-Polar succeeds the exceptionally productive BESS instrument that, in several progressively improved versions, made nine conventional one-day northern-latitude balloon flights between 1993 and 2002.

BESS originated as a prototype for the Astromag superconducting magnet facility on the International Space Station, initially intended to investigate cosmic-ray antimatter and measure cosmic-ray isotopic ratios to relativistic energies. Accelerator experiments had shown antiprotons must be produced in interactions of cosmic ray nuclei with constituents of the interstellar medium. Propagated to Earth, a “secondary” antiproton spectrum was predicted to peak at  $\sim 2$  GeV, due to interaction kinematics, with absolute intensity  $\sim 10^{-5}$  of the proton flux at 1 GeV. Around 1980, seminal balloon-borne instruments using magnetic spectrometers or annihilation signatures reported substantial excesses of antiprotons at both high and low energies compared to calculations. This gave rise to wide speculation on other sources of antiprotons, but definitive measurements would require magnetic-rigidity spec-



BESS-Polar II 95% confidence upper limits to the ratio of antihelium to helium in the 1–14 GV magnetic rigidity range compared to earlier limits from BESS and other investigations. The new limit improves on the first BESS limit by over two orders of magnitude and is the most stringent reported.

trometers capable of accurate particle identification by charge sign, charge, and mass.

Such data could also probe another enduring mystery: the dominance of baryonic matter and complete absence of antimatter except for that produced in high-energy interactions. In the earliest moments of the Universe, matter and antimatter should have been symmetric and have since almost completely annihilated. Because significant amounts of matter survived, the symmetry must have been broken. The Sakharov conditions successfully laid out the requirements for symmetry-breaking but did not rule out the possibility that it could be local and that antimatter domains might still exist. Gamma-ray measurements set a separation scale by searching for signatures of annihilation at the matter-antimatter boundary, but photon measurements could not distinguish light produced in a matter galaxy from that of an antigalaxy. Production of antinucleons had been demonstrated in

nuclear collisions, but the most optimistic predictions of the probability of coalescence into an antinucleus more complex than an antideuteron suggested that the detection of even a single antihelium or heavier antinucleus would show that antimatter domains remain. (Recent cross-sections for antihelium production at the Relativistic Heavy Ion Collider support this.) A magnetic spectrometer was needed with large acceptance and the resolution to eliminate contamination of the search by high-energy helium.

BESS used a solenoidal superconducting coil that was thin enough for particles to easily penetrate and filled with a drift-chamber tracking system with low multiple scattering. This allowed a wide opening angle and large geometric acceptance, ideal for rare-particle measurements. Detectors to measure the charge and velocity of incident particles, time-of-flight and later a Cherenkov counter, formed partial cylinders around the magnet. The GSFC High Energy Cosmic Ray Group collaborated in BESS. Data from its inaugural 1993 flight included some of the first definitive identifications of cosmic-ray antiprotons, a discovery shared with the GSFC-led 1992 IMAX (Isotope Matter-Antimatter Experiment). By 1997, BESS was recording about 500 antiprotons in each flight and moved from discovery to using them as constraints on dark matter models and to investigate charge-sign dependent distortion or modulation of cosmic rays by magnetic fields entrained by the outflowing solar wind. BESS showed that the great majority of antiprotons are secondary, but the possibility of a primary component remained. BESS spectra in 1995 and 1997, near solar-minimum, indicated possible low-energy excess over secondary predictions, modeled as evaporation of small ( $\sim 5 \times 10^{11}$  kg) primordial black holes by Hawking radiation. BESS also searched for antihelium and found none, setting strong upper limits on the ratio of antihelium to helium.

BESS-Polar uses refined BESS instrumental techniques with exposure greatly increased in long-duration polar balloon flights. Threshold energy is halved by using a thinner magnet and detectors, a Cherenkov counter moved below the magnet, no pressure vessel, and a time-of-flight hodoscope within the magnet bore to lower by a factor of four the mass that particles have to traverse. BESS-Polar I flew 8.5 days from McMurdo Station, Antarctica, in 2004 at a time of

low but significant solar activity. BESS-Polar II flew near solar minimum in 2007–2008 for 24.5 days with the magnet energized. From the BESS-Polar II data, 7,886 cosmic ray antiprotons between 0.17 and 3.5 GeV satisfied the most rigorous analysis requirements. The results and initial interpretation were submitted to *Physical Review Letters*. Some of the secondary models fit the BESS-Polar II spectrum well and a primary component is not needed. The likelihood of antiprotons from primordial black hole evaporation was quantified and excludes, by over nine sigma, the slight possibility of primary antiprotons suggested by BESS 1995/1997 data. Within statistics, BESS-Polar II finds no evidence of primary antiprotons from primordial black holes.

BESS-Polar II data is being carefully searched for evidence of antihelium. Preliminary analysis, reported at the 32nd International Cosmic Ray Conference in Beijing, identified  $4 \times 10^7$  helium nuclei from 1 to 14 GV, but no antihelium, for an upper limit on the antihelium/helium ratio of  $9.4 \times 10^{-8}$ . Combining this with data from all other BESS flights, including BESS-Polar I, gives an upper limit of  $6.9 \times 10^{-8}$ —the most stringent limit to date. Final analysis is underway and results will be submitted to *Physical Review Letters*.

Both BESS-Polar flights are being used to search for antideuterons to precisely determine the spectra of light cosmic ray elements to energies above 100 GeV, including transient effects from solar activity, and to measure light isotope abundances. BESS-Polar II was recovered in 2009–2010 from Antarctica, requiring the recovery team to camp for 13 days at a site about 1,000 miles from the U.S. base at McMurdo station. The instrument was disassembled at the recovery site in order to fit it into the transport aircraft. Tests after the instrument was returned to GSFC showed that the detectors and electronics are operational. The magnet, which had to be partly disassembled, has been reworked and tested in Japan.

Plans are underway to re-optimize the BESS-Polar instrument to measure light isotopes, particularly Be, to relativistic energies. The ratio of radioactive  $^{10}\text{Be}$  to stable  $^9\text{Be}$  acts as a radioactive clock measuring the storage time of the cosmic rays in the Galaxy and, by employing time-dilation, can measure the fraction spent in the Galactic halo. BESS-Polar is uniquely capable of making these important measurements.



## Research and Development

### Suborbital

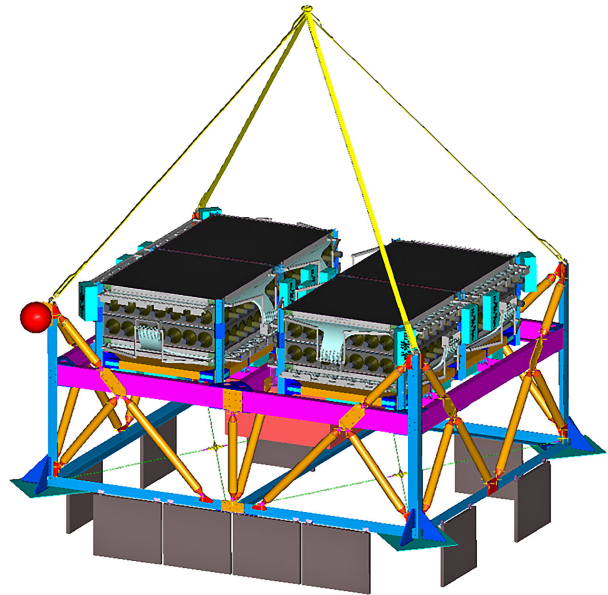
#### Super Trans-Iron Galactic Element Recorder (Super-TIGER)

Super-TIGER is a new, large-area balloon-borne instrument under development for long-duration Antarctic balloon flights, the first planned for December 2012. The Super-TIGER collaboration includes Washington University in St. Louis (PI, W. Robert Binns), GSFC, Caltech, and JPL. The GSFC team includes John Mitchell, Eric Christian, Georgia De Nolfo, Thomas Hams, Jason Link, Kenichi Sakai, and Makoto Sasaki.

Super-TIGER will measure the individual abundances of elements over the range  $30 \leq Z \leq 42$  with high statistical accuracy to test and clarify the emerging model of cosmic-ray origin in OB associations and models for atomic processes by which nuclei are selected for acceleration. Exploratory measurements with lower statistics will extend to  $Z = 60$ . Super-TIGER will also measure, with excellent statistical precision, the energy spectra of the more abundant elements  $14 \leq Z \leq 28$  at energies  $0.8 \leq E \leq 10$  GeV/nucleon. These measurements will provide a sensitive test of the hypothesis that microquasars or other phenomena could superpose features on the otherwise smooth energy spectra.

Super-TIGER is based on experience with the smaller TIGER instrument that was flown from Antarctica in 2001 and 2003 for a total of 50 days and produced the first measurements of individual element abundances for  $^{31}\text{Ga}$ ,  $^{32}\text{Ge}$ , and  $^{34}\text{Se}$ . Three layers of plastic scintillator and two Cherenkov detectors, one with an acrylic radiator and one with a silica aerogel radiator determine the charge and energy of incident nuclei. A scintillating optical fiber hodoscope gives particle trajectories to enable corrections for pathlength through the detectors, detector response maps, and interactions in the atmosphere and in the instrument.

Super-TIGER uses two independent detector modules, each with a  $1.15 \text{ m} \times 2.3 \text{ m}$  active area, giving a total detection area of  $5.4 \text{ m}^2$ . Each module is only 60 cm thick to maximize its geometric acceptance. The detector layout and minimal column



*The Super-TIGER instrument is under construction for a 2012 Antarctic long-duration balloon flight. Two independent detector modules are used to optimize performance and aid recovery of the instrumentation.*

density give an effective geometry factor of  $2.5 \text{ m}^2 \text{ sr}$  at  $Z = 34$ , over 4 times larger than TIGER. In two flights, Super-TIGER will achieve nearly an order of magnitude improvement in statistics compared to TIGER.

GSFC is responsible for the acrylic and aerogel Cherenkov detectors, the scintillators, and the mechanical structure of the instrument and payload. In addition, instrument and payload integration will be carried out at GSFC. Detector and payload system designs were finalized this year and construction is underway. Instrument integration will begin in November 2011.

Super-TIGER is a forerunner of the ENTICE (Energetic Trans-Iron Composition Experiment) instrument proposed for the OASIS (Orbiting Astrophysical Spectrometer in Space) mission. In a three-year mission, ENTICE would provide the first statistically significant elemental-abundance measurements in the actinide range.

#### Cosmic Ray Energetics and Mass (CREAM)

The balloon-borne CREAM instrument was developed for direct measurements of cosmic-ray spectra  $1 \leq Z \leq 26$  at total energies greater than  $10^{11} \text{ eV}$  to



*The CREAM instrument just prior to launch from Williams Field, McMurdo Station, Antarctica.*

test models of cosmic-ray acceleration. In addition, CREAM measurements of the energy-dependent abundance ratios of secondary cosmic-ray species to their primary progenitors test models of cosmic-ray transport and storage in the Galaxy. The CREAM collaboration includes the University of Maryland (PI, Eun-Suk Seo), GSFC, Pennsylvania State University, Northern Kentucky University, and Ohio State University as well as collaborators in Korea, France, and Mexico. ASD team members are John Mitchell and Jason Link.

CREAM has made a series of long-duration balloon flights to accumulate the large exposure needed to measure the energy spectra of the most common elements up to about  $10^{15}$  eV. At these energies, most measurements have been based on the detection by ground-based instruments of the showers of particles produced by interactions of primary cosmic rays in the atmosphere. These indirect measurements can only infer the identity of the incident particle. Direct measurements by CREAM provide invaluable information on cosmic-ray composition, as well as the calibration data required to interpret airshower results. CREAM

has flown six times over Antarctica, accumulating 162 days of exposure. The flight of CREAM-VII is planned for the 2012–2013 austral summer.

The combined CREAM and airshower data test models of Fermi shock acceleration of cosmic rays in supernova remnants. Standard models for this mechanism predict single-power-law spectra until a rigidity-dependent acceleration limit is reached. Above this “knee” the all-particle spectrum steepens accompanying a progressive composition change with increasing energy from dominance by light elements to dominance by heavier elements. CREAM has recently reported spectra that depart from single power laws, hardening above 200 GeV/nucleon, with the proton spectrum slightly steeper than those of helium and heavier nuclei. Among proposed explanations for these results are the effects of a nearby supernova remnant, or distributed reacceleration within an OB association.

CREAM measures the charge of incident nuclei using a plastic scintillator timing detector and a silicon pixel detector. Depending on the energy and species of the incident particle, its energy is measured by a

silica-aerogel Cherenkov camera (CREAM-III, IV, V, VI), a transition radiation detector (CREAM-I), and a tungsten-scintillating optical-fiber calorimeter (all versions). The geometric acceptance of the TRD is  $\sim 1.3 \text{ m}^2 \text{ sr}$  and the effective geometric acceptance (including interactions) for the calorimeter is about  $\sim 0.3 \text{ m}^2 \text{ sr}$  for protons and greater for higher  $Z$  nuclei. A new TRD has been developed for CREAM by CERN (Switzerland) and JINR (Russia) to enable improved measurements of secondary-to-primary ratios.

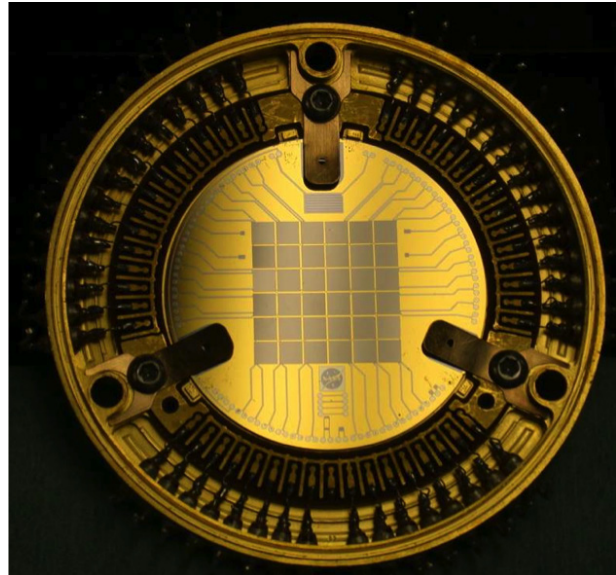
GSFC responsibilities are an acrylic Cherenkov detector for rapid particle identification to trigger the instrument on nuclei heavier than He and a scintillating optical-fiber penetration detector that aids triggering on high-energy events and gives a reference time for the timing scintillators. GSFC supports integration and test of CREAM as well as launch and flight operations.

GSFC is also involved in development of a new detector to measure neutrons produced in particle cascades in the CREAM calorimeter. Because more neutrons are produced in hadronic cascades than in electromagnetic showers of the same energy, the neutron count is a sensitive discriminator to determine whether a shower was initiated by a hadron, such as a proton or atomic nucleus, or by an electron or gamma ray. This detector will be tested using a pulsed neutron source and in accelerator beams at the CERN Super Proton Synchrotron. It will likely first be flown on CREAM-VIII in 2013.

### X-ray Quantum Calorimeter (XQC), Micro-X, and DXL Sounding Rockets

The X-ray Quantum Calorimeter (XQC) is a broadband, non-dispersive X-ray spectrometer built to study the soft X-ray background in the band from 0.05 to 2 keV. The ASD research team members include Porter, Kelley, Kilbourne, and Eckart. Collaborating institutions include the University of Wisconsin (Madison), the University of Miami, and Yale University.

The spectrometer was built to differentiate the spectral components that are thought to make up the ubiquitous soft X-ray background, including emission from the Local Bubble, the Galactic halo, and solar-wind charge exchange in the exo-atmosphere and the heliosphere. The superposition of these temporally and spatially variable sources can create a complicated spectral picture that requires high-resolution spec-



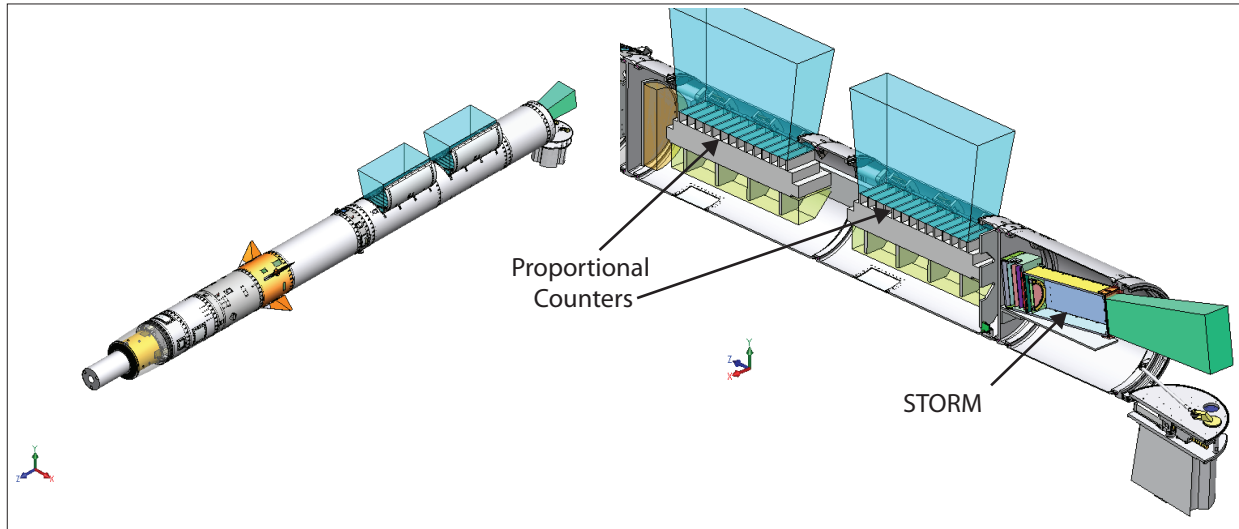
*The XQC payload uses a  $6 \times 6$  pixel X-ray calorimeter array developed and produced at GSFC. Each pixel in the array is  $2 \text{ mm} \times 2 \text{ mm}$ , and utilizes a  $0.8\text{-}\mu\text{m}$ -thick HgTe X-ray absorber. The detector array has an energy resolution better than 8 eV FWHM at 600 eV and has a nominal operating band from 0.05 to 2 keV.*

troscopy to unwind. Detailed spatial maps first were made with sounding rockets, then with ROSAT, and the first high-resolution spectra in the 0.25 keV band were made with the DXS shuttle-attached payload that used a scanning dispersive spectrometer.

The XQC, however, is the first broadband non-dispersive, high-resolution spectrometer to probe the entire X-ray-emitting range, from M-shell Fe emission at 70 eV up to 2 keV where the diffuse emission becomes dominated by unresolved extragalactic sources. In addition, the XQC payload is the first—and currently, the only—X-ray calorimeter array that has flown in space.

The XQC spectrometer is based on a 36 pixel X-ray calorimeter array that was designed and produced at GSFC. Each pixel in the calorimeter array is relatively large at  $2 \text{ mm} \times 2 \text{ mm}$ , and has an energy resolution at O VII Ka of better than 8 eV FWHM. The detector array is operated at 50 mK using a small adiabatic demagnetization refrigerator built at the University of Wisconsin and GSFC. The payload does not use an X-ray optic since this would significantly reduce the grasp of the experiment, but is instead collimated to a one-steradian field of view.

The XQC has flown five times since 1995, with the most recent flight in November 2011. The fourth



Left: An overview of DXL. Right: DXL's two 800 cm<sup>2</sup> proportional counters were built in the late 1970s at the University of Wisconsin. They will now be used to spatially disentangle heliospheric and magnetospheric emission from charge exchange. STORM is a technology demonstrator developed by ASD scientists.

and fifth flights used a detector array with four times the collecting area of previous flights and is based on technology developed for the Astro-E2 program. The data from the fifth flight is currently being processed, but preliminary results show significant contributions from C IV, O VII, OVIII, Fe XVII, and Fe XVIII. Previous flights have placed constraints on certain types of dark matter, and have detected and placed limits on Local Bubble emission from M-shell transitions in Fe IX, X, and XI. Flight six of the XQC is planned for early-2013 and will incorporate further mitigations against contamination of the outer filter, a serious problem for flights four and five.

The Micro-X payload is designed to be the first X-ray calorimeter payload using focusing X-ray optics. It uses significant design heritage from the XQC program, including a very similar adiabatic demagnetization refrigerator. However, the detector and readout technology are derived from the IXO program. The ASD research team members include Porter, Kelley, Kilbourne, Bandler, Adams, Eckart, Smith, Serlemittos, and Soong. Collaborating institutions include the University of Wisconsin (Madison), MIT, University of Florida, and the National Institute of Standards and Technology. The Micro-X payload will use a 121 pixel (11 × 11) X-ray calorimeter array with superconducting transition edge (TES) thermistors operating at 50 mK. It is designed to have an energy resolution of 2 eV (FWHM) across the energy band from 0.05 to 2 keV. The Micro-X payload will use a focusing optic

designed and produced at GSFC for the SXS sounding rocket that flew in 1989 and is the predecessor of the optics used for BBXRT, ASCA, Astro-E2, and Astro-H.

The Micro-X payload is scheduled to fly in late 2012 to observe the bright eastern knot of the Puppis-A supernova remnant. The detector array is designed and produced by GSFC and will be read out using a cryogenic SQUID multiplexer and room-temperature electronics jointly developed by GSFC and NIST. GSFC has already provided the refurbished SXS X-ray optic with 200 cm<sup>2</sup> collecting area at 1 keV and a 2.5 arcmin PSF.

Micro-X will provide some of the first detailed high-resolution spectra of a supernova remnant, with about 40,000 counts expected during the flight. The payload will be the first opportunity to utilize high-spectral-resolution, broadband, spatial-spectral imaging, and will provide a glimpse of what we can expect from Astro-H and future, larger scale, calorimeter instruments.

The DXL payload utilizes an old payload repurposed for new science. It is now widely believed that a significant component of the soft X-ray background results from the interaction of the solar wind with neutral atoms within our solar system. Observing from low Earth orbit, we have seen significant emission from the solar wind interacting with exospheric neutral hydrogen (magnetospheric emission), and also the solar wind interacting with interplanetary

hydrogen and helium (heliospheric emission). These two sources have very different spatial and temporal signatures, but are both the result of charge exchange recombination, where a highly ionized solar wind ion removes an electron from a neutral species, emitting photons, including X-rays, as it relaxes to its ground state. The DXL payload contains two 800 cm<sup>2</sup> proportional counters built in the late 1970s at the University of Wisconsin to map the soft X-ray background. However, DXL will use the same large-grasp instrument to spatially disentangle the heliospheric from the magnetospheric charge exchange emission and compare the results to modern spatial and temporal models of solar wind charge exchange.

The DXL project brings together scientists from several disparate fields who have a strong interest in these phenomena. ASD scientists include Porter, Snowden, Kuntz, Chiao, and Thomas who have a strong interest in the soft X-ray background and in understanding the solar wind charge exchange contamination of many soft X-ray observations with ROSAT, Chandra, XMM, Suzaku, and soon, Astro-H. This is in partnership with GSFC collaborators Sibeck (674) and Collier (690) who have a strong interest in the interaction between the solar wind and the earth's exosphere to understand the critical boundary layer that drives much of space weather. The PI institution is the University of Miami, with additional collaborating institutions: University of Kansas, the University of Wisconsin, and Leicester University.

The DXL payload will also include a GSFC provided instrument, STORM, as a technology demonstration. STORM is a microchannel plate X-ray detector with a wide field of view (10 × 10 degree) Lobster-eye slumped microchannel plate optic. This is a prototype instrument for a full-scale magnetospheric charge exchange X-ray imager, and DXL will be the first space-flight demonstration of this technology. The STORM instrument was developed at GSFC by ASD scientists Porter, Snowden, Kuntz, Chiao, and Thomas with collaborators Collier (690), Sibeck (674), and the University of Leicester.

### X-ray Advanced Concepts Testbed (XACT)

XACT is a new suborbital X-ray payload being developed at GSFC to test and advance Technology Readiness Levels (TRL) of several technologies that could

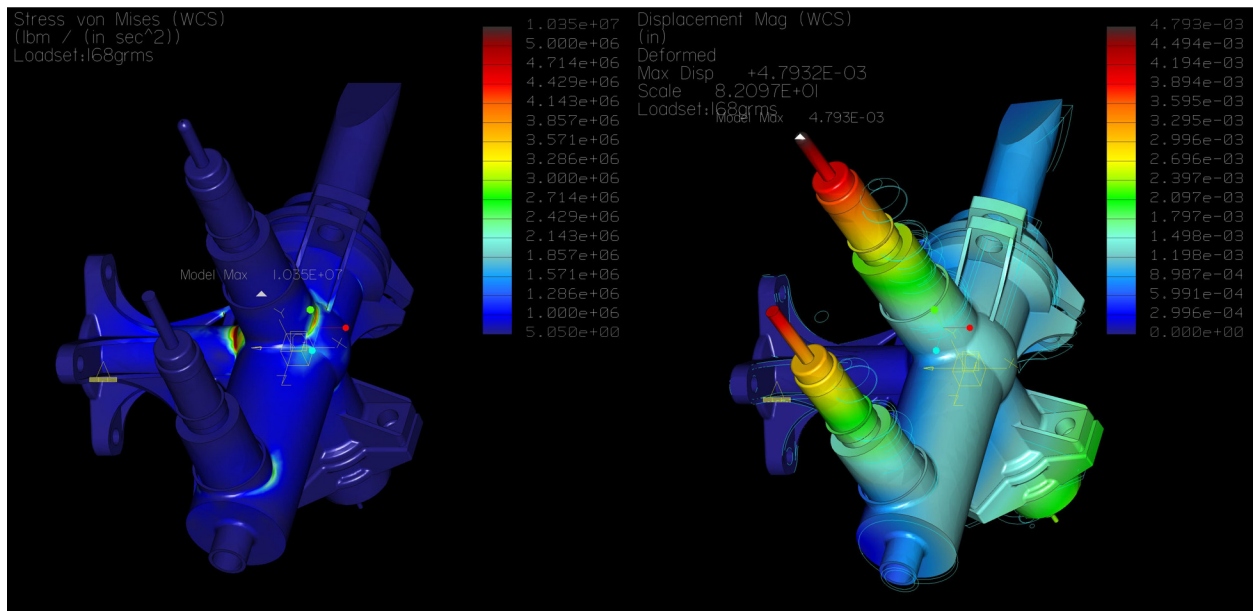
enable future missions (Gendreau, PI). The scientific objective of XACT is to measure the X-ray polarization properties of the Crab Nebula and pulsar and of the accreting binary Her X-1. Polarimetry is a powerful tool for astrophysical investigation that has yet to be exploited in the X-ray band, where it could provide unique insights into neutron stars, black holes, and other extreme-physics environments.

With powerful new enabling technologies, XACT will demonstrate X-ray polarimetry as a practical and flight-ready astronomical technique. The technologies XACT will bring to flight readiness will also provide important new capabilities for NASA missions in space-based X-ray spectroscopy, timing, and photometry. XACT combines new ultra-lightweight optics, advanced photoelectric X-ray polarimeters, and novel calibration sources in a standard sounding-rocket payload.

The XACT optics—lightweight concentrators optimized for unresolved sources—will provide the largest focused X-ray-collecting area ever achieved on a sounding rocket. Currently under development at GSFC, they will have the largest focused collecting-area-to-mass ratio ever flown, enabling future space-based missions that require truly enormous throughput and low background. Scientists Lalit Jalota and Yang Soong are leading this effort with assistance from mechanical engineer Devin Hahne and technicians David Ficau and Nick Spartana. As of early 2012, the XACT payload's optical bench has been fully fabricated, and one of three concentrators is complete. The foil shells for the second and third concentrators are in production, as are the spider assemblies that hold



*First integration test of the XACT optics with the spider assembly.*



Stress analysis of 3-D printed modulated X-ray source for XACT.

them in place. Integration of the optical bench will be complete by Summer 2012.

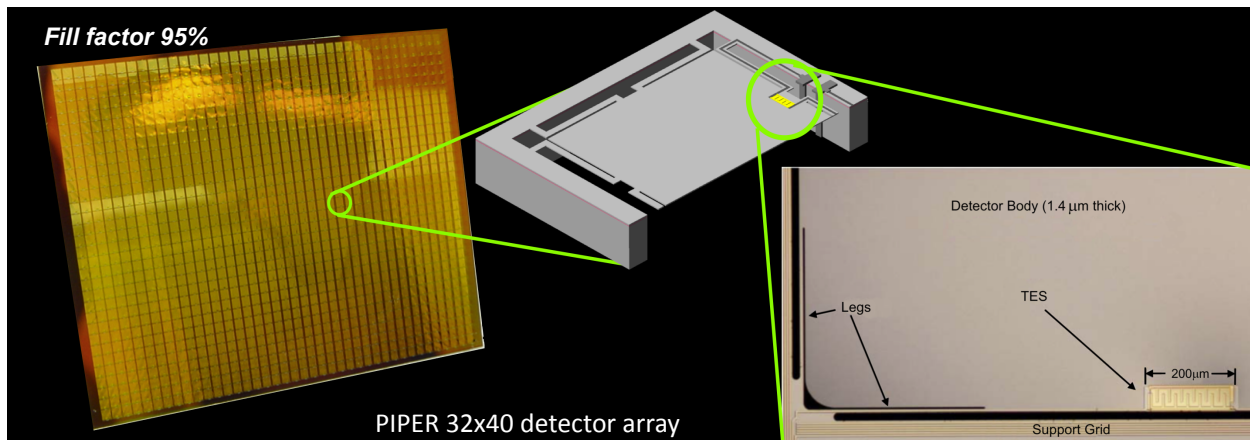
The XACT polarimeters are the latest innovation in photoelectron tracking devices, combining good polarization response with high quantum efficiency to achieve unprecedented sensitivity. ASD scientists originated this polarimetry technique based on Time Projection Chambers (TPCs), and are currently developing it for astrophysics and heliophysics missions in the 1–100 keV band. The TPC polarimeter is the basis for the GEMS mission. XACT leverages these efforts to deliver the polarimeters at a low incremental cost. Scientists Kevin Black, Keith Jahoda, and Joe Hill lead this effort.

XACT will demonstrate in-flight calibration using a novel electronic X-ray source that can be pulsed for arbitrary and commandable intervals. Such a modulated source can be used to provide calibration information on demand, minimizing the associated background and resulting in both higher sensitivity and observatory-scheduling freedom for future missions. Mechanical engineer Steven Kenyon has led the effort to miniaturize the technology and has successfully developed sources weighing 150 grams—a factor of 3 improvement over the course of just a few months. The team has also demonstrated sources made with 3D printing technology, including fabrication out of steel. The latest design will be used for the XACT

flight and is serving as an Engineering Test Unit for a similar source on the GEMS SMEX. The modulated X-ray source has been successfully used to calibrate drift velocities in several laboratory polarimeters.

The XACT program has included students from several schools. Three high-school students have participated in the design of the X-ray source. Eight undergraduate students from Olin College have worked on in-flight alignment monitoring system designs. One undergraduate from the U.S. Naval Academy has further refined this alignment system. One undergraduate from the University of Kentucky has helped with automation of X-ray mirror placement and alignment. A high school student developed code to provide robotic assistance to the assembly of the mirrors—incorporating video capture software and mechanism controls. An undergraduate from the University of Alabama used this to assemble two mirrors. A graduate student (Erin Balsamo) has assisted in the design of the collimator that will be used to align the instrument. Balsamo has also been working to streamline many aspects of the foil production and testing.

The XACT goals are accomplished with a simple flight plan that is well within the launch and recovery envelopes of a standard Black Brant IX at the White Sands Missile Range. The first launch will be in December 2012 to observe the Crab. Subsequent launches are anticipated with future funding.



Montage showing the PIPER  $32 \times 40$  detector array. Left: The Backshort-Under-Grid (BUG) architecture pioneered at GSFC tiles the array front surface to achieve 95-percent fill factor. Center: Schematic of a single pixel highlighting the absorber and sensor suspended in the BUG grid. Right: Close-up of the absorber membrane, legs and transition-edge superconducting thermometer. PIPER will fly four arrays for a total of 5,120 detectors.

### Primordial Inflation Polarization Explorer (PIPER)

The Primordial Inflation Polarization Explorer (PIPER) is a balloon-borne mission to measure the polarization of the cosmic microwave background in search of the signature of primordial gravity waves excited by an inflationary epoch in the early universe. Alan Kogut is the PI, and ASD team members include Benford, Chuss, Fixsen, Lazear, Lowe, Mirel, Moseley, Sharp, Staguhn, Weston, and Wollack.

PIPER addresses fundamental questions at the intersection of physics and cosmology. Cosmology posits a period called inflation, shortly after the Big Bang, when the expansion of space-time accelerated dramatically to “inflate” the Universe from subatomic to macroscopic scales. Inflation neatly explains the initial conditions of Big Bang cosmology (a spatially flat, homogeneous universe with scale-invariant density perturbations), but it relies on the extrapolation of physics to energies a trillion times above those accessible to direct experimentation in particle accelerators. PIPER will test inflation by measuring the polarization pattern in the cosmic microwave background caused by a background of gravity waves created during an inflationary epoch. Such a signal is expected to exist, with observable amplitude and a unique spatial signature. Detection of the gravity-wave signature of inflation would have profound consequences for both cosmology and high-energy physics. It would establish inflation as a physical reality, determine the relevant

energy scale, and probe physics at energies near Grand Unification to provide direct observational input for a “final theory” of quantum mechanics and gravity.

PIPER achieves unprecedented sensitivity by combining several technologies pioneered by Goddard researchers.

- Large-format bolometric detectors. PIPER will fly 5,120 transition-edge superconducting bolometers in a Backshort-Under-Grid (BUG) architecture. By moving all wiring *beneath* the array, the BUG architecture allows efficient 2-dimensional tiling of the focal plane without any reflective elements that would reduce the optical efficiency. PIPER has produced its first  $32 \times 40$  bolometer arrays for characterization.
- A Variable-Delay Polarization Modulator (VPM) injects a time-dependent phase delay between orthogonal linear polarizations to cleanly separate polarized from unpolarized radiation. The fast (3 Hz) modulation allows full characterization of the incident radiation into Stokes I, Q, U, and V parameters on timescales fast compared to instrument drifts or beam motion on the sky. VPM development for PIPER complements technology development for a future large mission (the Inflation Probe).
- Fully cryogenic optics. PIPER’s twin telescopes fit within the old ARCADE dewar and will operate at 1.5 K to provide background-limited sensitivity. Maintaining all optical elements at 1.5 K or colder improves mapping speed by a factor of 10

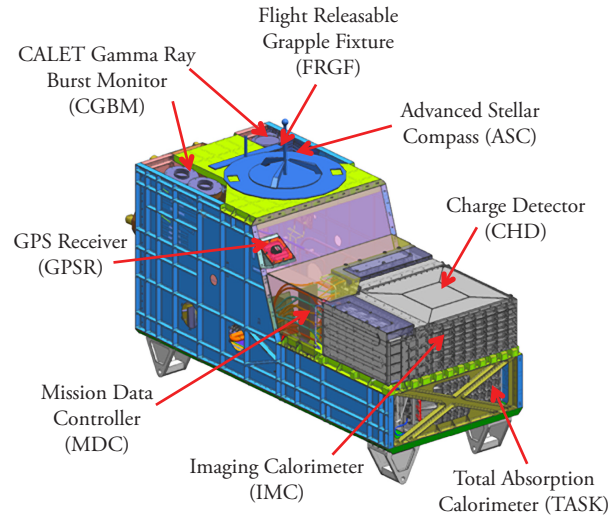
compared to ambient optics, allowing PIPER to use conventional (overnight) balloon flights instead of more challenging Antarctic operations.

PIPER's use of conventional ballooning allows nighttime observations when the sun has set. This in turn allows the mission to rapidly scan large fractions of the sky. By combining flights from northern and southern hemisphere launch sites, PIPER can achieve nearly full-sky coverage. PIPER is the only current mission capable of observing on angular scales larger than  $20^\circ$ , where the inflationary signal is expected to be largest.

PIPER will map the sky in both linear and circular polarization, at wavelengths 1,500, 1,100, 850, and 500  $\mu\text{m}$  (frequencies 200, 270, 350, and 600 GHz). It will detect the signature of inflationary gravity waves to a factor of three fainter than the lowest value predicted by inflationary models. The unbiased survey of sub-millimeter polarization will also provide an important probe of the interstellar dust cirrus and the large-scale structure of the Galactic magnetic field, and will be the first sky survey in circular polarization at these wavelengths. PIPER has begun integration and test activities and remains on schedule for a first flight in 2013.

### Calorimetric Electron Telescope (CALET)

CALET is a new mission selected by JAXA for the Japanese Experiment Module—Exposed Facility (JEM-EF) on the International Space Station, manifested for HTV-5 (H-II Transfer Vehicle 5) in 2014. CALET will measure the high-energy spectra of electrons, nuclei, and gamma-rays to address outstanding questions including signatures of dark matter, the sources of high-energy particles and photons, and the details of particle acceleration and transport in the galaxy. The CALET project (PI Shoji Torii, Waseda University) includes researchers from Japan, the U.S., Italy, and China. The CALET-U.S. team of Louisiana State University, GSFC, Washington University in St. Louis, and the University of Denver are working in CALET instrument development, testing, instrument modeling, flight operations, flight data processing and science analysis. The ASD team of John Mitchell, Thomas Hams, John Krizmanic, Alexander Moiseev, and Makoto Sasaki are responsible for the instrument simulation and performance model, technical support

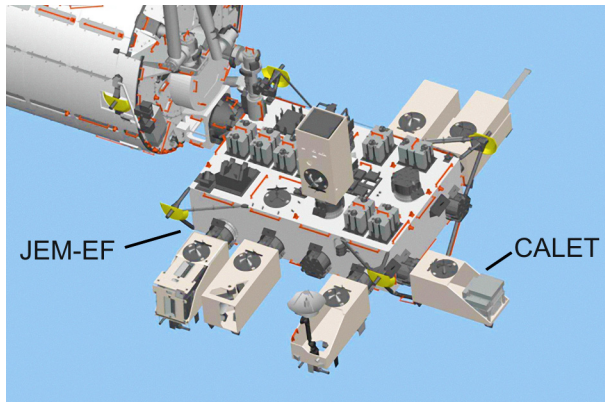


*The CALET instrument is under construction for flight to the JEM-EF platform of the International Space Station in 2014. CALET will measure high-energy electrons, nuclei, and gamma-rays, as well as gamma-ray bursts.*

for instrument development, and accelerator testing and calibration.

CALET uses a deep-imaging particle calorimeter for superior energy resolution and excellent separation between hadrons and electrons and between charged particles and gamma rays. The main telescope has a field-of-view of  $\sim 45^\circ$  from the zenith and a geometric acceptance of  $0.12 \text{ m}^2\text{-sr}$ . The calorimeter is divided into an imaging calorimeter (IMC) section that provides tracking and accurately determines the starting point of showers, and a total absorption calorimeter (TASC) section that measures total particle energy. The IMC contains  $\sim 3$  radiation lengths ( $X_0$ ) of tungsten interspersed between eight x-y layers of scintillating optical fibers read out by multi-anode photomultipliers. Most electrons and photons will initiate showers in the IMC, which measures the starting point of the shower and its development until it enters the TASC. The TASC is a stack of lead tungstate (PWO) crystals arranged in x-y layers to track the axis of the shower. Each crystal is read out by two photodiodes and an avalanche photodiode. The TASC has a total thickness of  $27 X_0$  and collects the total energy in the shower with a leakage of only a few percent for electrons. A charge detector subsystem at the top of the telescope measures the charge of incident particles and functions as an anti-coincidence detector for gamma-ray measurements.





CALET will be attached to port 9 of the JEM-EF on the ISS

CALET is focused on investigating the high-energy total electron spectrum into the trans-TeV energy range. These measurements have the potential to identify, for the first time, the signature of high-energy particles accelerated in a local astrophysical engine and subsequently released into the Galaxy. Electrons lose energy rapidly by synchrotron and inverse Compton processes. The distant-source spectrum is expected to be relatively featureless, falling approximately as  $E^{-3}$  and softening rapidly above 1 TeV. Electrons with TeV energy must have been accelerated within about  $10^5$  yrs and can have diffused at most a few hundred parsecs. The electron lifetime and the diffusion distance decrease rapidly with energy. Detection of electrons with energy significantly above 1 TeV would indicate the presence of a nearby source and the arrival directions of these electrons should also show detectable anisotropy. Individual sources might also produce features in the spectrum at lower energies. CALET will resolve discrepancies among recent results from balloon experiments (BETS, ATIC, PPB-BETS), space experiments (Fermi, PAMELA) and ground-based air Cherenkov telescope observations (HESS).

High-energy electrons and positrons may also be produced by dark-matter annihilation. CALET will search for signatures of dark-matter annihilation producing features in the electron or gamma-ray spectra. Together with measurements at the Large Hadron Collider, details of the spectra of high-energy cosmic-ray electrons and positrons may hold the key to revealing the nature of dark matter.

The spectra of primary cosmic-ray nuclei, and the important secondary elements such as boron, hold the key to understanding galactic particle transport at very high energy. CALET will measure the B/C ratio with precision to about a decade in energy beyond current

results, and thereby test many of the models currently proposed. CALET will also extend the measurements of the spectra of cosmic ray nuclei from hydrogen to iron, with high resolution, into the region of the spectral “knee” to investigate possible structure and energy-dependent composition changes.

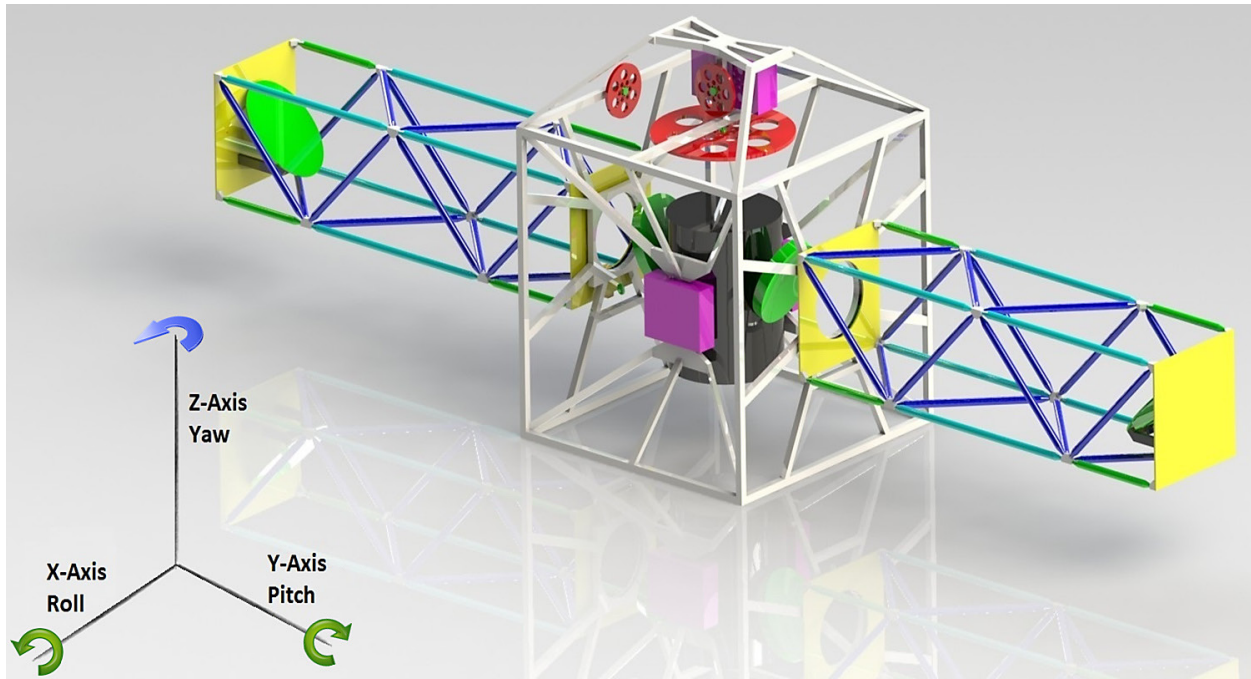
CALET will perform a gamma-ray all-sky survey, complementing Fermi and HESS observations, to detect intense high-energy sources, study the diffuse component, and search for new regions of emission. CALET includes a low energy (7 KeV–20 MeV) gamma-ray burst monitor. GRB measurements are also extended to high energy using the main telescope.

Construction of the instrument and spacecraft are well underway. A test of prototype detectors at the CERN (European Laboratory for Particle Physics) Super Proton Synchrotron (SPS) using proton and electron beams up to 350 GeV in energy showed the instrument to be capable of the needed discrimination between cosmic-ray electrons and the far more numerous protons, with energy resolution of a few percent for electrons. The engineering model of CALET will be calibrated in both singly-charged particle and heavy-ion beams at the SPS in Fall 2012.

The electron, nucleus, and gamma-ray measurements of CALET would be extended to higher energy and greater precision by the HEPCaT (High-Energy Particle Calorimeter Telescope) instrument studied by a team led by Mitchell and proposed as part of the OASIS (Orbiting Astrophysical Spectrometer in Space) mission. HEPCaT would measure cosmic-ray electrons to energies well above 10 TeV and nuclei to energies of  $10^{15}$  eV.

### The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII)

Astronomical studies at infrared wavelengths have revolutionized our understanding of galaxies, stars, and planets, as well as their origins. But further progress on major questions is stymied by the inescapable fact that the spatial resolution of single-aperture telescopes degrades at long wavelengths. Exciting physical processes lurk below our current far-infrared (FIR) resolution, including clustered star formation, powerful interactions between normal matter and monstrous black holes at the cores of galaxies, and the formation of planetary systems. Interferometry is a path to high



*BETTII's 8-meter boom will provide angular resolution of  $\sim 0.5''$  at 40 mm. Carbon-fiber construction leads to a stiff boom structure, while keeping the overall payload weight low.*

angular resolution in the FIR, making it a potent tool for scientific discovery.

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) is an 8-meter boom interferometer to operate in the FIR (30–90  $\mu\text{m}$ ) on a high-altitude balloon that was selected for funding under the ROSES/APRA program in 2010. The long baseline will provide unprecedented angular resolution ( $\sim 0.5''$ ) in this band. These wavelengths are inaccessible from the ground; the high atmospheric transmission at balloon altitudes, in combination with BETTII's unique double-Fourier instrument will allow spectral resolution of up to  $R \equiv \lambda/\Delta\lambda \sim 200$ . By combining these capabilities, BETTII will provide spatially-resolved spectroscopy on astrophysically important sources. BETTII's first flight will isolate the far-infrared emission from forming stars in cluster environments, allowing us to tightly constrain models of cluster formation.

The BETTII project is now one year old, and 2011 was a very busy and productive year. Over the course of the year, the majority of the instrument and gondola design has been completed, including optical design, structural design, and overall pointing control system architecture. Going into 2012, additional design work is continuing, but some procurements are in process, and by the end of 2012, we expect to have a

completed gondola structure, and will have both procured and tested a number of individual subsystems. The final design will be reviewed in June 2012.

The scientific goals of BETTII drive key technical requirements for the design. BETTII is a Michelson interferometer, combining the light from two separated collector mirrors (siderostats) at a 50/50 beam-splitter in the pupil plane. A scanning optical delay line is used to vary the optical path difference between the two arms of the interferometer; the interferometric fringe pattern is recorded on the detector. Relative astrometric information is derived from the optical path difference between the fringe packets corresponding to discrete sources. The angular size of a source can be derived from the ratio of the fringe amplitude to the amplitude from an unresolved calibration source. The fringe envelope contains spectral information. Thus, an interferometer like BETTII, when used to observe a source with a large number of interferometric baselines, yields integral field spectroscopic data, or a spatial-spectral data cube.

A successful flight of BETTII will pave the way for future space interferometry by demonstrating key technologies, including wide-field phase referencing for image reconstruction and the technique of double-Fourier interferometry. A traditional Michelson interferometer uses a single detector and has a field

of view determined by the size of the individual light-collecting apertures. By using a detector array, one observes interferograms corresponding to multiple contiguous primary beams simultaneously on different pixels. This technique—wide-field double-Fourier interferometry—has been demonstrated on a laboratory testbed, but never in a flight-like environment.

The first flight of BETTII is planned for Spring 2015. Data acquired with BETTII will be complementary to observations with space observatories such as Herschel and the James Webb Space Telescope, exploring the FIR wavelength range with unprecedented high angular resolution. These data will be powerful tools for understanding star formation in clusters. Further, BETTII will validate technologies and retire risks for future space interferometers, such as the Space Infrared Interferometric Telescope.

The BETTII project is a collaboration between NASA's Goddard Space Flight Center and the University of Maryland, with assistance from the Far-Infrared Telescope Experiment team in Japan. The BETTII team includes ASD scientists Stephen Rinehart, Rich Barry, Dominic Benford, Dale Fixsen, Bill Danchi, Johannes Staguhn, Robert Silverberg (Emeritus), as well as David Leisawitz (Science Proposal Support Office), Christine Jhabvala (Instrument Systems & Technology Division) and Lee Mundy (UMCP). The project also has had contributions from a UMCP graduate student (Maxime Rizzo), and a number of undergraduates from multiple different institutions. Information on BETTII interns can be found on the BETTII website: <http://asd.gsfc.nasa.gov/bettii/>.

## *Technology Development*

### **Laboratory Astrophysics Using an X-ray Microcalorimeter with an Electron Beam Ion Trap**

Our laboratory astrophysics program is designed to simulate astrophysical plasmas in the laboratory in order to benchmark and provide guidance to the atomic codes that form the basis of the spectral synthesis models used in X-ray astrophysics. These models are used to relate spectra observed from an astrophysical object to conditions in the source, including temperature, ionization-equilibrium, composition, density, turbulence and bulk motion. This work is fundamentally important as high-resolution spectroscopy becomes

the dominant tool in exploring the physics of X-ray-emitting objects.

This has already started with the observation of bright point sources with the high-resolution dispersive spectrometers on Chandra and XMM/Newton. It will become critically important with the upcoming Astro-H and International X-ray Observatory, which will produce a detailed, high-spectral-resolution image with every observation. Our program is designed to validate and correct the accuracy of the spectral synthesis models in controlled ground-based experiments, giving us confidence that we have correctly ascribed observed spectral features to known conditions in the astrophysical source.

The basis of our program is a high-resolution, non-dispersive, X-ray calorimeter spectrometer, a suite of very-high-resolution dispersive spectrometers, and the Electron Beam Ion Trap (EBIT) plasma generator at the Lawrence Livermore National Laboratory (LLNL). ASD scientists include Porter, Kelley, Kilbourne, Adams, Smith, Koutroumpa, and Leutenegger. Other collaborating institutions include Stanford University and the National Institute of Standards and Technology. The LLNL EBIT can produce nearly any plasma conditions, from low-charge states in light elements to bare uranium with electron beam energies of up to 200 keV. Nearly any charge state of any astrophysically interesting element can be produced, either as a pure charge state or in a Maxwellian distribution at known temperature.

Non-equilibrium ionization conditions can also be produced with almost any astrophysically interesting ionization parameter. Typical measurements in our program include spectral-line identification, absolute cross sections, recombination, charge-exchange recombination, and cross sections in thermal and non-thermal distributions. Measurements are related back to theory, the results of atomic calculations, and to the standard X-ray spectral synthesis models used in X-ray astrophysics.

A key instrument in these measurements is a broadband, high-resolution X-ray calorimeter instrument provided by GSFC beginning in 2000 and now on its third revision. This system has been operated almost continuously for the past 9.5 years. It has produced well over two dozen peer-reviewed articles, and it has made critical measurements of absolute cross sections in L-shell Fe and Ni, as well as charge-exchange measurements in S, C, O, and

Fe. Many investigations are ongoing. The emphasis in 2010 has been a detailed look at L-shell charge exchange, mostly with sulfur and iron, as a function of ionization state, a key component of magnetospheric charge exchange for which there exists no predictive theory. Magnetospheric and heliospheric charge exchange are key components of spatially, spectrally, and temporally variable foreground emission which complicate observations of, for example, the soft X-ray background, warm-hot intergalactic medium, and clusters of galaxies. Charge exchange emission is also very diagnostic and if observed in a celestial source can provide key information on the composition, ionization state, and relative velocity of both the donor and acceptor species. Our laboratory investigation is unique in the world at providing the first controlled high-resolution spectra of charge exchange in astrophysical elements and is geared to provide information to guide the development of a predictive atomic theory, especially for the key L-shell emission which dominates local charge exchange.

GSFC first installed an X-ray calorimeter instrument at the LLNL EBIT facility in the summer of 2000, the XRS/EBIT, based on the engineering-model detector system for the Astro-E observatory. The system was significantly upgraded using technology developed for Astro-E2 in 2003. A dedicated facility-class instrument designed from the ground up for laboratory astrophysics was installed in 2007. The current instrument, dubbed the EBIT Calorimeter Spectrometer (ECS), utilizes a 32-channel X-ray calorimeter array from the Astro-E2 program installed in a long-lifetime, automated laboratory cryostat that enables continuous experiments for up to 70 hours with a two-hour recharge. The detector array is populated with 16 mid-band (0.05–12 keV) X-ray absorbers with 4.5 eV FWHM resolution at 6 keV, and 16 high-band (0.1–100 keV) X-ray absorbers with 30 eV FWHM at 60 keV.

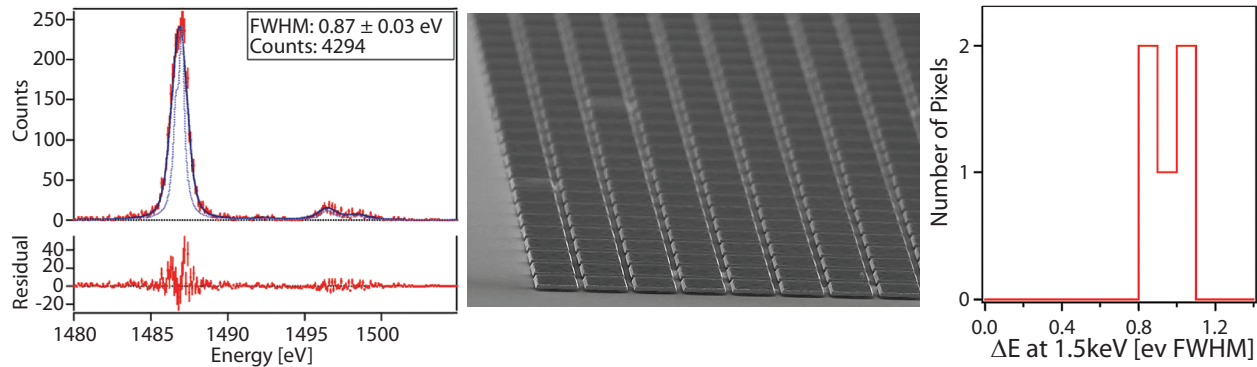
In addition to operating the ECS, we recently (spring 2011) refurbished the XRS/EBIT spectrometer to perform photoexcitation measurements at the SLAC Linac Coherent Light Source (LCLS). In this experiment we combined a portable EBIT, the XRS/EBIT spectrometer, and a monochromator with the LCLS light source to breed and observe X-ray emission from photoexcitation in highly charged ions. These measurements will continue in spring 2012.

We are currently designing and constructing the fourth-generation instrument that will be based on detector technology from the IXO/Athena development program. It will be installed in a completely automated cryogen-free cryostat. This fourth-generation instrument is dubbed the Transition-Edge Microcalorimeter Spectrometer (TEMS) and will be composed of a checkerboard hybrid of 128 low-band (0.05–1 keV) pixels with 0.8 eV resolution at 1 keV, and 128 mid-band (0.05–10 keV) pixels with 2.0 eV resolution at 6 keV. In addition, there will be a 64 channel high-band array (0.1–200 keV) with 30 eV resolution at 60 keV. The TEMS instrument will become the workhorse instrument in our laboratory astrophysics program to make sure that our measurements and understanding of atomic processes are ready to interpret the spectra we will obtain with the Astro-H and future observatories. TEMS will be installed at the EBIT facility in 2013.

### X-ray Calorimeter Development

An X-ray calorimeter determines the energy of an incident X-ray photon by measuring a small change in temperature. Three types of X-ray calorimeters presently dominate the field, each characterized by the thermometer technology. The first two types use temperature-sensitive resistors: semiconductors in the metal-insulator transition and superconductors operated in the superconducting-normal transition. The third type uses a magnetic thermometer. These can be considered the three generations of X-ray calorimeters, although further development of each is proceeding.

The Soft X-ray Spectrometer (SXS) on Astro-H, expected to launch in 2014, will use an array of silicon thermistors with HgTe X-ray absorbers that will operate at 50 mK. Both the semiconductor and superconductor calorimeters have been implemented in small arrays. Kilopixel arrays of the superconducting calorimeters are being produced, and it is anticipated that much larger arrays will require the non-dissipative advantage of magnetic thermometers. Goddard Space Flight Center is the only institution playing a leading role in the development of each of the three dominant X-ray calorimeter technologies. The scientists of the ASD microcalorimeter team include Joe Adams, Simon Bandler, Meng Chiao, Megan Eckart, Fred Finkbeiner, Richard Kelley, Caroline Kilbourne,



**Left:** Fit to Al  $K\alpha$  lines measured with a small TES with a  $0.065$  mm  $\times$   $0.065$  mm  $\times$   $0.0045$  mm Au absorber. **Center:** Array of such pixels on a  $0.075$  mm pitch, shown in an electron micrograph. **Right:** Histogram of resolutions obtained at  $1.5$  keV on five separate pixels.

Scott Porter, and Steve Smith, and postdocs Catherine Bailey, Sarah Busch, and Jan-Patrick Porst. Progress is made possible through a strong collaboration with Goddard's Detector Systems Branch.

The main developments in the silicon-thermistor calorimeters since XRS/Suzaku have been in their X-ray absorbers and heat sinking. GSFC worked closely with the small business EPIR to develop HgTe absorbers with substantially lower heat capacity than the material used for XRS that yet thermalizes the energy of X-ray photons reproducibly and uniformly. The SXS thermistor array itself is based heavily on the XRS design, but includes better heat sinking to reduce the impact of cosmic-ray heating. The SXS engineering-model calorimeter array and two flight candidate arrays have been completed, and the resolution at  $6$  keV ranges from  $3.6$ – $4.6$  eV across the arrays. The magnitude of thermal crosstalk has been reduced by more than a factor of ten relative to XRS.

Over the past few years, Goddard has been producing microcalorimeter arrays that incorporate a microns-thick Au or Au/Bi absorber, designed to thermalize the absorbed energy quickly, with a superconducting transition-edge sensor (TES) made from a Mo/Au proximity-effect bilayer. Arrays of such pixels with microstrip electrical contacts (for low crosstalk at high density) have demonstrated energy resolutions of  $2$ – $3$  eV FWHM at  $6$  keV. The group is presently refining the design in order to perform a technology demonstration relevant to the Athena mission concept being studied by ESA colleagues.

Recent Goddard TES calorimeter development has been enhanced by new understanding that many TES properties can be explained by considering these devices to be superconducting weak links, like Jo-

sephson junctions, even though the length scales in a TES are considerably more macroscopic than in a tunnel junction. In small TES devices, the effective superconducting transition temperature depends sensitively on current, one effect of which is to extend the linear operating range of such pixels. Pixels with a  $0.035$  mm TES and  $0.057$  mm absorber have demonstrated better than  $2$  eV resolution over a wide energy range. Such small pixels operate well without membrane isolation, allowing fabrication on a robust substrate with built-in heat sinking. These pixels are also about a factor of ten faster than the ones optimized for Athena; with the appropriate filter in the TES bias circuit, the rise and fall times will both be approximately  $30$   $\mu$ s. The group has also shown that small pixels can be optimized for sub-eV resolution at the expense of speed— $0.9$  eV FWHM resolution at  $1.5$  keV has been measured in five  $0.065$  mm pixels.

Goddard is part of an international collaboration (including Brown University, Heidelberg University, NIST/Boulder and PTB/Berlin) to develop magnetic calorimeters. The Goddard emphasis has been on designs that can be implemented in closely packed arrays. Goddard has been fabricating arrays of superconducting niobium meander inductors onto which a layer of magnetic material (Au:Er) is deposited. When a current is passed through the meander, a magnetic field is produced in the magnetic material. When an X-ray is absorbed, the heating changes the magnetic permeability, and therefore the inductance of the meander, which produces the signal. GSFC magnetic calorimeter arrays with absorbers have achieved  $3.3$  eV resolution at  $6$  keV, and there remains potential to substantially improve on this in the near future, perhaps even to under  $1$  eV. An outgrowth of this de-

velopment is yet another type of calorimeter, the magnetic penetration thermometer (MPT), which uses the same geometry but replaces the magnetic material with a superconductor in its transition. The MPT potentially combines the best of the magnetic calorimeter and TES technologies. The Goddard calorimeter group has obtained 2.3 eV resolution at 6 keV using a Mo/Au MPT.

The calorimeter group has also successfully demonstrated TES and MMC macro-pixels in the “Hydra” design, in which one thermometer is coupled to discrete separate absorbers via varied thermal links. For example, a single TES with 6 differently coupled 0.3-mm absorbers was tested; resolutions across the 6 pixels ranged from 5.4 eV to 7.8 eV.

### Next Generation X-ray Optics

X-ray optics is an essential and enabling technology for future X-ray astronomical missions. It is characterized by three quantities: angular resolution, effective area per unit mass, and production cost per unit effective area. This development, led by Dr. Will Zhang of the X-ray Astrophysics Laboratory, is a collaborative effort of scientists and engineers from ASD, AETD, as well as SGT and Ball Aerospace. Its objective is to develop a telescope-manufacturing process that achieves the highest angular resolution possible while maximizing the effective area per unit mass and minimizing the cost per unit effective area, advancing by at least an order of magnitude the state of the art of X-ray telescope construction represented by the three currently operating missions: Chandra, XMM-Newton, and Suzaku.

This development effort uses the segmented design approach. The technique is scalable and suited to building telescopes of any size—small ones for Explorer missions as well as large ones for flagship missions. The key steps of the process include: fabrication, coating, and measurement of mirror segments, and alignment and integration of mirror segments into modules.

The development effort is multi-pronged. It is investigating two methods for fabricating mirror substrates: precision glass slumping and the polishing and lightweighting of monocrystalline silicon. The precision glass slumping is a replication technique and has been developed for the former International X-ray Observatory mission (IXO). It is a mature and inexpen-

sive process and has been demonstrated to be capable of making mirror substrates at the 7-arcsecond level, enabling the manufacture of 10-arcsecond-resolution telescopes. The polishing and lightweighting of monocrystalline silicon is a new method under development that has the potential of making diffraction-limited X-ray mirrors, enabling a future telescopes with angular resolution comparable to, or better than, Chandra’s 0.5 arcseconds.

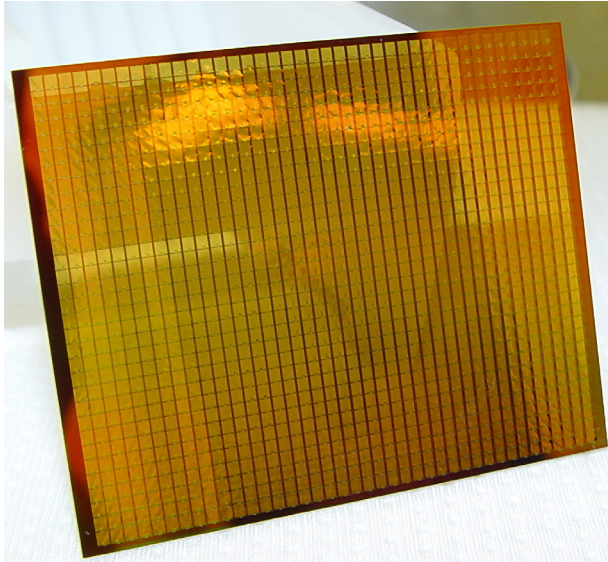
*The team has repeatedly aligned and bonded single pairs of parabolic and hyperbolic mirror segments, achieving X-ray images better than 10 arcseconds.*

The team is investigating both magnetron sputtering and atomic layer deposition (ALD) for coating thin X-ray mirrors to achieve the maximum possible reflectivity while minimizing figure distortion caused by coating stress. Both processes have been demonstrated to work on experimental samples. In 2012 they will be applied on full-size mirrors.

As part of their effort to develop a method of aligning and integrating mirror segments into a module, the team has built up a small laboratory in the Goddard Optical Test Site. The laboratory has a very stable thermal environment, with temperature variation less than 0.1° C over several days. They have repeatedly aligned and bonded single pairs of parabolic and hyperbolic mirror segments, achieving X-ray images better than 10 arcseconds and demonstrating the technique is well suited for making 10-arcsecond modules. In 2012 they will apply this technique to co-align and bond multiple pairs of mirror segments, to demonstrate that these modules can pass both X-ray performance tests and environment tests.

### Far-Infrared Detectors

The past decade has seen dramatic advances in many areas of long-wavelength astrophysics. WMAP, following the great successes of Cosmic Background Explorer (COBE), has confirmed our general understanding of the early universe and allowed us to quantify critical parameter—its age, composition and early evolution. Spitzer has provided an extraordinary imaging and mid-infrared spectroscopic capability, which has resulted in an increasingly improving picture of the



*The above prototype 32 × 40 bolometer array features 1,280 1.135 mm square pixels with a yield of 95.5%. The array is indium bump bonded to a dummy multiplexer capable of contacting 128 pixels within the array for test purposes.*

evolution of galaxies over the life of the universe. Herschel launched on May 14, 2009, and is providing our first large-scale look at the high-redshift universe in the submillimeter. WISE launched on December 14, 2009, and produced an all-sky map of hundreds of millions of sources in the mid-infrared. JWST, scheduled to be launched late in this decade, will provide a window into the epoch of galaxy formation to clarify the processes that produced the present universe.

Future far-infrared and millimeter facilities will play an important role in clarifying and extending this work. More than half the power of high-luminosity galaxies is emitted in the rest-frame far-infrared, so far-infrared and submillimeter imaging and spectroscopy are required for a full understanding of the physics of these systems. The next steps in NASA's profoundly successful science program are currently being developed and the priorities for space missions, supplemented by suborbital missions, are being established.

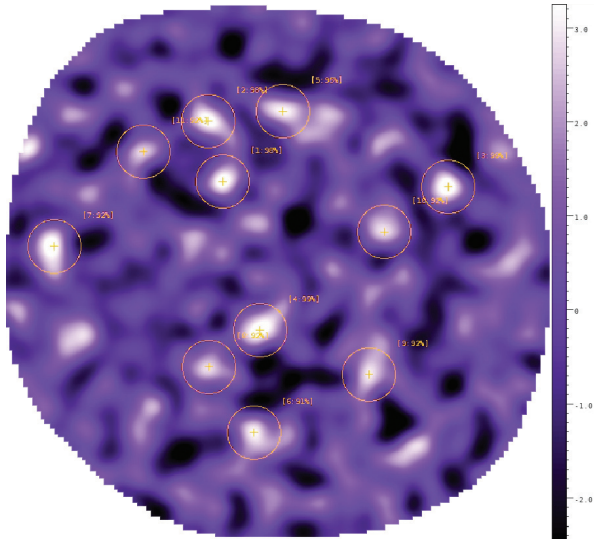
SOFIA, now producing early scientific discoveries, will be a key facility for imaging and spectroscopic follow-up of Spitzer, Herschel, and WISE. Measurements of the polarization of the CMB promise to allow us to distinguish among models of the first instants of our universe. Further in the future, great advances in sensitivity, angular resolution and overall instrument capability will be realized by large cryogenic telescopes in space, possible in the near term with SPICA, or in

coming decades with missions similar to CALISTO, SAFIR, SPIRIT, or SPECS. High-performance far-infrared detector arrays are required for all of this high-priority work. Novel experiments in the far-infrared on balloon-borne platforms will push the boundaries of our technological capability while providing important scientific advances.

The far-IR instrument development group in ASD (Benford, Chuss, Fixsen, Kogut, Moseley, Rinehart, Staguhn, Wollack) has ongoing research projects to develop, implement, and field these detector arrays. Our large-format filled arrays will enable major advances in space-borne, sub-orbital and ground-based infrared, far-infrared and sub-millimeter instrumentation. A sustained effort over the last several years has focused on producing arrays in a format of 1,280 pixels suitable for use in suborbital environments such as SOFIA and balloon-borne experiments. The last steps in this development are under way now, with their first use already being implemented.

A balloon-borne experiment to measure the CMB polarization signal, PIPER (PI: Al Kogut), is well underway and will use both the modulator (Chuss) and the large-format arrays (Benford, Staguhn, Moseley, Wollack). Four of these arrays, totaling 5,120 pixels, will produce the richest polarimetric imaging of the CMB sky on its flights in 2013–2014. Using superconducting transition-edge-sensor bolometers read out by SQUID multiplexers, the arrays flown in PIPER will provide the greatest sensitivity and pixel count of any yet fielded at submillimeter wavelengths.

For the past year, we have been working on the world's first suborbital far-infrared interferometer experiment. The Balloon-Borne Experimental Twin Telescope Infrared Interferometer (BETTII; PI: Stephen Rinehart) will enable the highest angular resolution ever obtained at its 30–90 micron wavelengths: resolving structures at a scale as fine as 0.5 arcseconds. BETTII has a double Fourier interferometer that provides spatially-resolved spectroscopy with resolution of  $\lambda/\Delta\lambda=200$  to trace important transitions in the heart of star forming regions in our galaxy and in the region close to active galactic nuclei. In addition to its cutting-edge scientific capabilities, BETTII will also demonstrate interferometry from a “near-space” platform, paving the way to space-based interferometry with even larger structures for improved sensitivity and angular resolutions. While the detector arrays for BETTII are relatively small (each of the four arrays



This observation of the GISMO Deep Field (GDF) is centered on the Hubble Deep Field and was obtained during our April 2011 observing run. With an RMS of  $\approx 130 \mu\text{Jy}$  in the inner few arcmin of the map, the GDF is three times deeper than any other millimeter/submillimeter deep-field observation ever acquired.

will feature 82 pixels), they must operate under unusually high loading and at higher than typical speed. Benford, Fixsen, and Staguhn are Co-Is.

Our ground-based instruments continue to provide cutting-edge scientific results. The ZEUS spectrometer at the Caltech Submillimeter Observatory, led by Cornell using GSFC detectors (Benford, Moseley, and Staguhn), has continued to provide new diagnostics of far-infrared atomic line emission from high-redshift galaxies, including the first detections of OIII at 88 microns and NII at 205 microns. These lines trace important physical parameters of galaxies at their epoch of peak star formation. The SHARC-II camera, also at the CSO and using a 384-pixel GSFC bolometer array (Benford, Moseley, Staguhn), continues to be the most productive submillimeter (350 micron) imager in the world.

Our recent long-wavelength (2 mm) camera named GISMO (PI: Staguhn; Benford, Moseley, Fixsen are Co-Is) had another successful observing run in April 2011. On that run, the deepest submm/mm-wavelength blind survey ever taken was conducted; many previously unknown sources were detected, and based on models, at least one of them is likely to be the most distant galaxy known in the universe. The GISMO camera is based on a 128-element close-packed planar bolometer array that uses supercon-

ducting thermistors read out by SQUID multiplexers. It is now installed at the IRAM 30m radio telescope in Pico Veleta, Spain, where it is a facility instrument available to the international astronomical community. Its first proposal cycle last fall has resulted in many new projects, with observations to begin this April.

*A promising new technique would enable entire instruments to be built on a single silicon wafer.*

Work has been ongoing to develop a new generation of detector technology and instrument concepts (PIs include Benford, Moseley, Wollack). A promising new technique, based on superconducting resonators and kinetic inductance detection, would enable entire instruments to be built on a single silicon wafer. A compact (4-inch wafer) microstrip spectrometer for the millimeter band that provides nearly octave-wide coverage with a spectral resolution sufficient to detect multiple emission lines from galaxies is in production (PI: Moseley; Benford & Wollack are Co-Is).

### Technology Development for Gravitational Wave Detection

The technologists in ASD's Gravitational Wave Astrophysics branch continued to develop and validate key technologies for space-based gravitational wave detection in 2011. While these efforts were initiated to support the joint NASA/ESA Laser Interferometer Space Antenna (LISA) mission, they remain equally relevant to ESA's Next Gravitational-wave Observatory (NGO) mission and NASA's Space-based Gravitational-Wave Observatory (SGO) mission study. Gravitational Wave Astrophysics branch scientists Camp, Guzmán, Livas, Numata, Stebbins and Thorpe led the technology development efforts with help from both civil servant and contract engineers. In addition, these activities also provided an opportunity for students from high school through graduate school to gain valuable experience. Students active in 2011 included high school students Lilian Sun and Zachary Schwartz, undergraduates Jennifer Harding and Phillip Cowperthwaite, graduate student Darsa Donelan, and Baltimore County Public School Teacher James Beam. Lilian Sun received an award from the National Space Club for her work during the summer of 2010

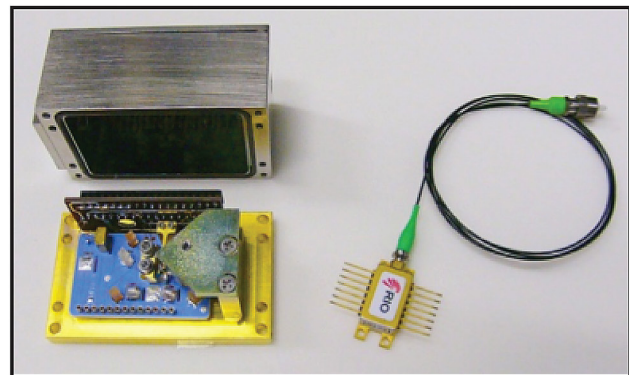
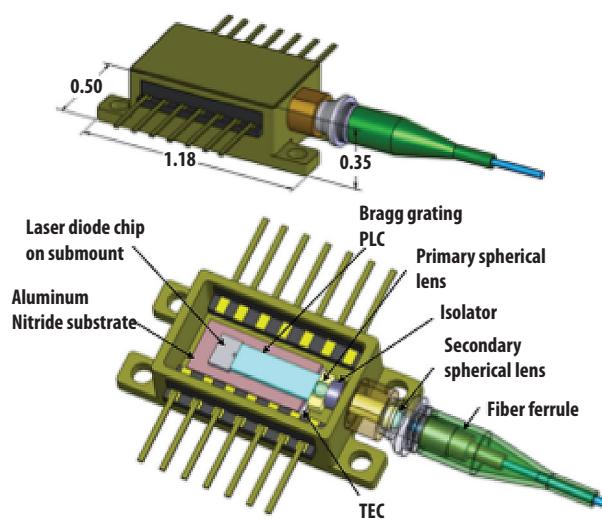




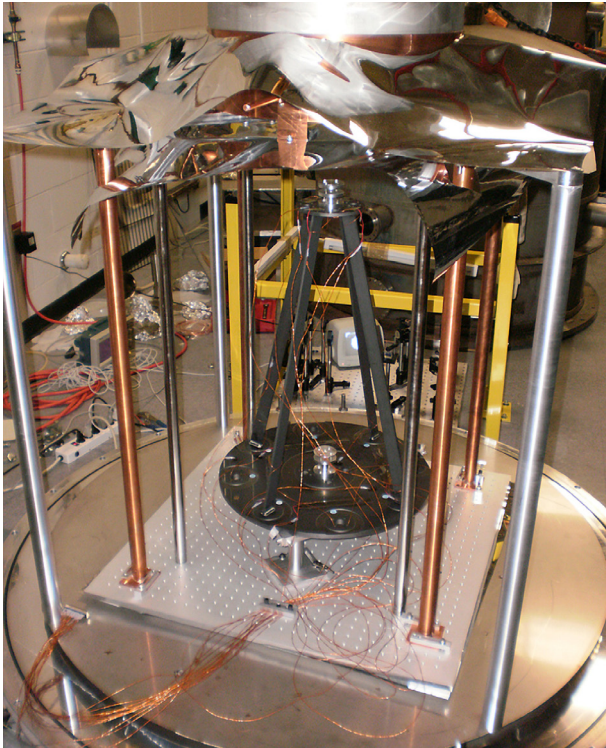
Student intern Lilian Sun (left), National Space Club President Marc Johansen (center) and Vice President and Award Chair Suzy Sterner at the 2011 National Space Club Annual Award Dinner on April 1, 2011.

and spoke at the April 2011 awards dinner. Ms. Sun was featured in the recent publication “Women of Goddard.” Results from technology development activities were presented at a number of conferences, including the 9th Eduardo Amaldi meeting, the American Astronomical Society High Energy Astrophysics Division meeting, and the 78th annual Southeastern Section of the American Physical Society.

**Fiber laser/amplifier development.** Laser technology for the telecom industry has undergone dramatic advances in the past decade. Lasers and optical amplifiers based on bulk optics have been replaced by technologies such as fiber lasers/amplifiers, waveguide devices, and semiconductor lasers. These components naturally fit into the precision laser systems needed for interferometric gravitational wave missions (e.g., NGO/SGO); they have high mechanical robustness, high reliability, compact form factor, and high wall-plug efficiency. Numata and Camp, together with technical support from the GSFC Laser and Electro-optics Branch and Lucent Government Solutions (LGS), are pursuing an all-fiber/waveguide space laser solution based on the MOFA (master oscillator fiber amplifier) configuration, namely, a waveguide-based oscillator followed by a pre-amplifier and a power amplifier. In 2011, detailed noise measurements of the power amplifier system were performed. It turned out that the power amplifier adds negligible frequency noise to the carrier light of the seed. The differential phase noise is factor  $\sim 4$  higher than the LISA requirement level. The intensity noise of the amplifier was also measured and stabilized. Numata and Camp have also looked into the latest telecommunications laser technology represented by the planar-waveguide external cavity diode laser (PW-ECL) as a possible alternative to traditional NPROs and fiber lasers. In 2011, various tests on the PW-ECL were performed to investigate its suitability for a space qualification program. It included gamma/proton radiation hardness tests, hermeticity test, and



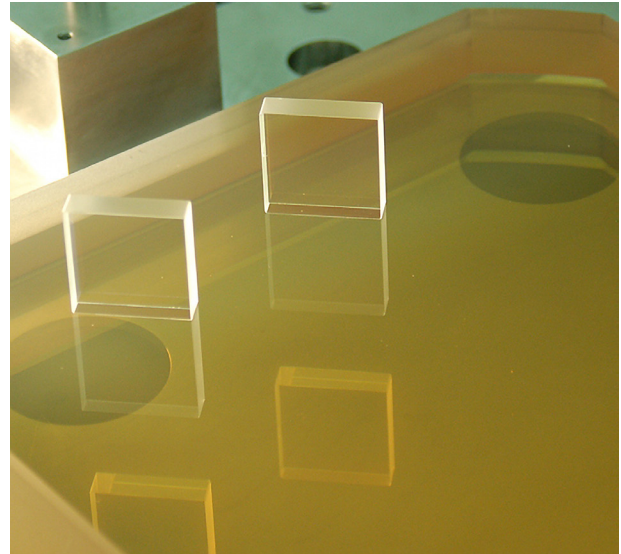
Left: Schematic of the planar-waveguide external cavity diode laser (PW-ECL). Right: Photo of the NPRO laser core optics and the PW-ECL package, demonstrating the associated size savings.



*Prototype telescope metering structure during installation in a University of Florida test facility. Testing has shown that the structure meets the basic stability requirements and is now focused on understanding the response of the spacer to thermal gradients.*

active vacuum thermal cycling. All performance and reliability testing done to date has indicated that the PW-ECL is robust for spaceflight. Construction of complete laser system (including pre-amplifier) and detailed performance tests will be performed in 2012.

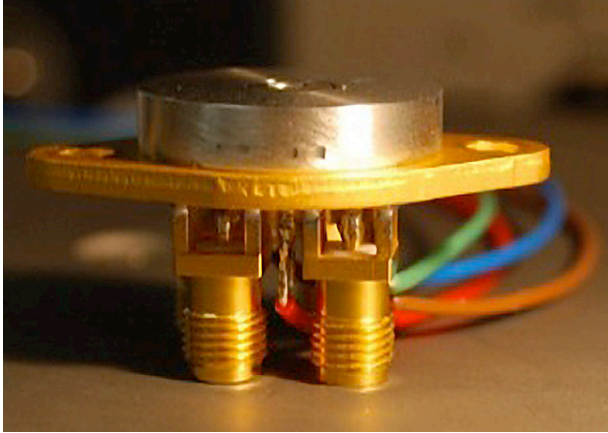
**Telescope structure stability.** A telescope is needed for gravitational wave measurements to increase the light-transfer efficiency between distant spacecraft. Since the telescope lies in the interferometric path, it is critical that the optical path length through the telescope remain stable at the picometer level. Livas, together with engineering support from GSFC and construction and testing support from the University of Florida, has developed a prototype metering structure of silicon carbide that will be used to evaluate the material for potential use in the LISA telescope. While not a true telescope in the sense that it does not focus light, the prototype is structurally similar to a telescope: four long legs attached to a large disk (the primary) support a smaller disk (the secondary). The six components of the telescope were manufactured individually and were then bonded together using



*Two fused-silica optics bonded to a Zerodur baseplate using hydroxy-catalysis bonding during the construction of the optical bench.*

hydroxide-catalysis bonding. Testing at the University of Florida has confirmed that the dimensional stability is limited by thermal effects in the environment and that the structure will meet requirements in the expected on-orbit environment. Continued testing in 2012 will study the response of the structure to thermal gradients.

**Optical bench construction.** The missions under study in Europe and the US detect gravitational waves by monitoring distance fluctuations between widely-separated, freely-falling test masses using laser interferometry. The optical structures used to perform this interferometry must be stable at the picometer level to ensure that they do not introduce disturbances that would corrupt the measurement. An innovative technique known as hydroxy-catalysis bonding has been applied in Europe to produce the optical benches for the technology demonstrator mission LISA Pathfinder. Thorpe is leading an effort funded by the GSFC IRAD program to build a small optical bench containing a frequency stabilization reference using the hydroxy-catalysis technique. The team consisting of A. Preston (Laser Remote Sensing Laboratory), L. Miner (Optics Branch), and K. Norman (SGT) successfully completed construction of the bench and have begun performance testing of the frequency reference. The success of this effort led to Thorpe's participation in an IRAD-funded effort to build a hydroxy-catalysis bonded optical bench for the Visible Nulling Coronagraph exoplanet instrument



Side view of the Quad Photoreceiver package. Basic requirements have been met. Devices are being tested for electrical crosstalk and will be evaluated for system-level operation.

in partnership with R. Lyon (Exoplanets and Stellar Astrophysics Laboratory).

**Laser stabilization through arm-locking.** To achieve the displacement sensitivity required to detect gravitational waves, the laser sources must be frequency-stabilized. In the laboratory this is typically accomplished by locking the laser frequency to a frequency reference such as an optical cavity or molecular absorption line. Long-baseline gravitational wave missions provide an alternative: using the long arms of the constellation as a frequency reference. This technique, known as arm-locking, has been extensively studied using analytic models of the LISA interferometry system. Thorpe, together with Livas and controls engineer P. Maghami (Attitude Control Systems Engineering Branch), have developed a time-domain simulation of arm-locking that allows the investigation of a number of effects that are not easily modeled analytically. This effort, which was completed in 2011 with the publication of the results, demonstrated that arm-locking is indeed a viable option for laser frequency stabilization in gravitational wave missions.

**Photoreceiver development.** Space-based gravitational wave detectors will use quadrant photoreceivers to detect the interferometric signals and measure the motion of drag-free test masses in both angular orientation and separation. Guzmán, Livas and Silverberg (Observational Cosmology Laboratory Emeritus) have set up a laboratory testbed for the characterization of photoreceivers. A custom photoreceiver with a 1.0-mm-diameter quadrant photodiode and the associated electronics has been developed through the

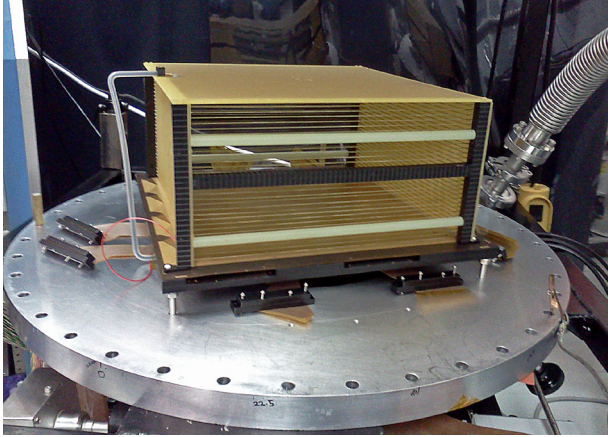
Small Business Innovative Research (SBIR) program. Demonstrated device performance shows an equivalent input current noise of better than  $1.8\text{pA}/\sqrt{\text{Hz}}$  below 20MHz and a 3 dB-bandwidth of 34 MHz, which meets nominal requirements. Next steps include spatial scanning of the photodiode surfaces, measurement of inter-quadrant cross-talk, system-level differential wavefront-sensing angle measurements, and design and testing of alternative topologies for photoreceiver electronics with lower noise and higher-bandwidth performance.

### Three-Dimensional Track Imager Detector for Gamma-ray and Neutron Imaging

Stanley Hunter, with Georgia DeNolfo, Seunghee Son, and Michael Dion continue the development of the Three-Dimensional Track Imager (3-DTI) for future gamma-ray telescopes and neutron imaging. The goals are to provide optimum angular resolution and polarization sensitivity in the medium-energy (5–500 MeV) gamma-ray range and fast neutron imaging ( $E_n > 0.1$  MeV) from passive and active interrogation of special nuclear materials (SNM).

The 3-DTI is a large-volume time-projection chamber (TPC) capable of three-dimensional tracking and momentum measurements used for particle identification. A two-dimensional micro-well detector (MWD) serves as a spatial readout and multiplication stage while the third coordinate is obtained from the drift time of the primary charge through the gas volume. Each well of the MWD—200-mm diameter on 400-mm centers—is an active gas proportional counter with gas gain of  $\sim 10^4$ . Negative ion drift is utilized to reduce the drift velocity and diffusion allowing for the large TPC volume. Development of the 3-DTI technology for gamma-ray imaging is funded by NASA/APRA and for neutron imaging by the Office of Naval Research (ONR), Code 35. The team's accomplishments this year include:

- The data from the over-water test of the  $30 \times 30 \times 7$  cm<sup>3</sup> 3-DTI/NIC prototype using <sup>252</sup>Cf and SNM sources was completed and a report was submitted to ONR. The measured omnidirectional RMS angular resolution was determined to be 6.1 deg.



The prototype 3-DTI. The  $30 \times 30 \text{ cm}^2$  MWD can be seen between the wires and supports forming the 15-cm tall drift volume. The flex-circuit connections between the MWD electrodes and the charge-sensitive front-end electronics have not been connected. The front-end electronics and high-voltage supply for the drift grid are located below the aluminum plate.

- Drs. Son and Dion made major improvements in our UV laser micro-machining facility allowing various machining techniques to be tested. MWD with Cirlex (thick Kapton) and Liquid Crystal Polymer substrates were fabricated and tested. Differences in the turn-on voltage and gain of these detectors were observed and are still being investigated. Dr. Dion is investigating techniques to fabricate higher gain MWDs that have a small post projecting from the anode.
- A 4-channel charge-sensitive amplifier ASIC being used on the JUNO, MMS, RBSP, NPOEES, Solar Orbiter missions was tested successfully with the anode and cathode signals of the 3-DTI.
- With Robert Baker, we designed a new “streaming mode” readout system that essentially eliminates the 3-DTI readout dead time. This system is currently being tested.
- **Publication:** *Negative Ion Drift Velocity and Longitudinal Diffusion in Mixtures of Carbon Disulfide and Methane* by M.P. Dion, S. Son, S.D. Hunter, and G.A. de Nolfo, Nuclear Instrument and Methods A 648, 186–91 (2011).

## 100-meter X-ray Calibration Beamline Facility

For more than 40 years, the high-energy astrophysics community at GSFC has employed the X-ray Calibration Beamline Facility for characterization and calibration of X-ray detectors and X-ray optics. The Beamline is a vacuum system that permits the generation, transmission and collimation of an X-ray source in an environment free of air that would otherwise attenuate the X-ray beam. The Beamline Facility, originally installed in 1970 in the Penthouse of Building 2, consists of an X-ray Generator section, a 43-m long X-ray Beam Collimator Tube, an X-ray Test Chamber, and an Exit X-ray Beam Tube from the Test Chamber to a focal plane instrument, typically an X-ray CCD camera. The Test Chamber, 1.5-m in diameter and 2.4-m long, contains a gimbaling system that can tilt, rotate, and translate the test article in the X-ray beam. Additionally, the Beamline Facility has a thermal control system that permits simulation of the temperature swings an instrument might encounter in space.

In 2010, when the Astrophysics Science Division was moving out of Building 2, a new Beamline Facility was constructed at the Goddard Geophysical and Astronomical Observatory site, Area 200, to house the existing vacuum system components. The new Facility consists of a Source Building (225) and a Detector Building (226), connected by the Collimator Tube. All of the vacuum equipment that had been in Building 2 was moved to Area 200, and the Collimator Tube was extended to a length of 100 meters. The new Beamline Facility is equipped with ample electrical power, heating and air conditioning, plus telephone and network capabilities.

Since 1995, the Beamline has been in almost constant use, testing X-ray telescope mirror components and assemblies for Astro-E, Astro-E2 (Suzaku), and now Astro-H and GEMS. In that same time, many of the original controls for the vacuum system, the gimbaling system and the camera system have been upgraded with a goal of end-to-end automation and integration of all sub-systems in the Beamline operation.

## Projects

Scientists assigned to NASA flight projects play vitally important roles during all phases of a mission's life cycle—from the development of science requirements, to concept and technology development, formulation and eventually operations. The Project Scientist works with project managers, engineers, NASA Headquarters, the mission science team (or science working

group) and the wider astronomical community to assure a successful outcome. Nearly half of the scientists in ASD serve NASA either as a Project Scientist (PS) or as a Deputy Project Scientist (DPS), Mission Scientist (MS), Instrument Scientist (IS), Principal Investigator (PI), and Deputy PI. The top-notch science that flows from ASD missions is a testament to the knowledge, hard work and dedication that the division's technical staff brings to these roles.

Project Scientists	
<b>ACE</b>	Tycho von Rosenvinge
<b>Astro-H</b>	Robert Petre (PS)
<b>SXS Instrument</b>	Rich Kelley (PI)
<b>Balloon Program</b>	Jack Tueller (PS), John Mitchell (DPS)
<b>Cosmic Origins</b>	Dominic Benford (Chief Scientist), Susan Neff (Deputy)
<b>International X-ray Observatory (IXO)</b>	Nick White (PS), Ann Hornschemeier (DPS), Robert Petre (Deputy for Observatory)
<b>Explorer Program</b>	Neil Gehrels (PS)
<b>GALEX</b>	Susan Neff (MS)
<b>GEMS</b>	Tim Kallman (PS), Jean Swank (PI), Keith Jahoda (DPI), Joe Hill (IS)
<b>Fermi</b>	Julie McEnery (PS), Liz Hays (DPS), Neil Gehrels (DPS), Dave Thompson (DPS)
<b>HEASARC</b>	Alan Smale (Director), Lorella Angelini (DPS)
<b>HST</b>	Jennifer Wiseman (PS), Ken Carpenter (Operations DPS), Jeff Kruk (Observatory PS)
<b>LISA</b>	Robin Stebbins (PS), Jordan Camp (DPS), Jeff Livas (DPS)
<b>JWST</b>	John Mather (PS), Jon Gardner (DPS), Mal Niedner (DPS for Technical), Matthew Greenhouse (ISIM PS), Bernard Rauscher (DPS for ISIM), Mark Clampin (Observatory PS), Charles Bowers (DPS for Observatory), George Sonneborn (Operations PS), Jane Rigby (DPS for Operations), Randy Kimble (DPS for I&T)
<b>JWST microshutters</b>	Harvey Moseley (PI)
<b>NASA Engineering Safety Center</b>	Ed Wollack
<b>Physics of the Cosmos</b>	Ann Hornschemeier (Chief Scientist), Alan Smale (Deputy)
<b>WFIRST</b>	Neil Gehrels (PS), Jeff Kruk (IS)
<b>RXTE</b>	Tod Strohmayer (PS)
<b>Sounding Rockets</b>	Scott Porter (DPS)
<b>Suzaku</b>	Rob Petre (PS), Lorella Angelini (DPS)
<b>Swift</b>	Neil Gehrels (PI), Scott Barthelmy (DPI)
<b>WISE</b>	Dave Leisawitz (MS), Dominic Benford (DMS)
<b>WMAP</b>	Ed Wollack (PS)
<b>XMM</b>	Steve Snowden (PS)

## In Operation

### Fermi Gamma-ray Space Telescope

#### Science

January 2011 brought the announcement that the Fermi Large Area Telescope (LAT) team had been awarded the American Astronomical Society High Energy Astrophysics Division Rossi Prize, “for enabling, through the development of the Large Area Telescope, new insights into neutron stars, supernova remnants, cosmic rays, binary systems, active galactic nuclei, and gamma-ray bursts.” ASD scientists were involved in all these topics.

The Crab Nebula gamma-ray results continued to surprise the astrophysical community. Often considered so stable that it is referred to as a “standard candle” in high-energy astrophysics, the Crab Nebula produced its largest GeV flare yet in April. Elizabeth Hays and Jamie Cohen were active in studying this

remarkable flare, attributed to synchrotron-emitting electrons in inner regions of the nebula. In response to a request from Hays, Fermi executed a Target of Opportunity (TOO), allowing the LAT to trace variability of the flare on a timescale of hours. Follow-up observations at other wavelengths, including Chandra X-ray observations, revealed no obvious changes associated with the huge gamma-ray flare.

Supernova remnants (SNR), thought to be a source of high-energy cosmic-ray particles, emerged in 2011 as another active area of research for the Fermi team. John Hewitt and Theresa Brandt, along with Hays and Cohen, were active in studies of individual SNR, including modeling the LAT results in a multiwavelength context. Hewitt and Brandt hosted a meeting of the Fermi LAT SNR catalog team at Goddard in December, in preparation for the upcoming release of the first LAT SNR catalog.

Gamma-ray pulsars also continue to grow in number, with the milestone of 100 reached near the



*The most powerful gamma-ray flare observed to date in the Crab Nebula was discovered by Fermi on April 12, 2011, and continued in outburst for six days. These before-and-after LAT sky maps show the number of gamma rays with energies greater than 100 MeV detected between pulses from the Crab pulsar. The bright source at bottom is the Geminga pulsar. Left: 20 days before the flare. Right: April 14. The Crab Nebula is not resolved by Fermi and its larger size is a saturation effect. NASA/DOE/Fermi LAT/R. Buehler*

end of the year. These gamma-ray pulsars are roughly equally divided among young pulsars found from known radio or X-ray timing information, young pulsars discovered in blind searches of the LAT data, and old, recycled millisecond pulsars. Elizabeth Ferrara has played a key role in coordinating all the detections and timing information for these pulsars. Megan DeCesar, Alice Harding, Tyrel Johnson and Christo Venter have focused their attention on various studies of the high-energy gamma-ray emission from millisecond pulsars (MSPs) and implications on emission models. Ozlem Celik is leading the spectral analysis work for the second Fermi LAT pulsar catalog, which will include 116 pulsars. Davide Donato has been doing follow-up work on some of these pulsars using Swift. David Thompson continues to reach out to multiwavelength pulsar observers.

Robin Corbet discovered a new high-mass binary system using the Fermi LAT data. Donato confirmed that this system is also seen by Swift.

Looking outside our Galaxy, Donato, Thompson, Julie McEnery, Jeremy Perkins, Roopesh Ojha, Michael Dutka, and Bill McConville have been pursuing studies of Active Galactic Nuclei (AGN). Numerous Astronomer's Telegrams have resulted from AGN flares spotted by Donato, Ojha, and Dutka while working as LAT Flare Advocates. McConville, Perkins, and Thompson have been involved in correlated multiwavelength studies of individual flaring AGN. Ojha and Dutka work closely on correlations with the southern hemisphere radio VLBI program TANAMI. Dutka, McEnery, McConville, Perkins, and Ojha were organizers of the Fermi and Jansky meeting in St. Michaels, Maryland, which brought together observers, theorists and modelers of AGN, particularly those using gamma-ray and radio observations.

Unidentified sources, those mysteries yet to be solved, occupy several members of the team. Ferrara led a paper with multiple approaches to source classification. Thompson contributed analysis to this paper, and Donato continued with multiwavelength searches for counterparts to these sources.

The second Fermi LAT source catalog was released. Thompson and Ferrara played significant roles in the development of the catalog and writing of the associated papers. With 1,873 sources, the 2FGL catalog provides a valuable resource to the astrophysical community. The Fermi Science Support Center (FSSC) team has made the catalog available in con-

venient electronic tables (Dave Davis, Don Horner, and Ferrara).

Alex Moiseev continued his work on cosmic-ray electrons measured with the LAT, extending the spectral energy range in papers in *Physical Review D*. Moiseev and Vlasios Vasileiou were involved in a related study searching for anisotropy in the electron arrival directions that might be related to local cosmic-ray sources.

Gamma-ray burst studies continue (Judith Racusin, Eleonora Troja, Eda Sonbas, Vasileiou, McEnery), with bursts seen by the LAT regularly (but not always) showing delayed onset compared to lower-energy gamma rays, GeV afterglows with a power-law decay, and an extra power-law spectral component that extends across the energy range of both Fermi instruments. Racusin and Troja have worked particularly on bursts seen by both Fermi and Swift.

Theoretical studies involving Fermi results include work by Rodrigo Nemmen (working with Neil Gehrels), which shows a correlation between kinetic power and gamma-ray luminosity for AGN and gamma-ray bursts. Tonia Venters continues to study constraints that Fermi results can place on intergalactic magnetic fields using anisotropy studies of the extragalactic background gamma radiation.

### *Outreach to the Scientific Community*

McEnery and Hays were organizers for the first Fermi Gamma-ray Summer School, held in Lewes, Delaware. Many other members of the local group and the Fermi Science Support Center supported this school.

Jerry Bonnell, Corbet, and Ferrara developed a list of Fermi-related papers sorted from journal and arXiv submissions and made it available from the FSSC.

### *Instrument and Mission Operations and Analysis*

Moiseev, Hays, Brandt, and David Green have continued studies of the performance of the Large Area Telescope Anticoincidence Detector, a subsystem built at Goddard.

McEnery, Racusin, and Hays continue to work closely with the spacecraft operations team and system experts at Goddard to guarantee that Fermi continues to achieve peak performance throughout the confirmed 10-year mission.

The FSSC released an updated science tools package expanding platform support and including new tools.

### Senior Review Preparations

McEnery, Racusin, and Thompson were key writers for the Fermi Senior Review proposal to be submitted for continuation of the Fermi mission, working with the LAT and GBM teams and the Fermi Users' Group. Important contributions were made by Brandt, Harding, and Hewitt.

### The Rossi X-ray Timing Explorer (RXTE)

The Rossi X-ray Timing Explorer is designed to facilitate the study of time-variable emission of X-ray sources with moderate spectral resolution. RXTE covers timescales ranging from microseconds to months in a broad spectral range from 2 to 250 keV, boasts a large collecting area, and is able to monitor bright sources over the entire sky. RXTE was designed for a required lifetime of two years and a goal of five, but on December 30, 2011, the spacecraft celebrated 16 years in orbit, and an exceptional legacy of scientific discovery.

Tod Strohmayer is the Project Scientist. In its long and productive history, RXTE is responsible for numerous discoveries resulting in four Rossi Prizes—to Bailyn, McClintock, and Remillard (2009); Strohmayer, Chakrabarty & Wijnands (2006); Kouveliotou and Thompson (2003); and Bradt and Swank (1999)—as well as more than 93 doctoral theses and over 2,500 refereed publications.

The observation planning, instrument monitoring, and calibration updates are carried out with the part-time contributions of an experienced team that includes Keith Jahoda, Craig Markwardt, Nikolai Shaposhnikov, and Evan Smith at Goddard. Improvements in background determination and response matrices continue to be made.

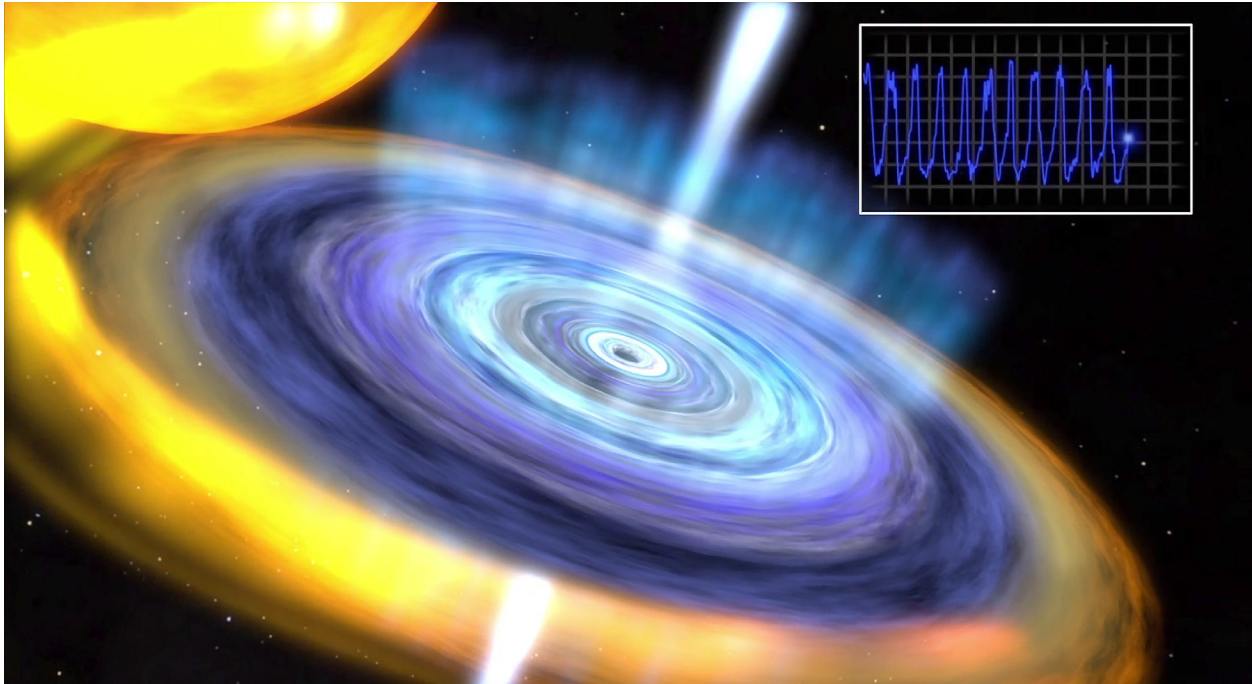
The Science Operations Center (SOC), with Frank Marshall as director, assisted by Robin Corbet as Science Operations Facility (SOF) manager, and the GSFC Mission Operations group have worked together to continue to automate operations and reduce manpower and expenditures, while preserving RXTE's ability to accommodate new information about targets of opportunity (TOOs, implemented by SOF scheduler Evan Smith). RXTE's most used follow-up

capability is for timescales of 1–2 days. It is possible to have follow-up observations within hours for a select subset of requests, but transients that harbor millisecond pulsars, active periods of magnetars, the lifecycles of galactic black hole transients, and, of course, the active periods of blazars require a response on the order of days that can be sustained for days to weeks. RXTE continued to be the mission most often requested to carry out such observations.

The RXTE project has submitted proposals to each of NASA's Senior Reviews of the Astrophysics Operating Missions since 1994. The 2006 review confirmed RXTE's operations through the 2008 review, by which time the project had developed a program to extend operations through February 2009. The 2008 review concluded that funds were not available for further funding of the longest operating of the competed astrophysics missions. However, continued reductions in operating costs, combined with additional funds and guidance from NASA HQ, enabled the mission to operate through September 2010. Operations beyond that were addressed by the 2010 Senior Review, to which RXTE was invited to submit a proposal. The panel did not recommend additional funding for RXTE operations but recognized the continued value and productivity of the mission to NASA and supported continuation if operating funds could be found. Some additional cost reductions were implemented, and funding to continue the mission in FY11 was approved by NASA, along with a Cycle 15 call for proposals, but with an expectation that this would be RXTE's last observing cycle. Indeed, the number of proposals received in Cycle 15 grew by ~18 percent, further confirming that researchers still highly valued RXTE observations. NASA did not invite RXTE to submit a proposal to the 2012 Senior Review.

The RXTE team executed the Cycle 15 observing program through FY11, and based on guidance from NASA HQ, additional funding was provided to continue operations through to the end of calendar year 2011, to be followed by decommissioning and mission close-out in the first several months of 2012. This additional extension of operations enabled rare opportunities to observe occultations of the Crab nebula by the Moon and a completion of the Cycle 15 program, both of which were successfully achieved. The RXTE satellite was decommissioned on January 5, 2012, and final mission close-out is ongoing at the time of writing.





Artist's rendering of the inner accretion disk, disk wind and jet from the black hole system IGR J17091-3624. The inset trace shows characteristic "heartbeat" oscillations produced by the black hole. The heartbeat is theorized to be associated with the formation of the wind and jet (the peak of the beat), and then drop as the inner disk is expelled and then refills. NASA/Goddard Space Flight Center/CI Lab

RXTE observations remained in high demand right up to the conclusion of scientific observations and Cycle 15 saw a steady flow of new results. The black hole system IGR J17091-3624 (hereafter J17091), which was first discovered in 2003 with INTEGRAL, was seen in outburst with RXTE and was extensively tracked from early February 2011 until virtually the end of the mission. During this latest outburst J17091 revealed X-ray properties and variability previously seen in only one other black hole binary, the luminous and highly variable source GRS 1915+105 (hereafter GRS 1915). Among the newly discovered properties were so-called "heartbeat" oscillations with a period close to one minute. Looking very much like the trace of an electrocardiogram, the heartbeats from J17091, while similar to those observed from GRS 1915, were found to occur at a factor of 8 times faster rate. The quicker heartbeats from J17091-3624 suggests that it may harbor a less massive black hole than GRS 1915.

In Cycle 15, RXTE also observed a unique accreting neutron star pulsar in the globular cluster Terzan 5. The source, IGR J17480-2446, is an 11 Hz X-ray pulsar in a 21.25 hr binary. Interestingly, the source was also found to be a prolific X-ray burster, producing thermonuclear X-ray bursts over a range of accre-

tion rates. At the highest accretion rates the bursting evolved into mHz (2 min) oscillatory burning likely due to marginally stable nuclear burning—a behavior that has only been observed from a handful of neutron star systems. This object is now a prime candidate for high-resolution spectroscopy during the X-ray bursts to search for red-shifted neutron star surface absorption lines. Detection of the surface redshift provides a direct measurement of the mass-to-radius ratio of the neutron star. This in turn provides exciting details of the properties of dense matter in the neutron star interior. The slow spin rate is crucial in that any absorption lines will not be smeared out by rapid rotation of the star.

### XMM-Newton Guest Observer Facility

ASD operates the U.S. XMM-Newton Guest Observer Facility (XMM GOF). XMM is a European Space Agency (ESA) X-ray astrophysics mission, and ESA allocates resources to support European XMM users but looks to the GOF to provide support to the large U.S. astrophysics community. GOF activities include facilitating the submission of GO proposals to ESA, distributing proprietary data to U.S. PIs, maintaining



*Composite of M31, the Andromeda Galaxy, using infrared data from Herschel (250 microns, in orange) and X-ray data from XMM-Newton (1.8–41.3 Ångstroms, blue-white). M31 is the nearest major galaxy to the Milky Way, which makes it ideally suited for galaxy-wide investigations of star formation and evolution. Infrared: ESA/Herschel/PACS/SPIRE/J. Fritz, U. Gent; X-ray: ESA/XMM-Newton/EPIC/W. Pietsch, MPE*

the full public science archive, and supplying expertise, analysis software and documentation to U.S. scientists.

The GOF works in conjunction with the ASD GOFs of other high-energy astrophysics missions (e.g., RXTE, Integral, Fermi, Swift and Suzaku) to lower costs and to ensure consistency in the areas of the budget proposal process, FITS tools, database structure, web pages and archival data access. Cost savings are leveraged by sharing resources, techniques, expertise and reusing software. GOF activities cover a very wide range of endeavors in support of XMM. A U.S. XMM-Newton Users Group under the chairmanship of Prof. Craig Sarazin (U. Virginia) provides community oversight of GOF activities. Dr. Steve Snowden is the NASA Project Scientist, and with Drs. Lynne Valencic and Kip Kuntz provides science support to the U.S. astrophysics community. Brendan Perry and James Peachy provide software support and Michael Arida maintains the U.S. XMM archive.

Kuntz and Snowden are involved in the particle background calibration of the XMM X-ray imagers and the cross-calibration between the XMM instruments and other X-ray observatories (e.g., Chandra, Suzaku, ASCA, and ROSAT), which enhances the utility of multi-observatory data analysis. This has been a major activity over the last several years with XMM GOF participation in the International Astronomical Consortium for High Energy Calibration (IACHEC). Snowden and Kuntz have developed the XMM-Newton Extended Source Analysis Software (XMM-ESAS) package which is now fully implemented within the mission software suite. This package significantly simplifies and improves the accuracy of data reduction for extended objects and the diffuse X-ray background.

Kuntz produced and maintains (by periodic updates to include recent observations) the Optical Monitor (OM) source catalog (Kuntz et al. 2008, PASP, 120, 740) to compliment the X-ray source

catalog produced by the XMM-Newton Survey Science Centre (SSC). The database contains entries for every source detected in OM observations. Kuntz and Arida work with STScI to make the OM catalog and data available through the Mikulski Archive at Space Telescopes (MAST), considerably increasing the data availability to optical astronomers.

Arida maintains the XMM-Newton archive at the GSFC GOF, which mirrors all public data in the ESA XMM-Newton Science Archive (XSA) at the SOC, as well as proprietary data for U.S. PIs. This mirroring of the data reduces the high data load at the European Space Operations Center site, and provides a much faster data-transfer rate within North America, as well as allowing use of the unique capabilities of the BROWSE database and providing a direct link for the use of XMM-Newton data within the HERA data analysis system.

Valencic maintains the ABC and D Guides which provide an introduction to the scientific analysis of XMM-Newton data, updates the XMM publication list on a quarterly basis—there are now ~1.3 refereed XMM publications per day—and supports the implementation of XMM-Newton analysis software within the HERA data analysis system. She has also developed extensive data analysis scripts, which can be used in HERA or on a user's local machine, for the user community.

Perry is an integral part of the ESA XMM mission software (Standard Analysis Software, SAS) development team and also contributes original software to SAS (e.g., XMM-ESAS). Peachy supports the image modeling software Sim-X (used for preparing science proposals), as well as the high-resolution spectral analysis tool Profit.

The XMM GOF was successful in the 2010 Senior Review process and will receive continued funding through FY12 for both GOF operations and GO support. Further funding through FY2014 was also recommended by the review. The GOF will submit a proposal to the 2012 Senior Review for continued funding through 2016.

## Suzaku (Astro-E2)

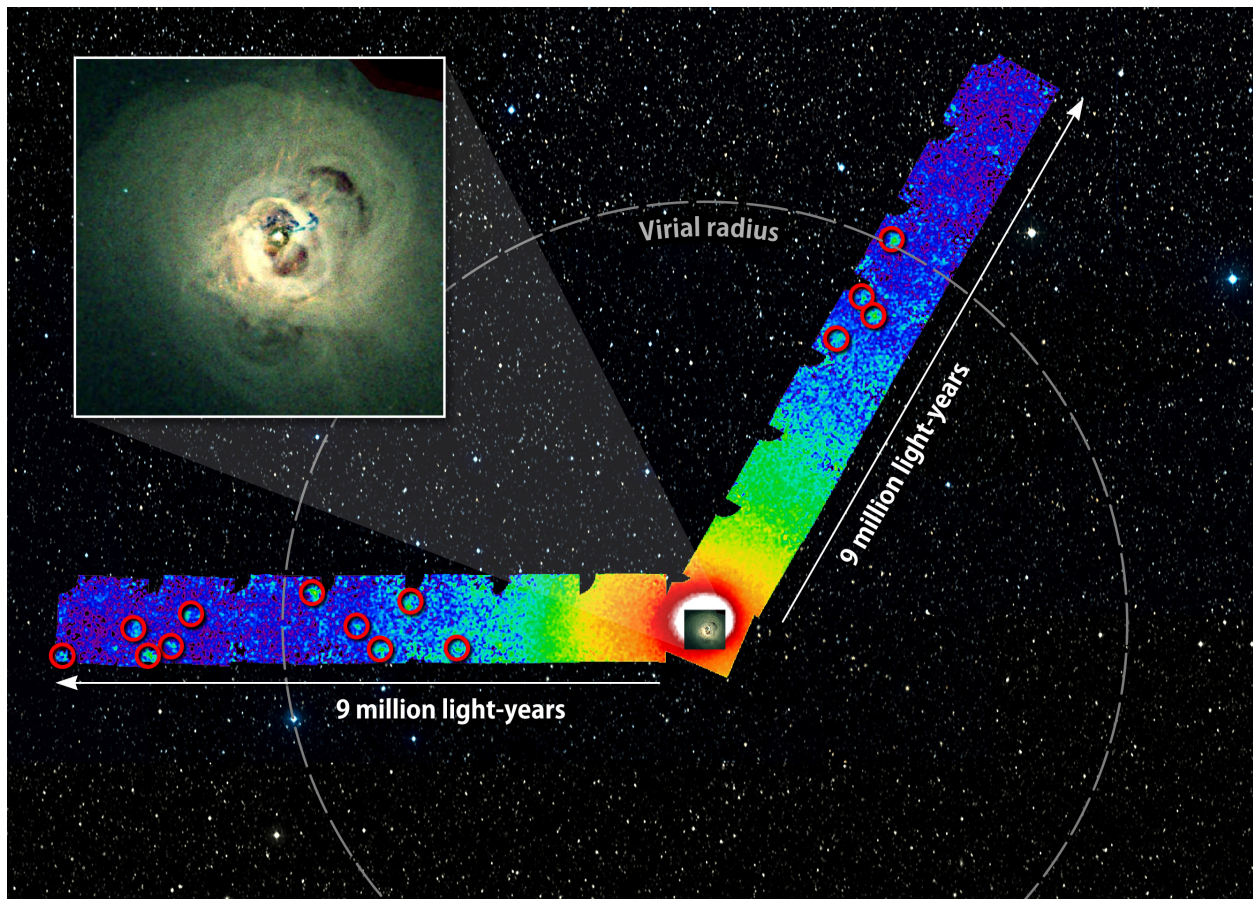
Suzaku is the fifth in a series of Japanese X-ray astronomy satellites, launched by the Japan Aerospace Exploration Agency (JAXA) on July 10, 2005. Like ASCA before it, Suzaku is a joint Japan-U.S. mission,

developed by the Institute of Space and Astronautical Science of JAXA (ISAS/JAXA) in collaboration with GSFC and many other institutions.

Suzaku's scientific payload includes three co-aligned instruments, of which two are functional. The X-ray Imaging Spectrometer (XIS) consists of four imaging CCD cameras, three of which are front-illuminated (FI: energy range 0.4–12 keV) and one back-illuminated (BI: energy range 0.2–12 keV). Each XIS is located at the focal plane of a dedicated X-ray telescope (XRT). One of the three FI chips was rendered inoperable by a micrometeorite impact in December 2006. A micrometeorite impact in June 2009 made a small portion of a second FI detector unusable. A third micrometeorite impact in December 2009 punched a hole in the optical blocking filter of the BI detector but otherwise did not affect its operation. The second functional instrument is a non-imaging, collimated Hard X-ray Detector (HXD) sensitive in the 10–600 keV band. The third instrument, the X-Ray Spectrometer (XRS), ceased operation shortly after launch due to a spacecraft design error.

GSFC's role includes supplying the five XRTs and the XRS "insert" (detector, blocking filters, adiabatic demagnetization refrigerator, and LHe cooler), development of data-processing software, operation of the U.S. Guest Observer Facility (GOF), and administration of the U.S. Guest Observer (GO) Program. Rob Petre is the NASA Project Scientist, Lorella Angelini is the Deputy Project Scientist, and Koji Mukai (CRESST) is the GOF Lead. Suzaku has produced an abundance of data from a wide variety of cosmic X-ray sources. Key unique Suzaku observations include: measurement of cluster properties at their virial radius; broadband measurements of AGN revealing simultaneously complex absorption, a relativistically broadened Fe K line, and a reflection continuum to 20–40 keV; determination of the spin of Galactic black holes and the radius of accreting neutron stars using their relativistically broadened Fe line; and measurement of the spectrum of a substantial fraction of the AGN detected by Swift.

U.S. observers have access to 50 percent of the observing time (including 5 percent through joint Japan/U.S. observations), as well as all archival data. The due date for proposals for the seventh observing cycle (April 2012–March 2013) was late November 2011. Over the most recent five cycles, an average of 90 proposals have been submitted, with a time over-



*Suzaku explored faint X-ray emission of hot gas across two swaths of the Perseus Galaxy Cluster. The images, which record X-rays with energies between 700 and 7,000 electron volts in a combined exposure of three days, are shown in two false-color strips. Bluer colors indicate less intense X-ray emission. The dashed circle is 11.6 million light-years across and marks the virial radius, where cold gas is now entering the cluster. Red circles indicate X-ray sources not associated with the cluster. Inset: An image of the cluster's bright central region taken by NASA's Chandra X-ray Observatory is shown to scale. NASA/ISAS/DSS/A. Simionescu et al.; inset: NASA/CXC/A. Fabian et al.*

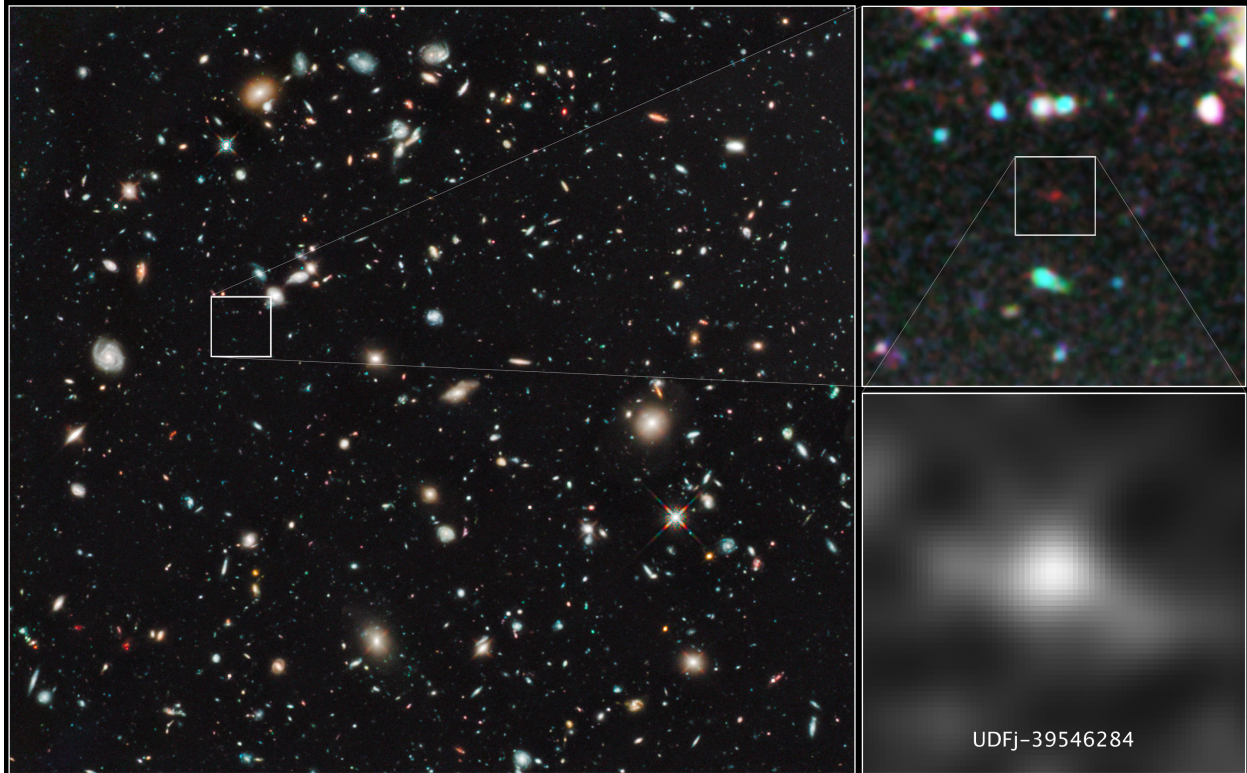
subscription of 3.5–4. Included in the submissions are proposals for key projects (observing time > 1Ms), the goal of which is to carry out major, multiyear observing programs that utilize Suzaku's unique capabilities. To date, seven key projects have been initiated, six of which have been completed. The completed ones include a deep observation of Kepler's SNR to characterize the explosion mechanism through measurements of modest-abundance metals, a census of broad Fe lines in AGN, and an extensive mapping of the Perseus Cluster of Galaxies (the brightest cluster in X-rays) to beyond its virial radius. Additional key projects will be started during the seventh observing cycle.

Suzaku has also developed relationships with other missions. Joint Suzaku-Chandra observations are now available through the Chandra GO program. It is possible through the Fermi GO program to obtain

Suzaku observing time to support coordinated observations. The Suzaku team is also collaborating with the MAXI team, following up flaring sources identified by MAXI.

The Suzaku data center is responsible for processing and archiving the full mission data set and distribution of data to U.S. GOs; development and maintenance of proposal and observation planning tools and documentation; maintaining the calibration database; supporting proposal reviews; assisting GOs in analyzing data; and ensuring grant funds are distributed in a timely way. The data center staff consists of three full-time scientists (Koji Mukai, Kenji Hamaguchi, Katja Pottschmidt) and one programmer, plus part-time support from HEASARC staff.

In early 2011, NASA announced the termination of U.S. participation in Suzaku. This decision was re-



*Astronomers have pushed the Hubble Space Telescope to its limits by finding what they believe is the most distant object ever seen in the universe. This dim, compact galaxy of blue stars existed 480 million years after the Big Bang, only four percent of the universe's current age, and its light traveled 13.2 billion years to reach the infrared detector of Hubble's Wide Field Camera 3. NASA/ESA/G. Illingworth (UCSC), R. Bouwens (UCSC, Univ. of Leiden) and the HUDF09 Team*

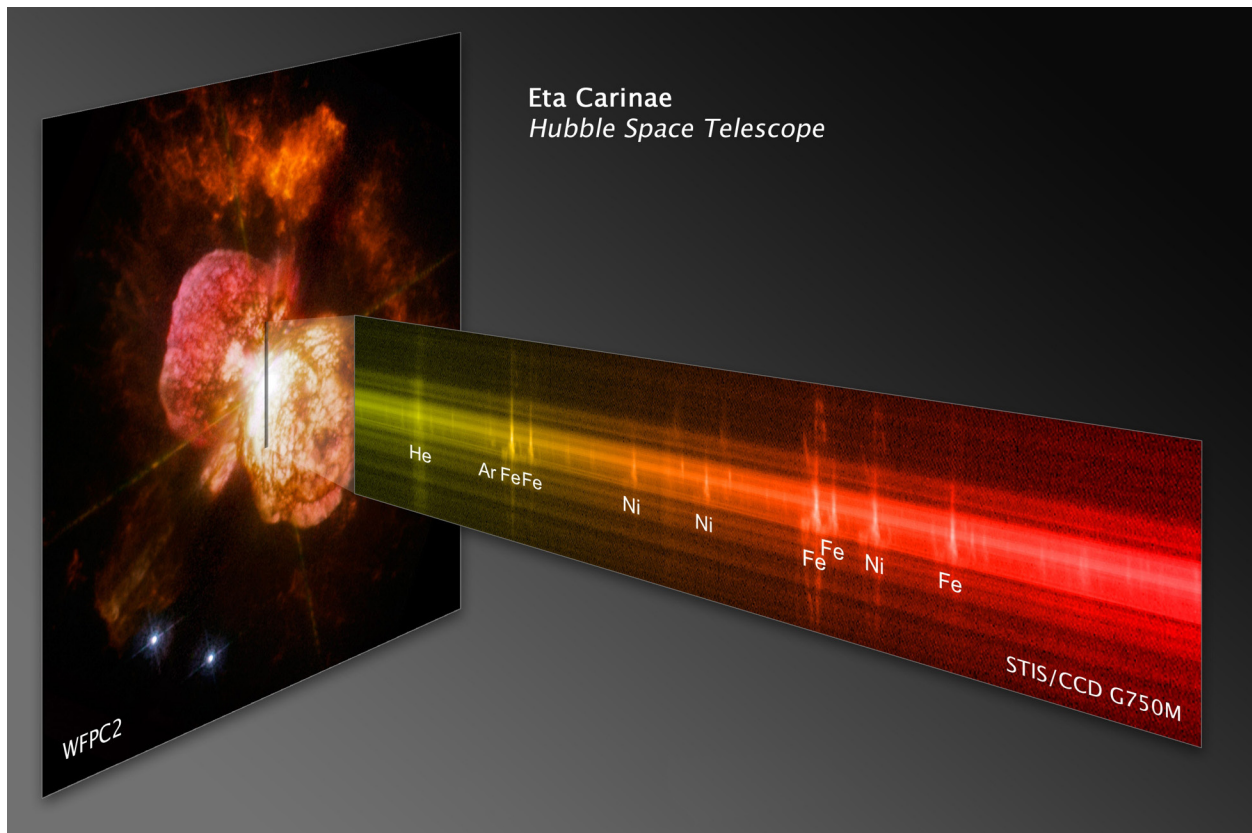
versed in October 2011, and Suzaku was invited to participate in the Astrophysics Senior Review. However, the U.S. data center budget for fiscal 2012 and 2013 was reduced by 80 percent, with no funding for GOs. Over the course of 2012, the data center activities will be constricted to fit within the new budget.

### The Hubble Space Telescope: Pushing New Frontiers

Hubble achieved a banner year in 2011, with the mission continuing to reap the fullest of scientific return from the success of Servicing Mission 4 (SM4) in 2009. Both new instruments, the Wide Field Camera 3 (WFC3), developed at Goddard, and the Cosmic Origins Spectrograph (COS), were utilized for ground-breaking science in regimes of wavelength, sensitivity or resolution where no space- or ground-based facilities could previously explore. The detection of a redshift  $z \sim 10$  galaxy was a cardinal achievement, utilizing the infrared capabilities of the pan-chromatic WFC3. This blue galaxy, actively forming stars and

shining from an era just a few hundred million years after the Big Bang, is tantalizingly close to the epoch of the very first proto-galaxies. The James Webb Space Telescope will be able to pick up at high redshift where Hubble leaves off, detecting pre-galactic clouds and stars beginning their assembly into the first galaxy fragments such as those Hubble is now detecting. In Goddard's Astrophysics Science Division (ASD), Hubble and JWST Project Scientists continued working together to plan science and its promotion that engage both flagship observatories.

Supernovae in distant galaxies also took prime stage for Hubble in 2011. The 250-orbit search led by Adam Riess of the Space Telescope Science Institute (STScI) made significant progress in finding supernovae at redshifts of  $z > 1$  by comparing multi-epoch Hubble survey images. His related gauging of "standard candle" Cepheid-variable-star light curves in nearby galaxies that also have type Ia supernovae enabled the most accurate calibration of the cosmic "distance ladder" and expansion rate ever obtained. A proud moment for the Hubble team both at Goddard



Goddard ASD scientist Ted Gull used Hubble's STIS imaging spectrograph to map the high ionization plasma in the inner arcsecond of Eta Carinae (the core of the larger region pictured at left). These are the first observations that fully image the extended wind-wind interaction region of this massive colliding wind binary star system. NASA/ESA/Hubble SM4 ERO Team

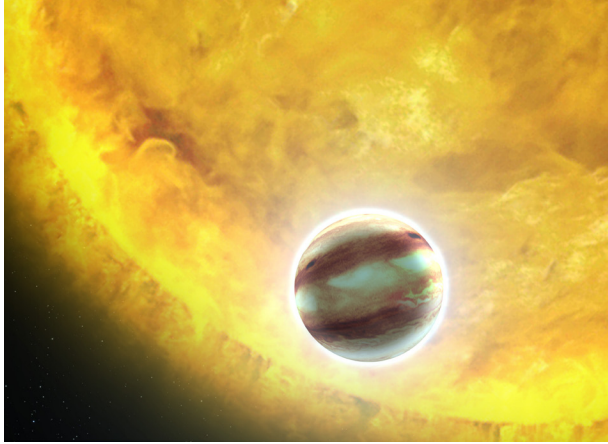
and at STScI this year was the awarding of the Nobel Prize in physics to Adam Riess (STScI), Brian Schmidt and Saul Perlmutter for discovering the acceleration of the universe. Hubble's unique capabilities at high redshift played the critical role of showing that a decelerating universe transformed into an accelerating universe just a few billion years ago. In fact, Hubble is the only observatory capable of making critical measurements of supernovae to constrain properties of dark energy at redshifts beyond  $z \sim 1$ .

Closer to home, exoplanets in our own galaxy were discovered by careful reanalysis of data in the Hubble archive from the NICMOS infrared camera. This is a marvelous demonstration of how the Hubble data archive is growing in its role as a major source of Hubble research. In our own solar system, Hubble detected a previously unknown moon of Pluto and the debris from an apparent asteroid collision.

Sensitive spectroscopy also made science headlines this year. Goddard ASD scientist Ted Gull used the repaired-in-SM4 Space Telescope Imaging Spectrograph

to map high ionization plasma in Eta Carinae, achieving the first observations that fully image the extended wind-wind interaction region of this massive colliding wind binary star system.

An innovative focus for about one-quarter of Hubble's observing time in 2011, and continuing into 2012, has been four visionary Multi-Cycle Treasury (MCT) programs. These were selected to tackle key scientific questions that cannot be fully addressed by the standard annual time allocation limits. The goals of these programs are astrophysically profound: mapping the constituent populations of the nearest spiral galaxy; constraining the nature of dark energy by searching for supernovae at redshifts  $z > 1.5$ ; tracing galaxy assembly from  $z \sim 1$  to  $z > 6$ , using massive clusters to test the Lambda Cold Dark Matter ( $\Lambda$ CDM) model; and probing star formation in strongly lensed galaxies at  $z > 7$ . ASD scientists Amber Straughn, Jon Gardner, and Duilia DeMello are active in the ambitious Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS) MCT program. The



On Monday, July 4, 2011, Hubble logged its one-millionth science observation during a search for evidence of water in the light spectrum of an exoplanet's atmosphere 1,000 light-years away. This is an artist's concept of Hubble's millionth exposure target, the extrasolar planet HAT-P-7b, also known as Kepler 2b. It is a gas planet larger than Jupiter orbiting a star hotter than our Sun. NASA/ESA/G. Bacon (STScI)

critical interplay of the new Wide Field Camera 3 and the repaired Advanced Camera for Surveys in these programs underscores the incredible scientific success and fruit of Servicing Mission 4.

The Goddard Hubble Space Telescope project science office continued its science leadership with ASD scientists Jennifer Wiseman and Kenneth Carpenter as Senior Project Scientist and Operations Project Scientist, respectively. The team was greatly enhanced in 2011 by the addition of Jeffrey Kruk as Observatory Project Scientist and Patricia (Padi) Boyd as Deputy Operations Project Scientist, each now contributing half-time to Hubble. Jeff's technical expertise is ideal for understanding the instrument issues on HST. He has extensive experience with the Far-Ultraviolet Spectroscopic Explorer (FUSE) mission and the Hopkins Ultraviolet Telescope (HUT). Currently, he is also Instrument Scientist for WFIRST and is also a co-investigator on the ACCESS sounding rocket. Padi has played key roles in support of a variety of operating missions, especially Swift and RXTE, where as subsystem lead of the Guest Observer and Science Centers she was critically involved in maximizing the science impact from these missions through the GO programs and archive. Her recent 2-year detail at NASA headquarters as program scientist for the Kepler, MOST and GALEX missions, as well as exoplanet research program manager, gives



The Nobel Prize in Physics was awarded to three physicists for the discovery of the accelerating expansion of the universe, now attributed to the effects of "dark energy." The Hubble Space Telescope played a key role by enabling the observations of supernovae in very distant galaxies and marking the epoch when cosmic deceleration transformed into acceleration.

her insights that are of great benefit in maximizing the operational effectiveness and science return of Hubble's mission. Padi continues also as Associate Lab Chief of the Astroparticle Physics Lab.

The ASD HST Project Scientists played important roles working seamlessly with Goddard Project Management and engineering teams as well as STScI science and technical staff throughout the year, addressing the scientific impact and mitigation of technical issues such as a continuing slow decline of sensitivity for the COS instrument and issues of declining charge transfer efficiency in the CCD detectors of the WFC3 and ACS cameras. "Gain sag" in the COS FUV detector also mandated this teamwork approach in consideration of changing where the spectrum currently falls on the detector to extend the detector's scientific life. A hallmark project achievement, as the Hubble project strives for reduced costs, was the initiation of "Automated Operations" in June 2011, reducing control room staffing hours for the mission to 8 hours a day, 5 days a week from what had been continuous coverage, while maintaining Hubble's continuous science return.



*A Birthday Rose: In celebration of the 21st anniversary of the Hubble Space Telescope's deployment into space, Hubble's Wide Field Camera 3 imaged an especially photogenic group of interacting galaxies called Arp 273. The larger of the spiral galaxies, known as UGC 1810, has a disk that is tidally distorted into a rose-like shape by the gravitational tidal pull of the companion galaxy below it, known as UGC 1813. A swath of blue jewels across the top is the combined light from clusters of intensely bright and hot young blue stars that glow fiercely in ultraviolet light. NASA/ESA/A. Riess (STScI/JHU), L. Macri (Texas A&M University) and the Hubble Heritage Team (STScI/AURA)*

The observatory is more scientifically powerful and productive than ever, reaching all time highs. In 2011, Hubble reached its millionth science observation! The mission passed a milestone of 10,000 refereed science papers with over 400,000 citations. The oversubscription for science time remained very high

at approximately 10:1, evidence of Hubble's prized capabilities. The Hubble project and enthusiasts throughout the world celebrated Hubble's 21st anniversary in 2011, and many more years of productive science are anticipated.



## Swift

Swift is a NASA Explorer mission, with international participation, that is designed to find gamma-ray bursts and study them over a wide range of wavelengths, from gamma-rays to optical light. It was launched in 2004 and is in its extended mission phase with re-entry no earlier than 2025.

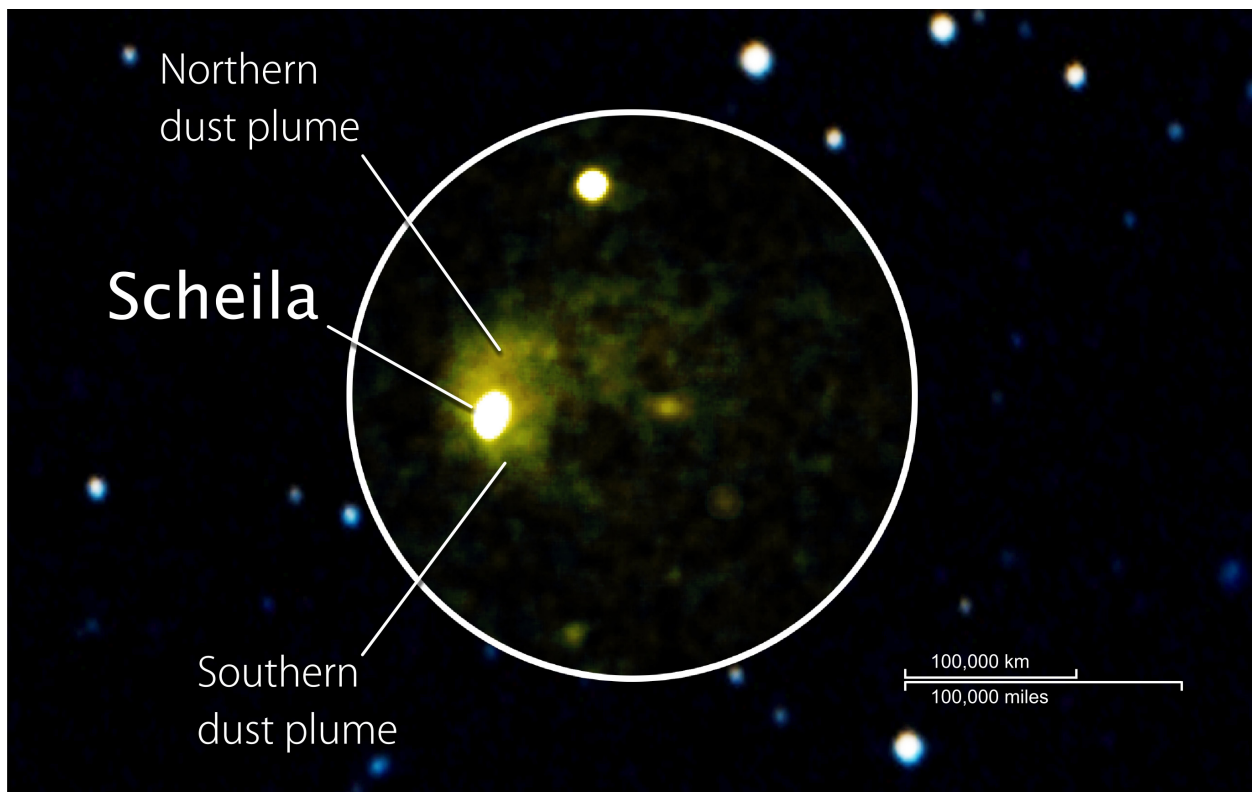
Gamma-ray bursts (GRBs) are the most luminous explosions in the universe since the Big Bang. They come randomly from all directions in the sky and last from a few milliseconds to a few hundred seconds. GRBs are believed to occur in the collapse of some massive stars into supernovae or when two neutron stars merge. The details of how such intense bursts of radiation are produced are still not well understood.

There are three telescopes onboard Swift: the Burst Alert Telescope is a coded-aperture gamma-ray detector that operates between 15 and 150 keV. It detects GRBs and rapidly localizes them to approximately two arcminutes. Immediately afterward (usually within one minute) the spacecraft slews to point its

two narrow-field instruments at the burst. The X-Ray Telescope measures the 0.2–10 keV X-ray flux from the GRB's afterglow and localizes the source to within two arcseconds. The Ultraviolet/Optical telescope collects data between 1,600 and 6,000 Angstroms and provides a sub-arcsecond position for the burst. Swift distributes these positions for each GRB to other observatories within seconds of obtaining them.

In the seven years since launch, Swift has detected and localized more than 600 GRBs. Some of the mission's key scientific accomplishments have been:

- Detecting some of the most distant known objects in the universe, with redshifts in the range  $z = 8.2-9.4$ . These bursts occurred more than 13 billion years ago when the universe was only a few hundred million years old.
- Observing GRB 080319B, a burst with an afterglow that was bright enough to see with the naked eye from a dark site.
- Discovering more than 60 short and hard GRBs, about half with likely host identifications and/or redshift estimates. These observations provided



*Faint dust plumes bookend asteroid 596 Scheila, which is overexposed in this composite. Visible and ultraviolet images from Swift's UVOT (circled) are merged with a Digital Sky Survey image of the same region. The UVOT images were acquired on Dec. 15, 2010, when the asteroid was about 232 million miles away.*

support for the theory that these bursts are due to the merging of binary neutron stars.

- Making metallicity measurements of star-forming regions at high redshift ( $z > 5$ ) using GRBs.
- Discovering the X-ray flash of the shock breakout from a star's surface during a supernova.
- Discovering how a star was tidally disrupted by a massive black hole at  $z=0.35$  (Swift J1644+57).
- The "Christmas burst," a bright bizarre transient that might be due to either an extragalactic He star-neutron star merger or a galactic neutron star capturing an asteroid.

Swift is a powerful and versatile observatory to study transient sources and is increasingly being used for non-GRB science. To date, around 3,000 targets-of-opportunity (TOOs) were performed as a result of requests from the community. Many of the TOOs are often made within a few hours of being requested.

By the end of 2011, more than 1,000 refereed papers have been published that are based on Swift results. These Swift papers have a very high citation rate of around 20 per paper on average ( $> 20,000$  total). More than half of all Swift papers are from non-GRB fields with an increasing fraction. A few examples include: performing multiwavelength observations of comets and asteroids; stellar flares, CVs and novae; obtaining ultraviolet light curves for almost 200 supernovae of all types; observing galactic transients and AGNs; performing a survey of nearby galaxies in the optical, UV, and X-rays; and undertaking the most sensitive all-sky hard X-ray survey yet performed.

Swift has been widely recognized as a groundbreaking mission. It was ranked four in the 2010 Senior Review. The PI Neil Gehrels and the Swift Team won the 2007 Rossi Prize, the 2009 Muhlmann award of the Astronomical Society of the Pacific, and the 2009 George Goddard award of SPIE. Swift J1644+57 was named one of the top ten science stories last year by *Astronomy* and *Discover* magazines.

The Swift Guest Investigator Program adds an important component to the Swift research and includes both GRBs and non-GRBs science. During the 2011 Cycle 8, 151 proposals were received, requesting \$3M in funds and 14 Ms total exposure time for 639 targets. The oversubscription rate has grown to a factor of 4.3 and the fraction of targets that are part of a monitoring campaign increased from 25% to 44% over the past three cycles.

Goddard scientists involved in Swift are L. Angelini, S. Barthelmy, W. Baumgartner, P. Boyd, J. Camp, J. Cannizzo, T. Cline, J. Cummings, N. Gehrels, S. Immler, H. Krimm, A. Lien, C. Markwardt, F. Marshall, J. Racusin, T. Sakamoto, G. Skinner, A. Smale, N. Troja, and J. Tueller.

## Galaxy Evolution Explorer (GALEX)

The GALEX observatory is a Small Explorer that consists of a telescope, two detectors, and a spacecraft. It collects wide-field ( $1.2^\circ$ ) images of the sky in two ultraviolet broad bands and is now in its eighth year of science operations. All flight and ground systems are currently healthy with the exception of the Far-UV detector.

GALEX is primarily a survey instrument, designed to obtain large, homogeneous imaging samples in two bandpasses (Far-UV, 1350–1800Å, and Near-UV, 1800–2800Å) that are sensitive tracers of recent star formation. The resulting samples are cross-matched with wide and deep surveys at other wavelengths, with the Sloan Digital Sky Survey providing a particularly rich match. GALEX also can provide wide-field low-resolution spectroscopy that is useful, for example, in identifying HST/COS targets or for variable objects in the Kepler field. Time-tag capabilities allow observers to determine a sampling time after the fact, which is useful for identifying flare timing or stellar pulsation modes.

Most of the GALEX science operations are at Caltech, and the core of the science team is also there, with smaller groups at Columbia, JHU, UCLA, Carnegie, and Goddard. Before 2011, approximately one-third of GALEX observing time was dedicated to a robust Guest Investigator program, operated by Goddard (30 to 35 GI programs annually). The GI program was discontinued at the end of 2010; researchers may now request funding for GALEX-based research through the ADP. Susan Neff (ASD) is the GALEX Mission Scientist.

In 2010, GALEX delivered its sixth (annual) GALEX Data Release (GR6) to MAST (Multi-Mission Archive at Space Telescope), which serves all GALEX data to the scientific community. The first release of two definitive catalogs of GALEX-detected point and extended sources (up to 1 arcmin) will be delivered to MAST in spring 2011. These catalogs are expect-

ed to become the go-to reference for UV detections, similar to the SDSS and 2MASS catalogs: They will contain 10 million sources with exposure time greater than 800 sec and more than 100 million sources with exposure time less than 800 sec. The catalogs will be updated with each future major GALEX data release.

The primary GALEX mission, which was completed in late 2007, had the goals of calibrating UV observables to the star-formation rate (SFR), measuring star-formation history ( $0 < z < 1.5$ ), and exploring the ultraviolet universe. The GALEX Extended Mission (EM), endorsed by the 2006, 2008, and 2010 Senior Reviews, is carrying out two Legacy Surveys designed to:

- Extend the UV/SFR calibration to low-mass, low-metallicity, transitional, or rare galaxies
- Relate star-formation history to other variables, such as environment, mass, halo mass, assembly history and star-formation regime
- Determine the relative importance of the primary drivers of star formation, such as galaxy assembly history, feedback from AGN, contributions from dust, or fractions of different gas phases.

In the 2010 Astrophysics Senior Review, the GALEX project was directed to discontinue the GI program and to focus on extending the GALEX Legacy Survey (GLS) to cover as much sky area as possible. About 5,000 deg<sup>2</sup> had been imaged to GLS depth by the end of 2010; another 16,000 deg<sup>2</sup> could be safely observed by GALEX. The community is providing recommendations on survey prioritization, with a focus on optimizing the long-term value of the GALEX archive.

GALEX observations have been used to determine the star-formation (SF) history in the nearby universe, and to show that while SF occurred mostly in massive galaxies over the period  $1 < z < 4$ , after that it moved to less and less massive hosts (Martin et al. 2007; Schiminovich et al. 2005; Arnouts et al. 2010, in prep).

The UV-optical color-magnitude diagram (UVOCMD) is a powerful tool for separating and relating galaxy types, properties, and evolutionary histories, largely because of the great leverage obtained with the UV (SFR)—optical/NIR (stellar mass) color. The UVOCMD can be measured accurately in very distant samples, and may be considered a Hertzsprung-Russell diagram for galaxies, in which stellar mass is the major predictor of galaxy properties. GALEX

UVOCMDs first identified the tendency of AGN to occur preferentially in the “green valley” and demonstrated that galaxies migrate both directions across the valley (Wyder et al., 2007; Schiminovich et al., 2007; Martin et al., 2007). More recent GALEX work has shown that low-mass galaxies in the green valley are mostly moving from blue to red (“quenching”), while higher-mass galaxies are more evenly split between “quenching” and “bursting.” This is consistent with small galaxies losing their gas and massive galaxies undergoing microbursts of star formation as they accrete new material (Martin et al. 2010).

Using GALEX data, Heckman et al. (2005) discovered a rare population UV-luminous Lyman-Break Analogs (LBAs), which are the fastest-evolving component of the UV galaxy population (Schiminovich et al., 2005). Their lack of dust (relative to other local starbursts, such as ULIRGs) suggests an early stage of chemical evolution (Basu-Zych et al. 2007; Hoopes et al. 2007). HST images show that they represent a complex merger of multiple, lower-mass, gas-rich subunits that echo the morphology and physical properties of high- $z$  LBGs, but seen in much more detail (Overzier et al. 2008; Basu-Zych et al. 2009). Recently, a new color-selected approach has identified a few hundred more UV-luminous galaxies that may be LBAs or may be a new type of object (Hutchings and Bianchi 2010); follow-up observations are in progress to determine the nature of these new objects (Basu-Zych, Neff, Hutchings).

GALEX has opened several new lines of investigation in the low-density regime. GALEX observations of Extended UV (XUV) disks have shown that these are frequent, occurring in  $\sim 30$  percent of late-type galaxies (Gil de Paz et al., 2007; Thilker et al., 2007; Zaritsky and Christlein, 2008). In these XUV disks, GALEX detects star formation occurring at gas densities lower than those previously suggested as a “threshold” level. Thilker et al. (2010) have found a new type of dwarf galaxy forming out of a possibly primordial cloud of HI. Recent work by Madore et al (2010) has found that XUV disks also occur in early-type galaxies. Bigiel et al. (2010, in prep) and Wyder et al. (2009) have found that the outer low-density regions of spirals and low-surface brightness galaxies as a group fall below the extrapolation of the “standard” star-formation relationship to gas density. Meurer et al. (2009) and Lee et al. (2009) have used GALEX

data to show that, in low-surface-brightness regions/low-mass galaxies, the IMF may be top-light relative to assumptions about a universal mass function. The GALEX project sponsored a conference on variable IMF's in June 2010 which was well attended.

GALEX is currently planning for closeout in 2013. However, if all systems remain healthy, the project will return to the 2012 Astrophysics Senior Review to request continuing operations until the GLS has been completed (~2014).

### High Energy Astrophysics Science Archive Research Center (HEASARC)

The HEASARC is the primary archive for NASA missions dealing with extremely energetic phenomena, from black holes to the Big Bang. Incorporating the Legacy Archive for Microwave Background Data Analysis (LAMBDA), HEASARC includes data obtained by missions that study the relic cosmic microwave background (CMB) as well as NASA's high-energy astronomy missions from the extreme ultraviolet through gamma-ray bands.

Since 1990, the HEASARC has been an essential element of NASA's astrophysics missions. The archive services allow scientists to identify, display, cross-correlate, download and analyze data from a variety of past and current missions—including ASCA, BeppoSAX, Chandra, CGRO, Einstein, Fermi, INTEGRAL, ROSAT, RXTE, Suzaku, Swift, WMAP, and XMM-Newton—and provide access to a wide range of multiwavelength sky surveys, astronomical catalogs, and other resources. The HEASARC's scientific and technical staff produces a number of widely used software packages, provides expertise in the analysis of archived data, and helps to evolve archive interfaces to better serve the science community. The data and software standards developed by the HEASARC provide the underlying infrastructure for the interpretation of data from a wide variety of missions, substantially reducing mission costs while increasing science return.

The HEASARC archive now contains about 40 Terabytes (TB) of data, having grown by ~7 TB in 2011, and contains data from eight active missions as well as more than 30 space-based missions and sub-orbital experiments that are no longer operational. Papers using HEASARC data comprise around 10 per-

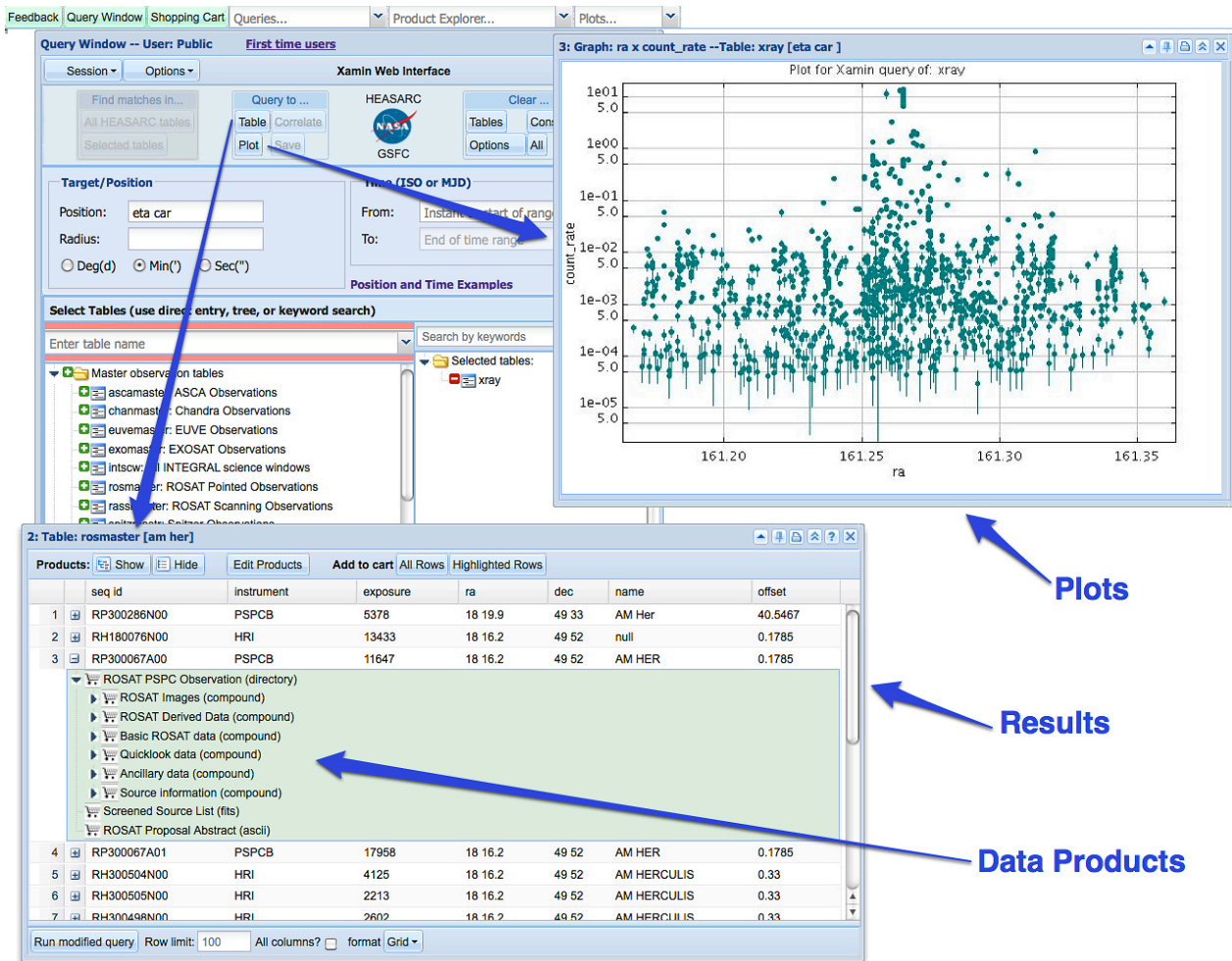
cent of the total astronomical literature and include some of the most highly cited papers in the field.

The HEASARC Office is led by Dr. Alan Smale, who in 2011 led the effort to write and submit the HEASARC proposal in response to the Senior Review of the Astrophysics Archives. In this high-level comparative review run by NASA HQ, the HEASARC tied for first place with MAST and the ADS, excellent validation of the HEASARC's premier role as a science center for the astrophysical community.

Dr. Smale also serves as the NuSTAR Archive Scientist, leading the HEASARC's extensive preparations to support the pipeline processing, software distribution, and data archiving for this important Astrophysics Explorer, due to launch in early 2012. Dr. Lorella Angelini leads similar preparations to support data archiving for GEMS and Astro-H, both scheduled for launch in 2014.

In 2011 the HEASARC released a major new interface, called Xamin, to our catalog and archive data, an effort led by Dr. Thomas McGlynn. Xamin is now fully available to our users. Xamin is faster and more powerful than our previous interfaces, and allows uploads of persistent user tables, integrated access to both HEASARC and Virtual Observatory data sets, easy correlations of two or more tables, clean integration of plotting, user-defined columns, the ability to save and return to queries, and a host of other capabilities. With a fully developed test suite and careful system engineering Xamin is designed to form the basis for user access to HEASARC data resources for the next decade or more.

The HEASARC is a core partner in a joint NSF/NASA program to manage and operate the U.S. Virtual Astronomical Observatory. McGlynn leads the HEASARC's involvement in the VAO, and serves as the VAO Lead for Operations. He and his staff have developed applications which monitor the health of VAO and other VO services and inform responsible parties of issues as they arise. The HEASARC also plays a major role in the development of portal tools within the VO. The HEASARC has developed a generic JavaScript library for rendering the VO standard format, VOTable, and has made major contributions to the release of the new VAO portal. All HEASARC catalogs are available through the VO. Our older Browse interface supports simple VO Cone Search ac-



Xamin is the HEASARC's next-generation interface to its archive and catalog holdings and to other datasets within the Virtual Observatory. A faster and much more powerful way to access astrophysical data, Xamin will gradually supersede the Browse interfaces that have served this role for the past 15 years.

cess, while Xamin support Cone Search and the much more general Table Access Protocol (TAP).

In addition, McGlynn continues to manage the SkyView virtual observatory. The number of images generated by SkyView in 2011 increased by over 60% from the previous year to about 8.1 million dynamically generated images. In addition to about 50 surveys hosted locally, SkyView provides access to SDSS, FIRST, and 2MASS data hosted at other NASA archives. Data is provided through its own web interface, batch access, and the VO Simple Image Access protocol. A library of user-contributed 'interesting' images celebrated its 10,000 entry this year.

During 2011, HEASARC programmers under the direction of Dr. William Pence coordinated two new releases of the HEASOFT data analysis software package, providing improved analysis capabilities for data

from the Swift, Suzaku, and RXTE observatories. The HEASOFT package is essential for deriving new scientific results from the HEASARC's large data archive. It contains about 2.5 million lines of code contained in 550 individual analysis tasks for the data from 11 high-energy missions supported by the HEASARC as well as for general analysis of astronomical data from other missions. In 2011, more than 3,000 registered external users installed the HEASOFT package on their local computers. As an alternative to installing the HEASOFT package locally, the HEASARC staff also continued to support and enhance the on-line Hera data analysis service which enables researchers to analyze their data with the HEASOFT package within the computing environment provided by the HEASARC over the Internet.

Dr. Steve Drake worked on the creation and/or updating of 80 database tables in 2011, bringing the total number of tables available to the HEASARC's Browse archive interface (and its successor Xamin) to about 625 unique tables by the end of 2011. Among the newly created tables, 14 were Chandra source lists and 10 were XMM-Newton source lists, and the others included a broad range of missions including ACT, AGILE, ANS, ASCA, BeppoSAX, EUVE, GALEX, INTEGRAL, IRAM, Kvant and Planck, as well as tables of stars, galaxies and quasars, and radio sources. Drake also continues to support the HEASARC's web pages and RSS feed. This feed combines feeds from projects ranging from XMM-Newton through WMAP, items such as upcoming proposal and meeting deadlines, and links to selected press releases. In 2011, four to five new items per week appeared in the HEASARC RSS/Latest News, providing an important and timely resource to the astronomical community. Drake also served as XMM-Newton and RXTE Archive Scientist.

Dr. Mike Corcoran continued to serve as Fermi Archive Scientist, and is now assisting the NuSTAR mission archive as well. There are currently 10 Fermi tables incorporated into the HEASARC Browse tables, and the HEASARC FTP archive contains all Fermi GBM data, along with LAT weekly data files (which can now be searched and downloaded via Browse). The Fermi project released a number of updates to the Fermi calibration data for both the GBM and LAT instruments in the previous year, and Corcoran has installed these in the HEASARC calibration database (CalDB). In 2011, there were a total of 35 updates of the Swift, Suzaku, Chandra, RXTE, and Fermi CalDB areas. As CalDB manager, Corcoran implements these updates and maintains the HEASARC CalDB website, including the news archive and the RSS feed. Corcoran also writes the HEASARC Picture of the Week website, and administers a HEAPOW Facebook group which currently has over 150 members from around the world. Corcoran also maintains the Astro-Update website, used by scientists to keep track of updates to important high-energy astrophysics software packages. In 2011, Corcoran was PI of a successful Chandra proposal and acted as the chair of the science organizing committee for the conference, "Stars, Companions and their Interactions: a Memorial to Robert H. Koch", held at Villanova, Aug 8–10

2011. During 2011, Dr. Corcoran was co-author on 14 refereed publications and served as referee on three papers. Dr. Corcoran also serves as USRA director for the Center for Research and Exploration in Space Science and Technology, with oversight of 11 PhD research scientists in the Astrophysics Science Division.

Dr. Arnaud has continued his support of X-ray astronomical data analysis in a variety of ways. A new version of XSPEC was released this year including the usual enhancements, bug fixes and new models. A major feature was the beta-release version of the new Python interface. This Python interface provides improved flexibility when scripting XSPEC as well as the ability to use XSPEC in combination with other packages. For instance, plotting can be performed using matplotlib instead of the native XSPEC plotting package. Dr. Arnaud also set up an XSPEC Facebook group to provide an additional forum for discussion on XSPEC issues. This group currently has 173 members.

Dr. Arnaud participated in another workshop organized by the COSPAR capacity building program which aims to extend expertise in space-based science to regions without large active space programs. The latest workshop on X-ray astronomy was held in Argentina with participants from a number of Latin American countries.

Throughout 2011, Dr. Steve Sturmer maintained the INTEGRAL public data archive at the HEASARC, mirroring the public data archive maintained at the ISDC. The ISDC has public data releases approximately once per month which are downloaded and installed in the HEASARC archive.

Within the HEASARC, the Legacy Archive for Microwave Background Data Analysis (LAMBDA) is NASA's thematic archive devoted to serving Cosmic Microwave Background (CMB) and related data sets to the research community. LAMBDA's holdings include data from NASA's two CMB missions: the Cosmic Background Explorer (COBE) and the Wilkinson Microwave Anisotropy Probe (WMAP). Other holdings include data from the Submillimeter Wave Astronomy Satellite (SWAS), the InfraRed Astronomical Satellite (IRAS), numerous ground and balloon-based CMB experiments, and a collection of diffuse Galactic emission maps that are needed to enable foreground subtraction from CMB data.

In 2011 LAMBDA significantly increased its data holdings. Additional WMAP data products based on the 7-year release are now available. LAMBDA has added new products from the Atacama Cosmology Telescope (ACT) and has expanded its CMB holdings with the addition of data from the South Pole Telescope (SPT) and NASA's Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission (ARCADE). A large SPT data release in December included full maps. ACT and SPT are fine-scale ground-based CMB instruments that complement space-based measurements and provide exciting probes of dark matter, dark energy and the large-scale structure of the universe.

As part of its function as a comprehensive data archive for the CMB and as a complement to the SPT and ACT data archives, LAMBDA is mirroring the Planck SZ catalog. LAMBDA also added user-generated educational products to share with the astrophysics community.

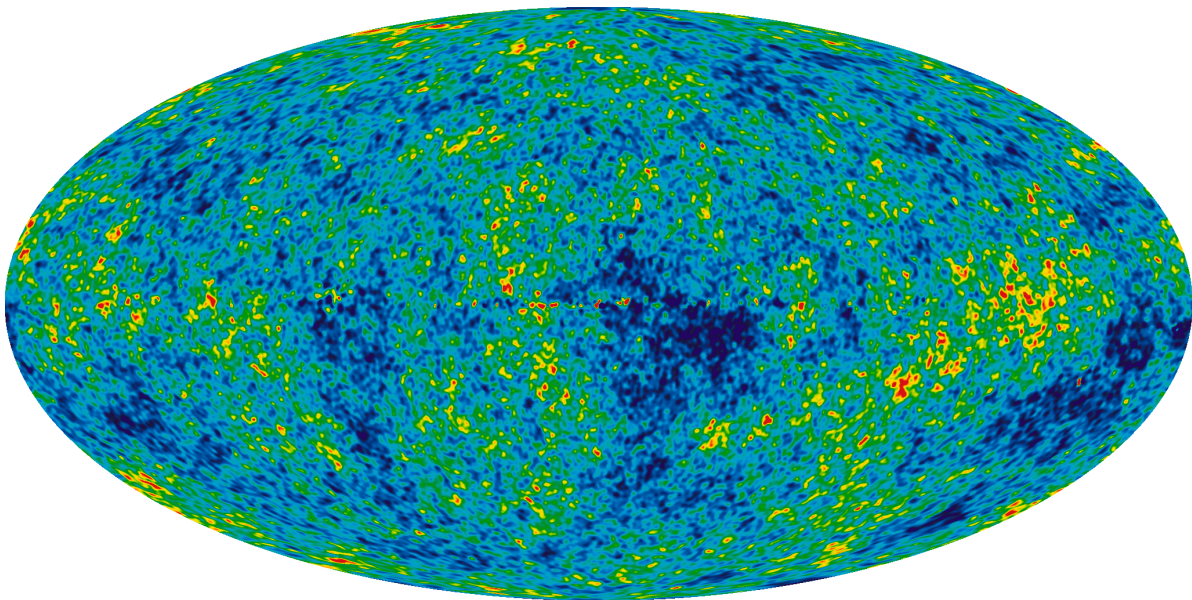
## WMAP

The Wilkinson Microwave Anisotropy Probe (WMAP) has mapped the Cosmic Microwave Background radiation—the oldest light in the universe—and helped establish a simple and comprehensive cosmological model connecting the physics of the very early uni-

verse to the properties of the universe today. In this standard model, the universe is flat, homogeneous and isotropic on large scales. The universe is composed of radiation and atoms, but it is currently dominated by dark matter and dark energy. It is believed to have undergone a period of rapid inflation at its beginning, expanding by more than 50 e-foldings in a fraction of a second.

The first results from WMAP, based on one year of data, were released in 2003 and were followed up by three-year results in 2006 and five-year results in 2008. In 2010, the WMAP team released six papers with results based on seven years of data. These papers were published in a dedicated issue of the *Astrophysical Journal Supplement Series* (February 2011). As of this writing, the six seven-year papers have already accumulated more than 2,800 citations. The WMAP team at GSFC includes ASD scientists Hinshaw (now at UBC), Wollack, Kogut, and Bennett (now at JHU).

For Gaussian random-phase fluctuations, the angular power spectrum encodes the full statistical information in the map. Classic papers (Peebles and Yu, 1970; Sunyaev and Zeldovich, 1970) relate the parameters of the universe to the structure in the angular power spectrum. The standard  $\Lambda$ CDM model, defined by the six parameters given in the table below, is a good fit to the seven-year WMAP spectrum, with a reduced chi-square of 1.047 for 1,170 degrees of free-



*This detailed, all-sky picture of the infant universe was created from seven years of WMAP data. The image reveals 13.7-billion-year-old temperature fluctuations (shown as color differences) that correspond to the seeds that grew to become galaxies. The signal from our Galaxy was subtracted using the multi-frequency data. This image shows a temperature range of  $\pm 200$  microKelvin. NASA /WMAP Science Team*

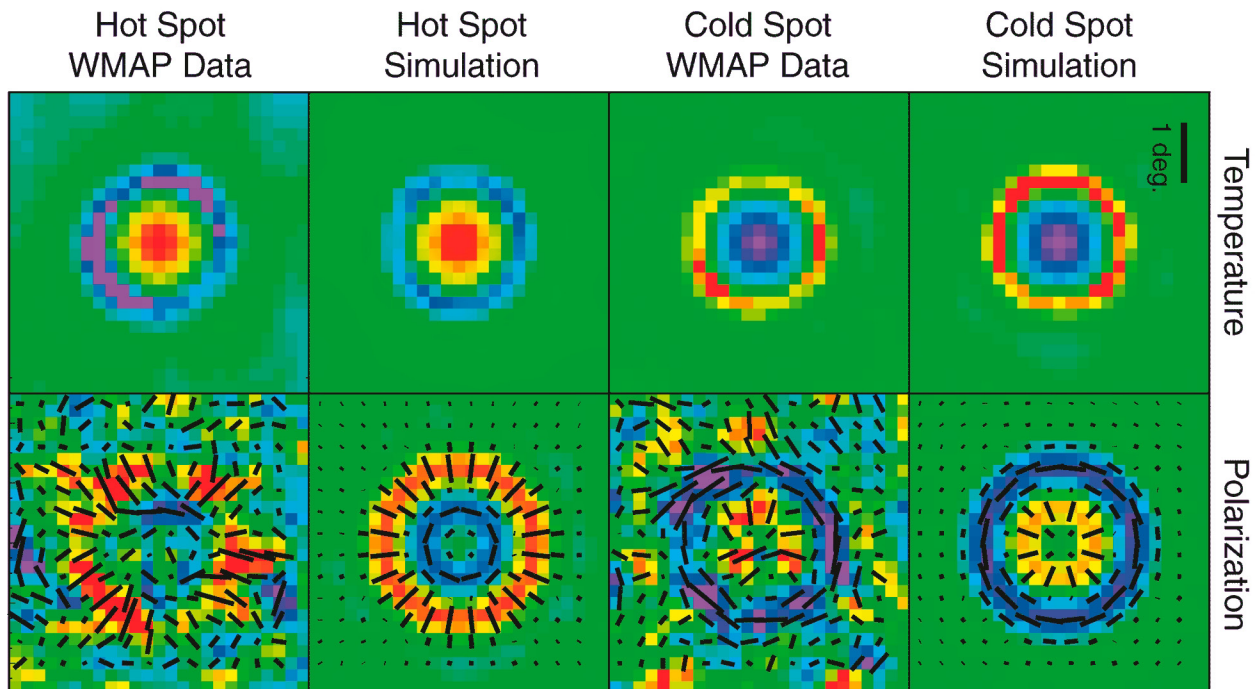
Best-fit $\Lambda$ CDM parameters with seven-year WMAP data		
$\Lambda$ CDM Parameter	WMAP data only	WMAP+BAO+H0
Matter density, $\Omega_m h^2$	$0.1334 \pm 0.0055$	$0.1349 \pm 0.0036$
Baryon density, $\Omega_b h^2$	$0.02258 \pm 0.00057$	$0.02260 \pm 0.00053$
Cosmological constant, $\Lambda$	$0.734 \pm 0.029$	$0.728 \pm 0.015$
Scalar index, $n_s$	$0.963 \pm 0.014$	$0.963 \pm 0.012$
Optical depth, $\tau$	$0.088 \pm 0.015$	$0.087 \pm 0.014$
Amplitude @ $8h^{-1}$ Mpc, $\sigma_8$	$0.801 \pm 0.030$	$0.809 \pm 0.024$

dom. WMAP has improved its measurements of sub-degree-scale fluctuations, especially the third acoustic peak. As a result, the seven-year data shrinks the allowable volume of the six-dimensional  $\Lambda$ CDM parameter space by 50 percent over the five-year results. The age of the universe as measured by WMAP is  $13.75 \pm 0.11$  Gyr—a better-than-1-percent measurement.

The new WMAP data are now sufficiently sensitive to test dark energy, providing important new information with no reliance on previous supernovae results. The combination of WMAP data with measurements of the Hubble constant and of baryon acoustic oscillations (BAO) in the galaxy distribution, limits the extent to which dark energy deviates from

Einstein's cosmological constant. The simplest model (a flat universe with a cosmological constant) fits the data remarkably well. The new data constrain the dark energy to be within 14 percent of the expected value for a cosmological constant ( $w = -1.1 \pm 0.14$ ), while the geometry must be flat to better than 1 percent ( $0.99 < \Omega_{\text{tot}} < 1.01$ , 95% CL) if the dark energy is a cosmological constant.

One of the key predictions of the hot Big Bang model is that most of the helium in the universe was synthesized in the hot early universe only a few minutes after the Big Bang. Previously, cosmologists studied old stars to infer the helium abundance before there were stars. WMAP data, in combination with



With the 7-year results, WMAP has produced a visual demonstration that the polarization pattern around hot and cold spots in the cosmic microwave background follows the pattern expected in the standard model. The standard model predicts a specific linked pattern of temperature and polarization around hot and cold spots in the map, which WMAP now sees in the map. NASA /WMAP Science Team



smaller-scale data from the ACBAR and QUaD experiments, show the effects of helium in the microwave patterns on the sky indicating the presence of helium long before the first stars formed. This is a fundamental test of Big Bang cosmology.

The seven-year WMAP data places new constraints on the number of relativistic neutrino species in the early universe. Neutrinos are nearly massless elementary particles that permeate the universe in large quantity but they interact very weakly with atomic matter. Nonetheless, they leave an imprint on the microwave fluctuations and the new WMAP data, together with BAO and  $H_0$  data, show that the effective number of neutrino-like species is  $4.34 \pm 0.87$ . The standard model of particle physics has 3.04 effective species of neutrinos.

The improved sensitivity in the noise-limited polarization measurement has made possible a visual detection of the CMB polarization signal in the seven-year sky maps. When the polarization maps are dissected into regions centered on hot and cold spots in the temperature map, and then stacked, the telltale pattern of polarized rings around the spots are exhibited for the first time.

The CMB temperature in the direction of known galaxy clusters is expected to be slightly cooler than the average CMB temperature, due to interactions between CMB photons and the gas in the clusters. This effect has been observed in aggregate by WMAP and is consistent with analogous observations by the South Pole Telescope (STP) and the Atacama Cosmology Telescope (ACT). These observations are in conflict with extrapolated X-ray observations of clusters (X-rays probe a smaller volume of cluster gas than the CMB observations) and with numerical simulations, which must be missing some of the complex gas physics in the outer regions of the clusters.

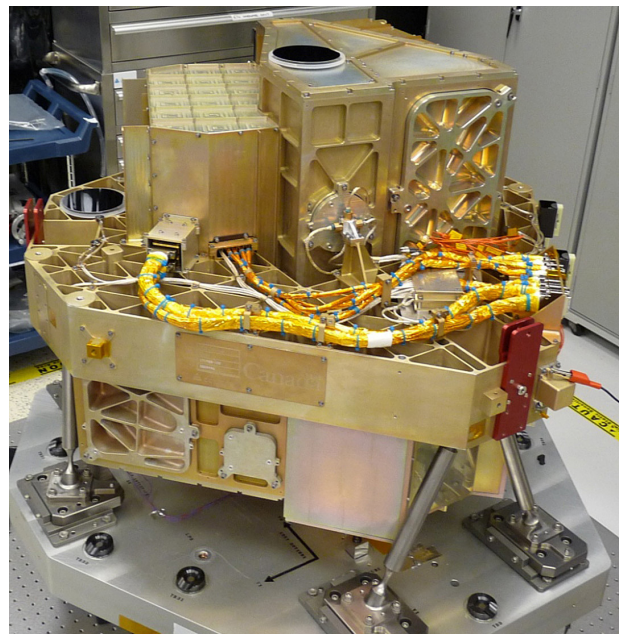
For all of these cosmological results to be meaningful, the systematic measurement errors must be extremely well understood. Enormous effort has been expended to characterize the WMAP experiment: its calibration, systematic errors, noise properties, and foreground signals. These activities, which are intricate, challenging, and time-consuming, are the focus of the WMAP science team's effort.

## *In Development*

### James Webb Space Telescope

The James Webb Space Telescope (JWST) is a large (6.5m), cold (50K), facility-class, general-purpose observatory that will be launched into orbit around the Sun-Earth L2 point. It is the successor to the Hubble and Spitzer space telescopes. Its science goals range from detecting the first galaxies to form in the early universe to exoplanets and objects in our solar system. Time on the telescope will be allocated to the community through annual peer-reviewed proposals in a manner similar to Hubble. The prime contractor is Northrop Grumman; the Science and Operations Center is located at the Space Telescope Science Institute. JWST is a partnership between NASA and the European and Canadian Space Agencies.

The ASD provides scientific direction for JWST through a team consisting of 11 project scientists. The Senior Project Scientist is John Mather, his deputy is Jonathan Gardner and his technical deputy is Malcolm Niedner. The other members of the team: Matthew Greenhouse (Instrumentation), Bernard Rauscher (deputy); Mark Clampin (Observatory), Charles



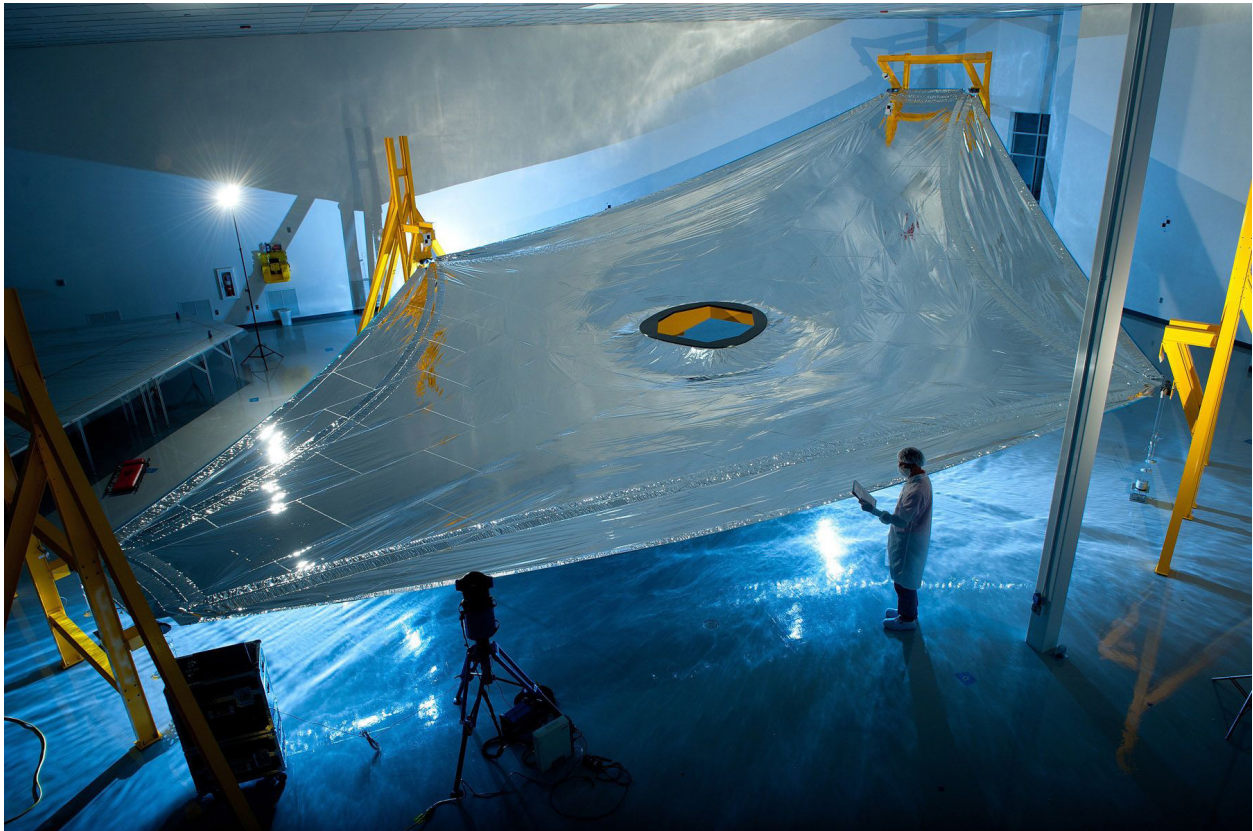
*The flight model of the Fine Guidance Sensor (FGS) prepares to undergo cryogenic testing. COM DEV Canada*

Bowers (deputy); Randy Kimble (Integration and Test); George Sonneborn (Operations), Jane Rigby (deputy) and Amber Straughn (Education and Public Outreach). ASD science staff is also directly involved in the provision of key flight systems for the JWST near-infrared multi-object spectrometer (NIRSpec), including its detector and microshutter array systems.

Mather chairs the JWST Science Working Group (SWG), and the Project Scientists work closely with the management and engineering teams, participating in reviews, project meetings, serving on change-configuration boards, and participating in decisions. The JWST SWG published a thorough description of the JWST science goals and technical implementation as a special issue of the refereed journal, *Space Science Reviews* (Gardner et al. 2006). It has since also updated and extended the science case in a series of white papers that include astrobiology, dark energy, exoplanet coronagraphy, exoplanet transits, first-light galaxies, resolved stellar population, solar system observations and the role of JWST in the decadal survey,

*New Worlds, New Horizons*. The *Space Science Reviews* paper and the white papers are available from [jwst.gsfc.nasa.gov/scientists.html](http://jwst.gsfc.nasa.gov/scientists.html).

The JWST Project is now in phase C/D, and the project successfully completed its Critical Design Review (CDR) in 2010. The budget and schedule went through a replan in 2011 and the mission is now fully funded for launch in 2018. All four flight instruments have passed their CDRs and are in the integration and testing phase. Two of the instruments have now completed their thermal vacuum testing and all four instruments will be delivered to Goddard within the next year. The Integrated Science Instrument Module (ISIM) consists of the four science instruments and nine subsystems. ISIM began its integration and testing phase in 2011 (Greenhouse, et al., 2011, Proc SPIE, vol. 8146, p. 8146606). The GSFC Space Environment Simulator (SES) cryogenic vacuum chamber was modified by the JWST project with a gaseous helium shroud to support testing of the ISIM system at approximately 30 K. The project is currently integrat-



A full-scale JWST sunshield membrane deployed on the membrane test fixture at Mantech in Huntsville, Alabama, is ready for a precise measurement of its three-dimensional shape. The JWST sunshield comprises five of these layers, each of which has to be precisely spaced with respect to the next. Northrop Grumman Aerospace Systems



*The gold-coated primary mirror segment engineering design unit (EDU) is inspected at Goddard Space Flight Center, Md. NASA/Chris Gunn*

ing the cryogenic telescope simulator that will be used in the SES chamber to test the ISIM.

The ASD is directly responsible for provision of two flight systems, both within the Near-Infrared Spectrograph (NIRSpec), an instrument that is part of the ESA contribution to the mission. The Microshutter Assembly (MSA) is led by PI Harvey Moseley with contributions from a number of contractor scientists. The MSA will enable simultaneous spectra of more than 100 objects—the first time that a true multi-object spectrograph has flown in space. The flight MSA was delivered to ESA in 2010. The NIRSpec detector system is also being built at Goddard, under the leadership of PI Bernard Rauscher. Moseley and Rauscher are members of the NIRSpec Science Team and will participate in their Guaranteed Time Observations.

The JWST Project reached a major milestone in 2011 with the completion of the flight mirror segments. There are 18 flight Webb primary mirror segments plus 3 spares including the pathfinder Engineering Demonstration Unit (EDU). The segment blanks were all machined out of beryllium billets and

light-weighted. All of the primary mirror segments have completed polishing and gold coating. The final acceptance measurements of their cryogenic figure at Marshall Space Flight Center (MSFC) for the segments were completed in 2011. The overall surface figure error (SFE) of the primary mirror was measured to be  $\leq 25$  nm, meeting the requirement of 26 nm SFE. The secondary mirror has also completed acceptance testing and meets its SFE requirement. The tertiary and fine steering mirrors have completed acceptance testing as well. By the end of 2011, all of the JWST telescope mirrors were complete.

Development of the JWST Science and Operations Center at Space Telescope Science Institute is progressing with the rest of the project. Design reviews were completed in 2011 for the JWST planning and scheduling system, the wavefront control system to monitor and maintain the telescope image quality, and the Operations Scripts Subsystem, which will autonomously execute JWST observations in an event-driven schedule.

## Astro-H

The X-ray Astrophysics Laboratory is collaborating with ISAS/JAXA to implement an X-ray calorimeter spectrometer for the Astro-H mission. The project, headed by Richard Kelley of the X-ray Astrophysics Laboratory, is implemented as an Explorer Program Mission of Opportunity to provide key components of a high-resolution X-ray calorimeter spectrometer that will constitute one of the observatory's primary science instruments. Among laboratory scientists, Caroline Kilbourne and Scott Porter are responsible for the detector subsystem, and Peter Serlemitsos and his team of Takashi Okajima and Yang Soong are responsible for X-ray mirrors for both the SXS and the ISAS/JAXA Soft X-ray Imager (SXI). Megan Eckart and Maurice Leutenegger are developing the calibration program for the detector system. Prof. Dan McCammon of the University of Wisconsin, a long-term collaborator with the X-ray Astrophysics Laboratory and a pioneer in X-ray calorimeters, is developing a new generation of blocking filters for the instrument. Rob Petre is the U.S. Project Scientist for Astro-H.

The Soft X-ray Spectrometer (SXS) will consist of a 36-pixel X-ray calorimeter array with better than 7-eV resolution to provide high-resolution X-ray spectroscopy over the 0.3–12 keV band with moderate imaging capability. The Goddard team is to provide the detector system, adiabatic demagnetization refrigerator (50 mK operational temperature), electronics, blocking filters, and X-ray mirror, while ISAS/JAXA is responsible for the dewar system and the rest of the science instruments, the spacecraft, launcher, and mission operations. The Space Research Organization of the Netherlands (SRON) is separately providing to JAXA a filter wheel and in-flight calibration sources based on the technology developed by Keith Gendreau.

The dewar will be a hybrid cryogen/mechanical cooler system for redundancy, and the X-ray mirror will build on the Goddard legacy of providing lightweight, high-throughput mirrors.

Astro-H is a facility-class mission to be launched on a JAXA H-IIA into low Earth orbit in 2014. The Astro-H mission objectives:

- Trace the growth history of the largest structures in the universe
- Provide insights into the behavior of material in extreme gravitational fields

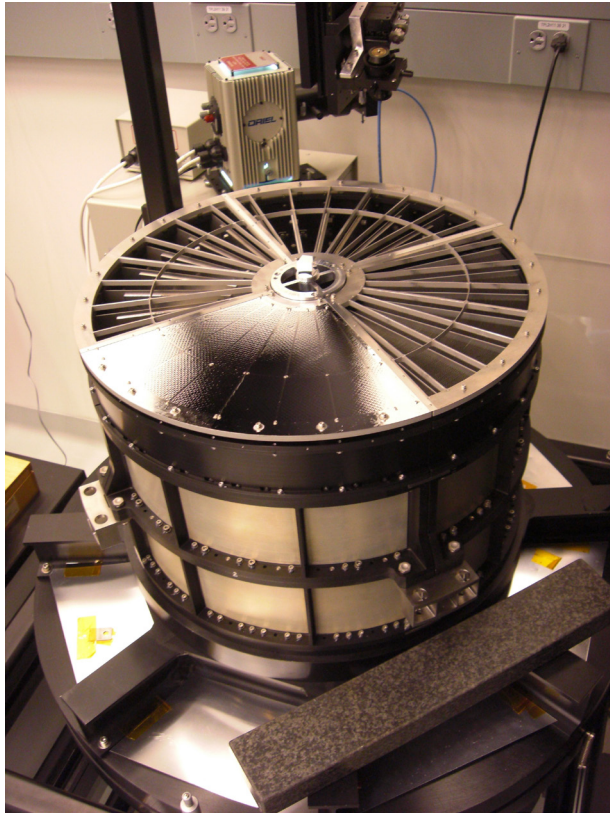


*The engineering model of the detector and cooling stage for the Astro-H Soft X-Ray Spectrometer. The cooling stage consists of a three-stage adiabatic demagnetization refrigerator that cools the 36-pixel array to 50 mK for more than 40 hours at a time before needing to be recycled for about 1 hour. The detector system achieved an energy resolution of about 4.5 eV.*

- Determine the spin of black holes and the equation of state of neutron stars
- Trace shock-acceleration structures in clusters of galaxies and supernova remnants
- Investigate the detailed physics of jets

Achieving these objectives requires the SXS and three additional scientific instruments to provide a very broad, simultaneous energy bandpass. The Hard X-ray Imager (HXI) will perform sensitive imaging spectroscopy in the 5–80 keV band; the non-imaging Soft Gamma-ray Detector (SGD) extends the Astro-H energy band to 600 keV, and the Soft X-ray Imager (SXI) expands the field of view with a new-generation CCD camera.

The SXS science investigation comprises building and delivering the SXS instrumentation and carrying out a six-month observing program in collaboration with ISAS/JAXA. The baseline mission includes two years of funding for the SXS science team and support

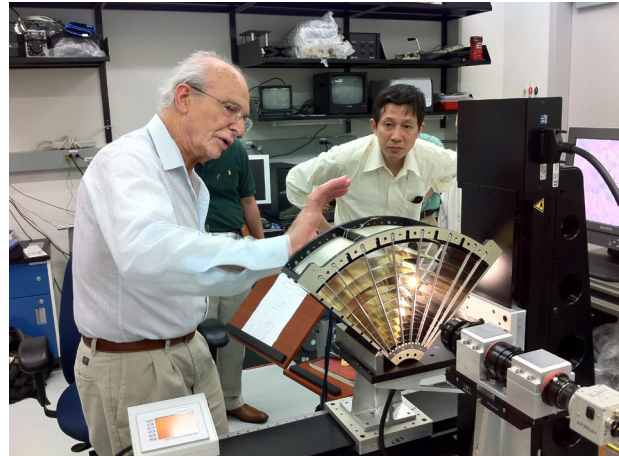


*The engineering model of the mirror module for the Astro-H Soft X-Ray Spectrometer. The unit was used to develop the design and qualify it for flight. The mirror is 45 cm in diameter and the flight version will have a mass of 45 kg. The image quality has a half-power diameter of 1 arcmin, which is nearly twice as good as the previous generation of this mirror technology now in use on Suzaku.*

for processing and archiving the SXS data for a total of three years. An approved Science Enhancement Option (SEO) will provide the U.S. community with access to Astro-H beyond the baseline program. Under the SEO, U.S. scientists will be able to propose for Astro-H observing time and obtain grant support.

Working collaboratively with JAXA, the U.S. Guest Observer Facility will process, distribute, and archive data from all four Astro-H instruments, and provide observers with analysis tools and support. Lorella Angelini is leading the design and development of this program.

There were several major accomplishments this year. The most significant of these include successfully completing the engineering model components of the SXS and passing the instrument critical design review. The team is preparing for delivery of the engineering model components to Japan throughout 2012 and will support subsequent integration and testing there.



*Dr. Peter Serlemitsos, who celebrated 50 years as a civil servant at Goddard in 2011, describes the Astro-H X-ray mirror to Prof. Tadayuki Takahashi, the mission's principal investigator.*

The detector system achieved an energy resolution of about 5 eV (FWHM).

These milestones were made possible in part due to our instrument scientists taking on additional leadership roles this year on various subsystems to provide technical and scientific expertise to AETD engineers to ensure that the detailed requirements of the instrument are successfully implemented. Scott Porter has taken on responsibility for the day-day operations of the detector/cooling-stage subsystem in addition to the detector assembly, while Caroline Kilbourne is guiding the implementation of the aperture components of the SXS, which includes the non-X-ray blocking filters.

Meng Chiao is working closely with Porter and Kilbourne to supervise the daily detector assembly work. Having completed the engineering model hardware, the detector system team is now fully engaged in the production of the flight model. Caroline Kilbourne has successfully qualified the first of two flight candidate arrays, with an energy resolution of 4–5 eV across the array, and assembled a second array that is undergoing acceptance testing.

The engineering model X-ray mirror was completed and demonstrated an imaging quality of 1 arcmin (HPD), a new record for this mirror technology. X-ray reflector production for the flight mirrors is nearly complete and the next step is to begin assembly and deliver to Japan in mid-2012.

Finally, Megan Eckart and Maurice Leutenegger have successfully brought several engineering model

non-X-ray blocking filters to the Brookhaven NSLS for a pilot calibration program and are bringing several X-ray monochromators online for calibration of the flight detector system in mid-2012.

### Gravity and Extreme Magnetism SMEX (GEMS)

GEMS was selected in June 2009 as a Small Explorer (SMEX) to be launched between April 2014 and October 2015. Limited funding for a slow ramp up of the project was available until 2011. The core team, led by Jean Swank (Principal Investigator), Keith Jahoda (Deputy PI), and Timothy Kallman (Project Scientist), developed the requirements and built engineering test units for the detector and the required telescope boom. In order to meet the constraints of cost, mass and power, it was necessary to take a de-scope from three to two telescopes. During 2011 the new configuration was developed and the engineering test units passed requirements of technical readiness. Engineering peer reviews of all the subsystems were completed and the preliminary design review of the spacecraft. The instrument and mission preliminary design reviews are scheduled for the end of February 2012, the confirmation review in April 2012, with the launch scheduled for November 2014.

GEMS will carry out the first survey of the polarization of a variety of X-ray sources that is sensitive enough to make significant constraints on our physical models. While polarization of radio, optical and ultraviolet fluxes often has been utilized to constrain the emission mechanisms and the geometry of astrophysical sources, only for the Crab Nebula has this information been accessed in the 2–10 keV X-ray band of their maximum flux densities.

X-rays are the electromagnetic probe of black holes from closest to the event horizon and are thus the best probe of black-hole effects on space-time. Jeremy Schnittman on the GEMS Science Team has contributed the most current models for the X-ray production and propagation that predict X-ray polarization behavior. GEMS can test these predictions and provide determinations of spin complementary to determinations from spectra or timing. The X-rays from supermassive black holes may come from coronae at significant distances from the black hole, and the geometry of this corona has been a question for over 30 years. X-ray polarization has the potential to deter-

mine it. Black hole sources range from the brightest transient X-ray binaries to quasars and Seyfert Galaxies, the brightest of which have X-ray fluxes a few thousandths of the Crab Nebula.

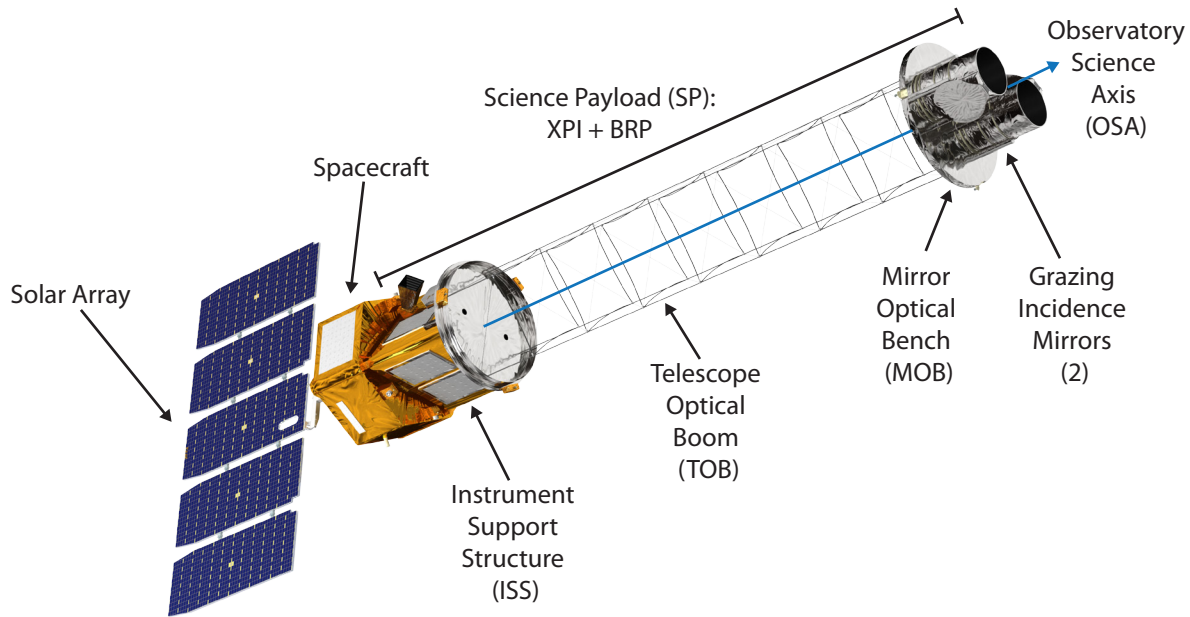
Neutron star X-ray sources also range nearly a factor of a thousand in X-ray brightness, from the classical accreting pulsars to pulsed non-burst flux of magnetars. The determination of the orientation of the magnetic poles of classical X-ray sources will give answers of long-standing questions; for example, X-ray production mechanisms from magnetars has been a subject of speculation since the discovery of these objects some 15 years ago. Fermi Gamma-ray Space Telescope results on rotation-powered pulsars have refined the picture of particles and gamma-ray processes in the magnetospheres, Alice Harding, also on the GEMS Science Team, has calculated the X-ray polarizations expected for contributions from different populations of electrons.

Polarization will test models of the structures of emission regions around compact objects. X-ray polarization also can be used to study diffuse sources, such as supernova remnants. GEMS will use telescopes with grazing-incidence mirrors that focus X-rays onto polarimeters designed to maximize sensitivity. One consequence of this is that the polarimeters do not form images of the sky, but the field of view of the telescope is about 10 arcminutes, which allows coarse spatial mapping of large supernova remnants.

It has been shown from spectra that the shocks in outer shells accelerate cosmic-ray electrons in magnetic fields amplified from the swept-up interstellar fields, but the order and orientations of the fields responsible for synchrotron X-rays is not known and can be addressed with polarization information. In pulsar wind nebulae, there are jet flows from the pulsars. INTEGRAL measurements of the gamma rays from the Crab pulsar indicate synchrotron radiation from electrons in fields perpendicular to the jet. Other (much fainter) pulsar wind nebulae have jets which probably also determine the fields and the polarization in the nebulae. GEMS observations will measure the coherence of their fields.

The polarimeter design was developed by Kevin Black, Phil Deines-Jones, Keith Jahoda, and Joanne Hill. The polarimeter is a time projection chamber that images the track of an electron ejected by an incoming X-ray. The distribution of tracks produced by





*GEMS in its current configuration, which was developed in 2011 following a descope that reduced the number of telescopes from three to two.*

the incoming flux shows the polarization of the source. Joanne Hill has led the polarimeter team in developing engineering test polarimeters. They were subjected to testing during 2011 to assure that they meet the technical readiness required to proceed to flight development. Asami Hayato has found that a modulated X-ray source designed by Keith Gendreau gives accurate results for the drift velocities of the electrons in the polarimeter. University of Iowa co-Is Phil Kaaret and Daniel Gall have built polarized and unpolarized sources and are helping test detector performance. Tod Strohmayer has shown that the data read-out from typical detector events can be accurately deconvolved when noise is included. Simulations of the performance by Tim Kallman, Wayne Baumgartner and Tod Strohmayer have led to optimizing the algorithms for determining the electron directions. John Krizmanic and Steve Sturmer, as well as our RIKEN collaborators, have calculated expected in-orbit detector background due to cosmic rays.

The mirrors will have the 4.5m focal length of one of the Suzaku mirrors, but with a smaller diameter. Yang Soong, Takashi Okajima, and Rob Petre have developed the design for GEMS that is evolved from the foil mirrors first flown by Peter Serlemitsos on the Broad-Band X-Ray Telescope, a shuttle payload, and

subsequently on ASCA and Suzaku. Films across the mirrors to control heat loss will be supplied by Yuzuru Tawara, from Nagoya University. Science Operations of GEMS will be from Goddard, while the spacecraft developer, Orbital, will operate the mission. Craig Markwardt has shown that the observations required to reach the required sensitivities can be scheduled within the constraints on the spacecraft. The data will be archived in HEASARC according to plans worked out with Lorella Angelini.

Work is on-going in the lab to measure the predicted lifetime for good performance of the polarimeters. A nine-month period of observations is needed to accomplish the science objectives of GEMS, but a 16-month lifetime is required to accommodate observatory testing. A general-observer phase, to make possible longer observations and additional targets, would require the lifetime of two or more years that are likely to be possible for the spacecraft and observatory.

GEMS has a university-level Student Collaboration with the University of Iowa, for a small Bragg reflection polarimeter. The Education and Public Outreach program is a combination of Goddard ASD and Ames Research Center initiatives. Sara Mitchell is passing the growing responsibility of the development of this proposal on to Sarah Eyer mann.



## Mission and Instrument Concepts

### Neutron Star Interior Composition Explorer (NICER)

NICER is a proposed Explorer Mission of Opportunity (PI: Keith Gendreau), an International Space Station (ISS) payload devoted to the study of neutron stars through soft-X-ray timing. Neutron stars are unique environments in which all four fundamental forces of nature are simultaneously important. They squeeze more than 1.4 solar masses into a city-size volume, giving rise to the highest stable densities known anywhere. The nature of matter under these conditions is a decades-old unsolved problem, one most directly addressed with measurements of the masses and, especially, radii of neutron stars to high precision (i.e., better than 10% uncertainty). With few such constraints forthcoming from observations, theory has advanced a host of models to describe the physics governing neutron star interiors.

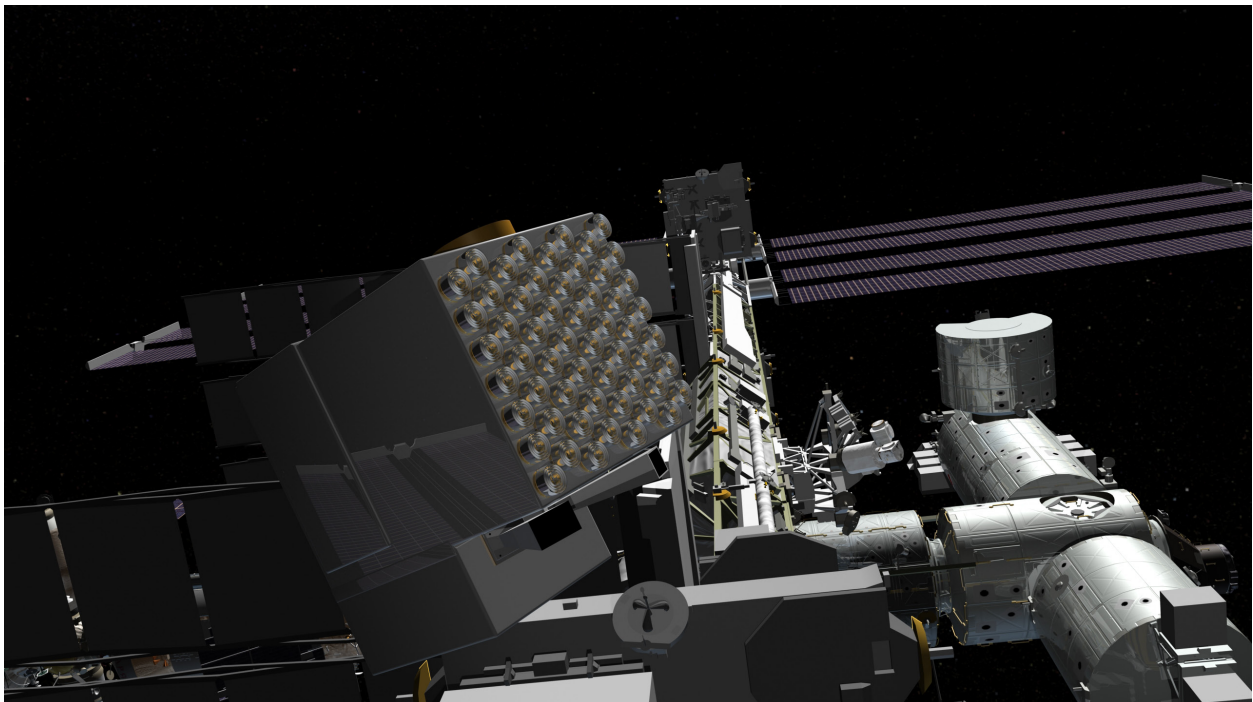
By answering a long-standing astrophysics question—How big is a neutron star?—NICER will confront nuclear physics theory with unique measurements, exploring the exotic states of matter within neutron stars and revealing their interior and surface

compositions through rotation-resolved X-ray spectroscopy. The capabilities that NICER brings to this investigation are unique: simultaneous fast timing and spectroscopy, with low background and high throughput, are not available anywhere. These capabilities will also enable NICER to:

- Probe the dynamic processes associated with neutron stars
- Establish the sites and mechanisms of radiation in their extreme magnetospheres, and
- Definitively measure the stability of neutron stars as clocks, with implications for gravitational-wave detection, timekeeping, and spacecraft navigation.

Through deep synergies with radio and gamma-ray investigations, NICER enables a vital multiwavelength approach to neutron star studies. NICER will also provide continuity in X-ray timing astrophysics post-Rossi X-ray Timing Explorer (RXTE), a rapid response capability for study of the transient sky, and new discovery space in soft X-ray timing science. NICER achieves these goals by deploying its X-ray Timing Instrument (XTI) as an attached payload on a zenith Express Logistics Carrier (ELC) aboard the International Space Station.

NICER's XTI represents an innovative configuration of high-heritage components. The heart of the in-



*This artist's concept shows the NICER instrument (cube in left foreground) on board the International Space Station. The circular objects protruding from the cube are the concentrators that focus X-rays onto the detectors. NASA*

strument is an aligned collection of 56 X-ray “concentrator” optics (XRC) and silicon drift detector (SDD) pairs. Each XRC collects X-rays over a large geometric area from a 10 arcmin<sup>2</sup> region of the sky and focuses them onto a small SDD. The SDD detects individual photons, recording their energies and times of arrival to high precision. The instrument is calibrated so that flux is known to better than 5%, energy resolution to better than 10%, and time tagging to better than 200 nanoseconds relative to universal time (UT). Together, this assemblage provides a photon-counting capability with large effective area, unprecedented time resolution, moderate energy resolution, and low background in the 0.2–12 keV X-ray band, perfectly matched to the typical spectra of neutron stars as well as a broad collection of other astrophysical sources.

From NICER’s ELC platform, a star tracker-based pointing system allows the XTI to point to and track neutron stars and other celestial targets over a full hemisphere. The pointing system design accommodates the ISS vibration and contamination environments, and enables (together with NICER’s GPS-based absolute timing) ultra-deep exposures for high-precision measurements spanning the baseline mission lifetime of 18 months. Anticipated launch of NICER is in August 2016.

NICER was first proposed in February 2011 and selected into Phase A in September 2011. Detailed engineering studies to demonstrate the mission’s feasibility and technical readiness are under way, to culminate in the submission of a Concept Study Report to the Explorer program in the Fall of 2012.

ASD members of the NICER team are Zaven Arzoumanian (Deputy PI) and co-Investigators Lorella Angelini, Fotis Gavriil, Alice Harding, Michael Loewenstein, Craig Markwardt, Takashi Okajima, Peter Serlemitsos, Yang Soong, and Tod Strohmayer. Partnering institutions include MIT (detector development) and the Naval Research Laboratory.

## Lobster

Lobster is an Explorer mission concept proposed to the 2010 NASA EX opportunity. It is Goddard-led with science hardware partners at MIT and University of Arizona, and international participation by University of Leicester and the Italian Space Agency. The primary scientific objectives are to study the first

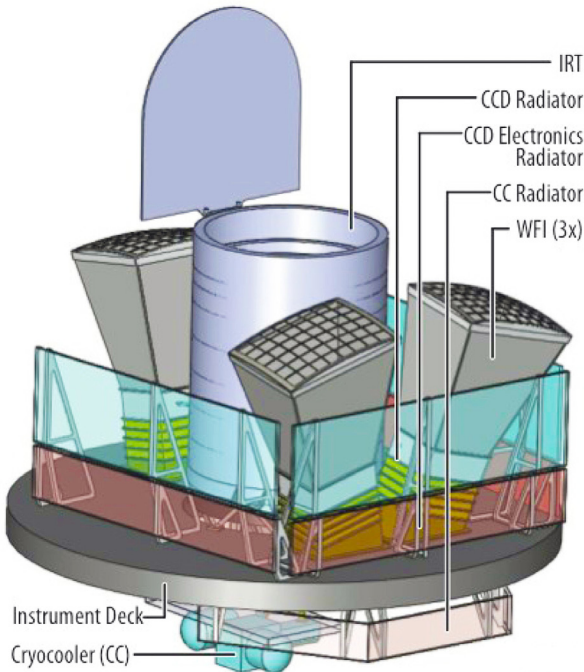
stars and reionization of the universe using gamma-ray bursts (GRBs) and to determine the chemical evolution across time. An important capability for secondary science is to monitor the transient X-ray sky at ten times better sensitivity than currently possible. The mission consists of a wide-field X-ray telescope (Wide Field Imager, WFI) and narrow-field InfraRed Telescope (IRT). A rapid-slewing autonomous spacecraft enables rapid IRT and continuing WFI observations of transients detected by the WFI. The proposal received a category 1 ranking in the NASA review, but was not selected for a Phase A Study. Work is underway to prepare the mission for proposal to future Explorer opportunities.

**First stars and reionization.** Lobster will discover GRBs out to substantially higher redshifts than previous missions, such as Swift, due to a softer X-ray triggering bandpass, higher sensitivity, and prompt autonomous infrared follow-up. It will make the most complete census of faint distant GRBs and use these ultra-luminous sources to find the earliest stars in the Universe and determine the timeline of reionization.

**Chemical evolution.** Infrared observations made by the IRT within minutes of GRB explosions facilitate follow-up by large ground-based telescopes. This follow-up will include high-resolution spectroscopy that probes the environment around GRBs and their host galaxies. Measurements of the host galaxies and circumstellar environments of high-redshift GRBs provide insight into the process of element formation in the Universe.

**Transient Universe.** Lobster’s all-sky X-ray transient monitoring will be an order of magnitude more sensitive than the best current instruments. This revolutionary capability will lead to the discovery of significant numbers of new transients and transient classes, including supernova shock break-out flashes, tidal disruption events of stars torn apart by the strong gravity of a black hole and electromagnetic counterparts of gravitational wave events.

The Lobster WFI instruments operates in the 0.3–6 keV X-ray band to detect and determine the position of GRBs and transients. It is composed of 3 modules, each with a micro-channel “lobster” optic that focuses X-rays onto an X-ray solid state detector. The lobster optic technology was first proposed by Roger Angel and has been developed for space flight by the University of Leicester. It allows both focusing of the X-rays



The Lobster mission consists of a wide-field X-ray telescope (WFI) and narrow-field InfraRed Telescope (IRT). The spacecraft will discover gamma-ray bursts out to substantially higher redshifts than previous missions due to a softer X-ray triggering bandpass, higher sensitivity and prompt autonomous infrared follow-up.

for improved sensitivity and the large FoV. The IRT is a 40-cm near-infrared telescope with a bandpass of 0.6–2.1 microns. The sensor is a HgCdTe detector.

The future of the Lobster concept depends on what opportunities are offered through the Explorer program. Both free-flying missions and instruments mounted on the International Space Station are possible options. GSFC scientists involved are Neil Gehrels (PI); Rob Petre (Depty PI); Ann Hornschemeier (Proj. Sci.); Scott Barthelmy (Inst. Sci. and WFI), Jeff Kruk, Harvey Moseley and Alexander Kutyrav (IRT); Jordan Camp (gravitation wave science); Frank Marshall, Lorella Angelini and Padi Boyd (ground system); Joan Centrella, Ori Fox, Stephen Holland, Stefan Immler, Craig Markwardt, Andy Ptak, Judy Racusin, Taka Sakamoto, Gerry Skinner, Tod Strohmayer and Nora Troja (science team).

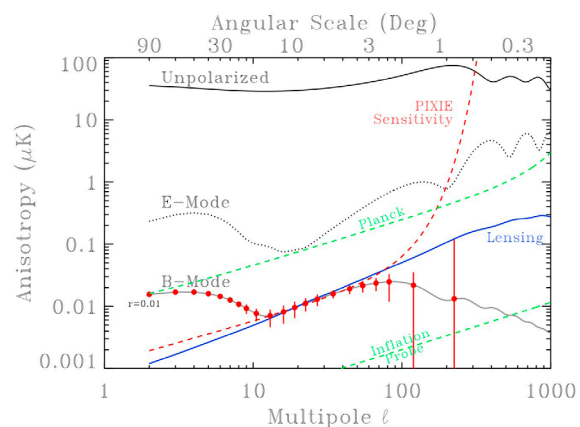
### Primordial Inflation Explorer (PIXIE)

How did the Universe begin? Humans have asked this question since our species first looked skyward. Recent progress in cosmology suggests that we may have

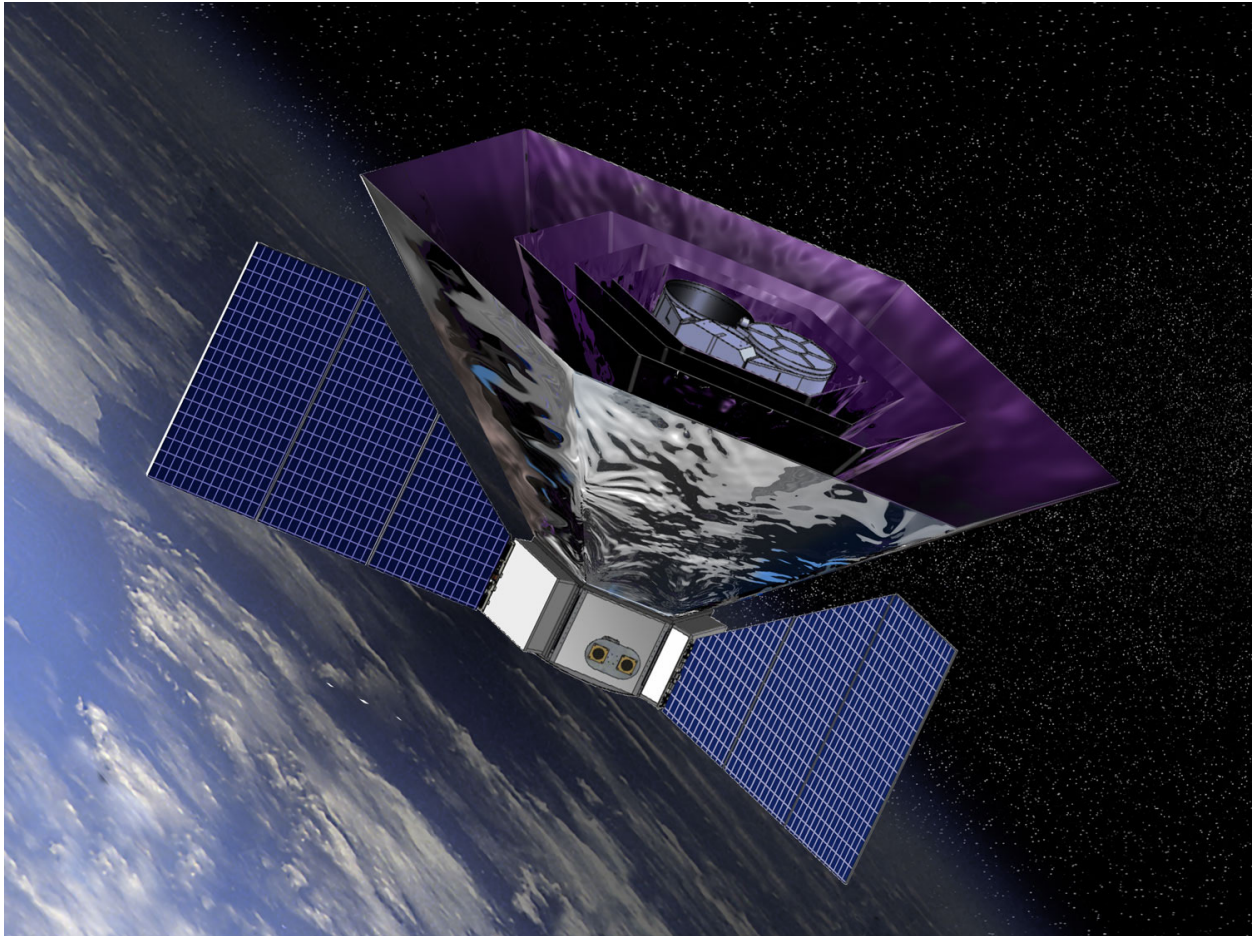
begun to answer it. We live in an expanding Universe filled with microwave background radiation, the left-over heat from the Big Bang. In this “concordance” model, the universe is flat, largely composed of dark energy and dark matter, and seeded with density fluctuations from the early universe.

The concordance model postulates that early in its history, the universe underwent a rapid period of superluminal expansion called inflation. The exponential growth of the scale size during inflation neatly produces the observed conditions of our universe, but relies on extrapolation of physics to energies a trillion times beyond those accessible to direct experimentation in particle accelerators.

The Primordial Inflation Explorer (PIXIE) will test the inflationary paradigm by searching for the “smoking gun” signature of primordial inflation in the linear polarization of the cosmic microwave background (CMB). Quantum fluctuations in the space-time metric during inflation create a stochastic background of gravity waves, which in turn imprint a distinctive spatial signature in the CMB. The amplitude of the gravity waves depends on the energy scale at inflation. Detection of the gravity-wave signature would establish inflation as a physical reality, provide a model-independent determination of the relevant energy, and probe physics at energies near the Grand Unified Theory scale ( $10^{16}$  GeV). The search for the inflationary signal is widely recognized as one of the most compelling questions in cosmology, endorsed as a priority for the coming decade in the 2010 Decadal



PIXIE sensitivity (red) compared to the predicted signal from inflationary gravity waves (grey line). PIXIE will measure the power spectrum of even the minimal predicted inflationary signal to characterize physics at energies near Grand Unification.



Artist's concept of the PIXIE observatory.

Survey of Astronomy and Astrophysics, *New Worlds, New Horizons*.

PIXIE is an Explorer mission concept to detect and characterize the signature of primordial inflation. Principal Investigator Alan Kogut (665) leads a team including GSFC Co-Investigators D. Chuss, E. Dwek, D. Fixsen, S.H. Moseley, and E. Wollack. PIXIE's innovative design uses a multi-moded "light bucket" and a polarizing Fourier Transform Spectrometer to measure the differential spectrum between two co-aligned beams in orthogonal linear polarizations. PIXIE will measure the frequency spectra in 400 spectral bands from 30 GHz to 6 THz for each of the Stokes I, Q, and U parameters in each of 49,152 independent pixels covering the full sky.

The combination of sensitivity and broad spectral coverage answers exciting questions across cosmic history. PIXIE's primary science goal is the characterization of primordial gravity waves through their signature in the CMB polarization. PIXIE will measure linear polarization to sensitivity 70 nK per  $1^\circ \times 1^\circ$  pix-

el. Averaged over the sky, PIXIE can detect CMB polarization to 3 nK sensitivity, a factor of 10 below the minimum signal predicted from large-field inflation models. PIXIE reaches the cosmological "noise floor" imposed by the gravitational lensing below which further instrumental sensitivity is unimportant.

PIXIE's unique combination of high sensitivity and broad spectral coverage enables a broad range of ancillary science goals. PIXIE will measure both the temperature and ionization fraction of the intergalactic medium at redshifts 5–30 to determine the nature of the first luminous objects in the Universe. Measurements of the spectrum and anisotropy of the far-IR background test models of star formation at redshift 2–4. PIXIE determines the properties of the diffuse dust cirrus and maps the far-IR line emission from the molecules and ions that cool the interstellar medium within the Galaxy.

PIXIE was submitted to the 2011 Explorer Announcement of Opportunity. Although the mission was not selected for Phase A study, both the science

and technical implementation were rated as Category 1. PIXIE can reach fundamental sensitivity limits imposed by unavoidable cosmological foregrounds, achieving key goals of NASA's planned Inflation Probe mission at a small fraction of the cost and complexity. As such, the mission retains considerable interest for NASA. The PIXIE team has been urged to re-propose at the next MIDEX opportunity.

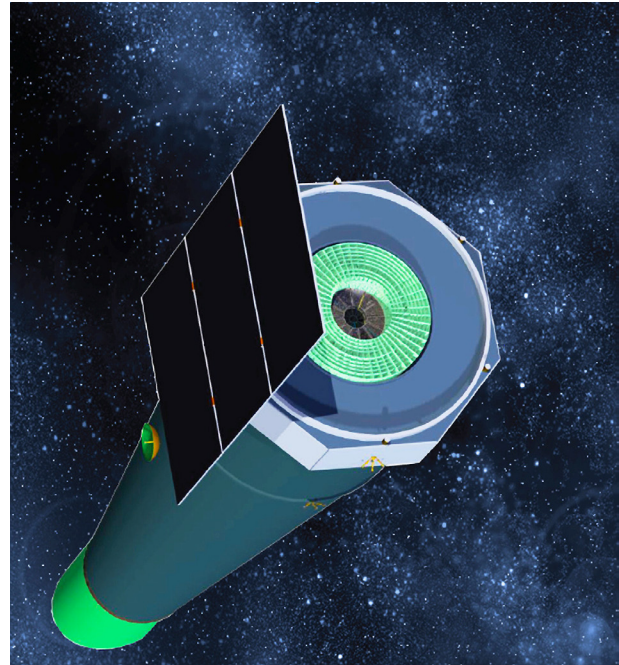
### International X-ray Observatory (IXO)

IXO was to be an international flagship X-ray observatory with joint participation from NASA, the European Space Agency (ESA) and Japan's Aerospace Exploration Agency (JAXA). The mission was created in 2007 by the merger of NASA's Constellation-X and ESA's XEUS. IXO is a facility-class mission for launch in the 2020's that will address the leading astrophysical questions in the "hot universe" by providing breakthrough capabilities in X-ray spectroscopy, imaging, timing and polarimetry.

IXO was ranked as the fourth priority for NASA in the 2010 decadal survey report *New Worlds, New Horizons*. The scientific topics central to IXO were ranked highly in several panels, as was the need for the measurements IXO will provide, particularly high-resolution X-ray spectroscopy. The panel recommended that NASA support a substantial technology development program over the next decade, primarily to mature the X-ray mirror technology.

Nearly in parallel with the 2010 decadal survey, ESA was evaluating future missions through its Cosmic Visions study. IXO was one of three L-class missions, along with LISA and a Jupiter probe, which were to be ranked by ESA in June 2011. As all three missions relied on substantial NASA contributions, and none were ranked highest in their respective U.S. decadal surveys, ESA decided in March to reconstitute all three L-class candidates at a lower cost and without substantial U.S. participation. NASA's response was to terminate the IXO (and LISA) studies.

The replacement L-class candidate for IXO is called the Advanced Telescope for High ENergy Astrophysics (ATHENA). It has very different architecture: a pair of identical co-axial mirrors, one of which illuminates an X-ray calorimeter, the other a Wide Field Imager. ATHENA would address most of the IXO science objectives, at a considerably lower cost. U.S. participation would be limited, but might in-

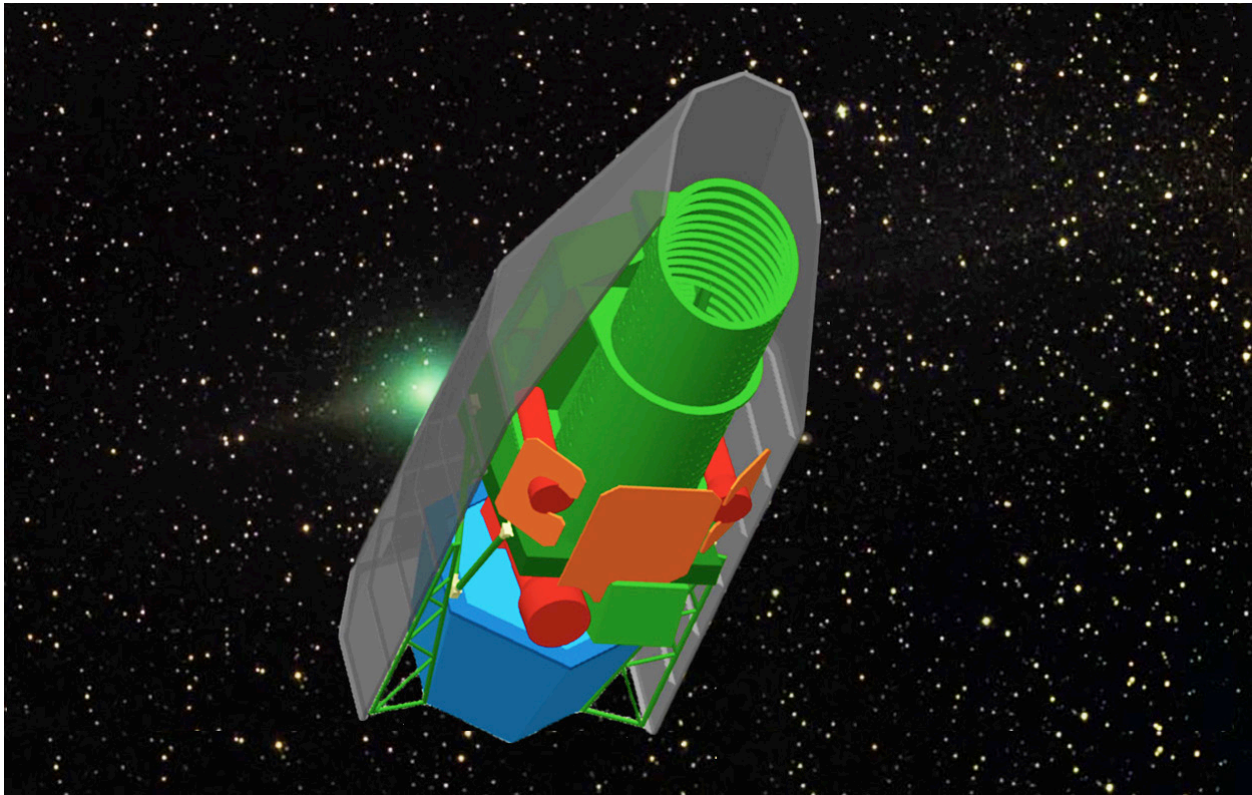


*The Advanced X-ray Spectroscopy and Imaging Observatory (AXSIO) mission concept would perform the high-priority IXO science at lower total cost. The design features an X-ray calorimeter and a retractable grating spectrometer behind a single large mirror.*

clude contribution of the sensor for the calorimeter, and processing electronics for the Wide Field Imager.

Subsequent to the termination of IXO, three important study activities have occurred. A plan was developed that establishes a timeline for bringing the IXO mirrors to the state of technical readiness advocated by the Senior Review within the recommended timescale and budget. A concept for a mission that performs the high-priority IXO science at a total cost below \$2B was developed and validated through the GSFC Mission Design Laboratory. This mission concept, the Advanced X-ray Spectroscopy and Imaging Observatory (AXSIO), features an X-ray calorimeter and a retractable grating spectrometer behind a single large mirror, preserving IXO's key components.

The third activity is a broader study of mission concepts requested by NASA Headquarters and coordinated by the PCOS Program Office. Its goal is to study the degree to which the IXO science objectives can be accomplished by missions at various cost levels between \$300M and \$2B. Rob Petre is serving as Study Scientist, and Andy Ptak is a member of the Science Support Team. This study was initiated in September 2011 through an HQ Request for Infor-



*The WFIRST observatory as conceived for the Interim Design Reference Mission features a 1.3m off-axis telescope.*

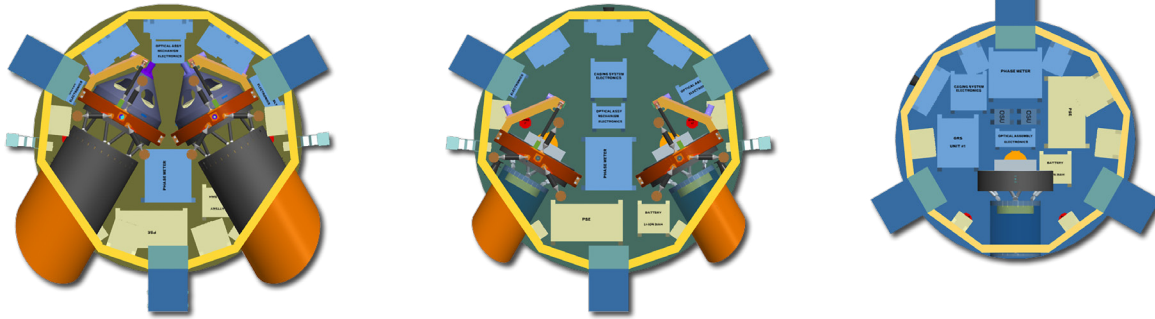
mation (RFI) for mission concepts and supporting technology. Responses were due in late October; a total of 29 responses were received, 15 of which described mission concepts. In November, NASA HQ selected a Community Science Team (CST) to provide science input for the study. The Study Team hosted an open, two-day workshop at the Maritime Institute, Linthicum, Maryland, in mid-December to involve the larger community; attendance exceeded 100. The lead author of every RFI response had an opportunity to make a presentation, and there was ample and lively discussion. Using the workshop discussion and the RFI responses as input, the CST then recommended three notional missions representing the various cost bins for further study through the GSFC design labs. These are a calorimeter, gratings and wide-field imager single-instrument missions. The study will also consider descopes in these cases to ensure that the cost bins span the requested range. Conversely the science and cost tradeoffs of including a second instrument on one or more of these notional missions may also be considered. These notional missions, the degree to which they fulfill IXO science objectives, and the results of the design lab analysis will be compiled into a final report due in June 2012, which is also when ESA

is expected to make a decision concerning ATHENA. This report will be presented to the newly reinstated NRC Committee for Astronomy and Astrophysics (CAA), which will recommend a course of action to NASA.

### **Wide Field InfraRed Survey Telescope (WFIRST)**

The Astro 2010 report, released August 13, 2010, selected the Wide-Field Infrared Survey Telescope (WFIRST) as the top priority for large space missions in the coming decade. This mission combines the dark energy science previously planned for the NASA/DOE Joint Dark Energy Mission (JDEM) project, with observing programs to obtain a census of exoplanets by means of microlensing and to obtain a wide range of near-infrared surveys. The JDEM Omega mission concept was to serve as the basis for the new mission design. NASA HQ designated GSFC as the lead center for managing the WFIRST project, with significant portions of the mission assigned to JPL.

A Science Definition Team (SDT) representing the full spectrum of WFIRST science objectives was appointed at the end of 2010 to provide scientific ad-



Configurations under review for different versions of the SGO spacecraft.

vice on optimizing mission performance during the WFIRST pre-Phase A study and to develop a Design Reference Mission. An interim report was to be delivered in June 2011, with a final report due in Summer 2012. The SDT worked closely with scientists and engineers from the WFIRST Project Office to develop an “Interim Design Reference Mission” (IDRM) for the interim report. This report summarized the scientific objectives of the mission, and described the expected scientific return from the IDRM implementation. This initial concept was based closely on the JDEM Omega design, given the tight schedule, but one particularly promising change was studied early and adopted: the 1.5m on-axis telescope was replaced with a 1.3m off-axis telescope. The two designs have comparable collecting area, but the clean point-spread function of the off-axis telescope provided significant benefits to the challenging WFIRST observing programs.

The plan forward is to complete the study of mission performance and designs with the Project Office and SDT. The recent selection of the Euclid dark energy mission by ESA may provide opportunities for joint science and possible design modifications for WFIRST.

The WFIRST Project science team at GSFC includes Neil Gehrels (Project Scientist), Jeff Kruk (Instrument Scientist), Richard Barry, Ken Carpenter, Ed Cheng, Harvey Moseley, Bernie Rauscher and Ed Wollack. This team joined the engineers from the Project Office in working with the SDT to study the implementation of WFIRST. Rauscher and Gehrels are members of the SDT. Recently, the scope of this group has expanded to include a comprehensive study of the scientific performance requirements. Amber Straughn and Andy Ptak have joined this group to aid in this effort.

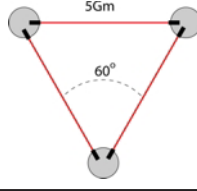
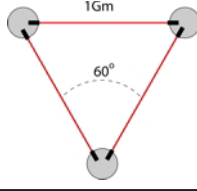
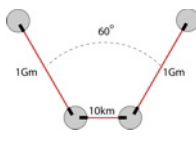
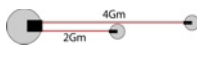
### Space-based Gravitational-Wave Observatory (SGO) and Next Gravitational-Wave Observatory (NGO)

For the past decade, ESA and NASA have partnered to develop a mission concept for a space-based gravitational wave observatory. That concept was the Laser Interferometer Space-based Antenna (LISA) that has been highly ranked in several reviews by the National Academy of Sciences, most recently in *New Worlds, New Horizons*, the Astro2010 Decadal Survey. In March, the two agencies ended their partnership because of mismatched funding schedules. Both agencies then set about identifying new mission concepts compatible with their respective programmatic constraints.

ESA initiated a study to identify a less ambitious mission concept that was compatible with the L1 opportunity in its Cosmic Visions Programme. ESA invited NASA to name a scientist to the Science Team in anticipation of NASA partnering in the resulting project at a minor level. NASA HQ named R. Stebbins, the former U.S. LISA Project Scientist, to fulfill that role and act as a liaison for the U.S. gravitational-wave research community. Stebbins participated in the early design study, a design lab study at ESA’s Concurrent Design Facility. Members of the former LISA team at Goddard and JPL supported many of these activities through orbital and trajectory calculations and trade studies. About ten members of the U.S. science community participated in the analysis of the science performance.

The sum of these efforts produced a LISA-like design of a gravitational wave observatory, referred to as the Next Gravitational-wave Observatory (NGO). Like LISA, NGO has three spacecraft orbiting the Sun in a triangular formation with laser interferom-

## NASA SGO Mission Concepts

Acronym	SGO High	SGO Mid	SGO Low	SGO Lowest
				
<b>Novel Idea</b>	LISA with all known cost savings	Smallest LISA-like design with 7 links	Smallest LISA-like design with 4 links	Smallest in-line LISA-like design with 4 links
<b>Cost Estimate (FY12 \$M)</b>	\$1,660	\$1,440	\$1,410	\$1,190
<b>Arm Length</b>	$5.0 \times 10^6$	$1.0 \times 10^6$	$1.0 \times 10^6$	$2.0 \times 10^6$
<b>Spacecraft/Constellation</b>	3/equilateral triangle	3/equilateral triangle	4/triangle (60° Vee)	3/inline: Folded SyZyGy
<b>Orbit</b>	Heliocentric drift-away	Heliocentric drift-away	Heliocentric drift-away	Heliocentric
<b>Trajectory</b>	Direct injection to escape, 14 months	Direct injection to escape, 21 months	Direct injection to escape, 21 months	Direct injection to escape, 18 months
<b>Inertial Reference</b>	Two, rectangular	Two, rectangular	Single, rectangular	Single, rectangular
<b>Displacement Measurement</b>	3 arms, 6 links	3 arms, 6 links	2 arms, 4 links	2 unequal arms, 4 links
<b>Launch Vehicle</b>	Shared Falcon Heavy	Falcon 9 Block 3	Shared Falcon 9 Heavy	Falcon 9 Block 2
<b>Baseline/Extended Mission Duration</b>	5/3.5	2/2	2/2	2/0
<b>Telescope Diameter (cm)</b>	40	25	25	25
<b>Laser power out of telescope, EOL (W)</b>	1.2	0.7	0.7	0.7

etry measuring the distance between free-falling test masses enclosed within drag-free spacecraft. NGO differs from LISA in that there are two, rather than three, interferometer arms, and the arms are 1 rather than 5 million kilometers long. NGO would launch on two Soyuz spacecraft. NGO has nearly the science performance of LISA, despite being less capable, because of improving data analysis methods.

At the close of 2011, the NGO mission concept has been defined and analyzed. It relies on European technology developed for the LISA concept, and fits within the constraints of the L1 opportunity. Importantly, it uses the technology developed for ESA's LISA Pathfinder, expected to launch in mid 2014. That technology has largely been flight-qualified, and much of the development risk has been retired.

A decision as to which mission to pursue is currently expected in April 2012. If the NGO mission is chosen as the L1 Cosmic Visions mission in June 2011, the mission is expected to enter a mission-definition phase that would last approximately 18 months and enter the B1 phase near the beginning of Q2 FY2014.

To prepare for the possible selection of NGO by ESA, NASA has funded two new technology development efforts: development of a phasemeter that meets the NGO requirements, led by JPL, and development of a telescope, led by J. Livas.

During Summer 2011, NASA initiated a mission-concept study to explore lower cost options as well. This study is exploring alternate architectures to establish how science performance varied with cost. The mission concept study began with a Request for Infor-



mation and the formation of a Community Science Team.

The gravitational-wave community answered with 15 responses. The respondents were invited to a workshop held near Goddard in December 2011 for further discussion. NASA's LISA team developed four separate mission concepts, summarized below, ranging in cost from \$1.66B to \$1.19B. This family of concepts, called Space-based Gravitational-wave Observatory (SGO) is a step-wise progression from the full LISA concept (SGO High) to a minimal LISA-like configuration (SGO Lowest).

The NASA team is currently evaluating three representative concepts for technical readiness, risk, science performance, and cost. These concepts will be studied and costed at JPL's concurrent design facility, Team-X. The results of this evaluation will be compiled for a report for NASA Headquarters, due June 2012. That report will be subsequently presented to the National Academy's Committee on Astronomy and Astrophysics for consideration and recommendation to NASA.

J.I. Thorpe has continued to support the LISA Pathfinder (LPF) mission. The effort includes development of data analysis tools and pipelines, development of a plan for the Science Operations Center (SOC), and plans for U.S. operation and experiments with the control systems of the spacecraft. In October, Thorpe organized a workshop to facilitate the exchange of data analysis software between the LISA Technology Package, ESA's payload on LPF, and ST7, NASA's payload on LPF.

## Visible Nulling Coronagraph for Exoplanets

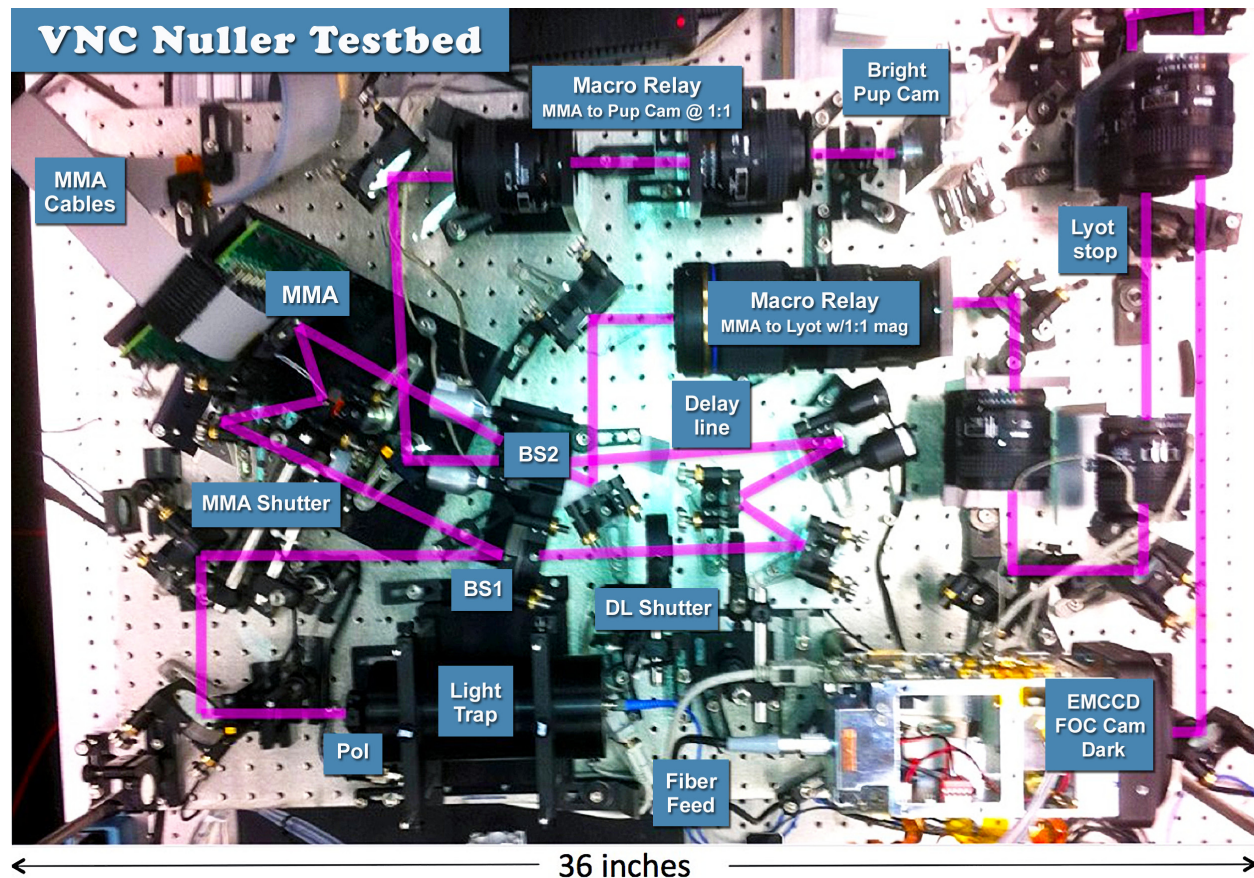
Three of the completed NASA Astrophysics Strategic Mission Concept (ASMC) studies addressed the feasibility of employing a Visible Nulling Coronagraph (VNC) as the prime instrument for exoplanet science. The VNC approach is capable of exoplanet science with filled-, segmented- and sparse-aperture telescopes, spanning all realizable future mission architectures. A hybrid of a classical coronagraph and nulling interferometer, it uses destructive interference to null starlight and has an inherent advantage due to its ability to control amplitude and wavefront errors in near real time. This is due it being *its own interferometer*, and as such gives both bright (stellar) and dark (plan-

etary) output channels that enable a direct approach to extreme wavefront control.

NASA Goddard Space Flight Center has an established effort to advance VNC technologies through an incremental sequence of testbeds and technology development efforts. The VNC was previously funded with GSFC IRAD for FY08/09/10 and is now for FY12 to study the VNC as an instrument for a balloon payload. The VNC was awarded a ROSES Technology Development for Exoplanet Missions (TDEM) for FY10/11 (PI: M. Clampin) and recently won a follow-on TDEM for FY12/13 (PI: R. Lyon). These TDEM's are to achieve contrast milestones on the GSFC Vacuum Nuller Testbed (VNT), first narrowband at contrasts of  $10^8$  and  $10^9$  at inner working angles (IWA) of  $2 \lambda/D$  to characterize exosolar planets, and then with successively wider spectral band passes. The VNT was developed to lower risk, advance technological readiness, quantify performance, develop and assess control algorithms, and assess internal VNC technologies. It is an ultra-stable vibration-isolated testbed operating under high control bandwidth within a vacuum chamber. Each of the milestones, one per year, is traceable to one or more of the ASMC studies.

The critical technologies needed to realize the VNC are (i) the MEMS-based hex-packed segmented multiple mirror array (MMA), (ii) a spatial filter array (SFA) or a coherent fiber bundle, (iii) achromatic phase-shifting coatings, (iv) precision wavefront and amplitude control (WFC), and (v) the photon-counting camera.

The MEMS DM has been developed by IRIS-AO (Berkeley, Calif.) under multiple SBIRs, and GSFC has received multiple deliverables of these MMAs. Additionally GSFC has received a new phase-II NASA SBIR and has been awarded a FY12/13 TDEM to advance the mirror technology to 313 segments. The current MMA consists of 169 segments  $\sim$ 606 microns across (flat-to-flat) and each segment is articulated in three degrees-of-freedom over the range of 1 micron in steps of 0.015 nm (1-bit) and has stable 16-bit electronics control. Significant advances were made under these SBIRs, including thicker segments, from 10, to 20 and finally 50 microns, to remove print-through and segment flexing. Electronics were advanced from 12, to 14 to 16 bits and segment flatness started at  $\sim$ 20 nm rms/segment and is now at  $\sim$ 4 nm rms/segment; flight requirements are 2 nm rms/segment.

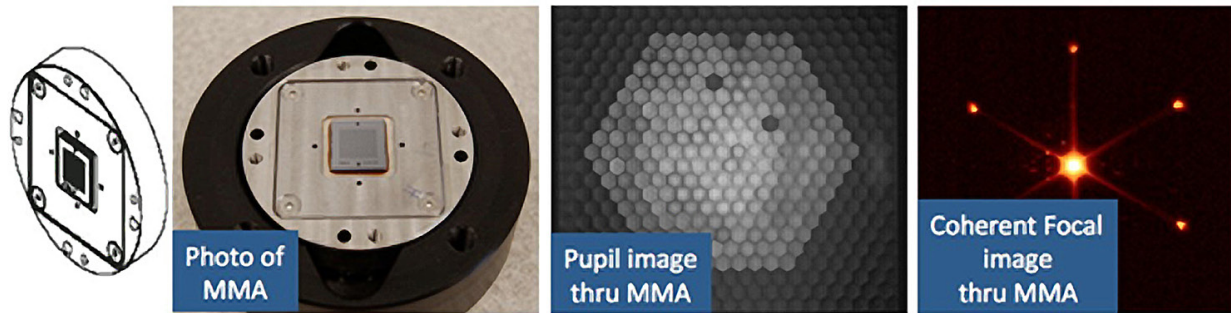


The GSFC Vacuum Nuller Testbed. Light enters from the fiber feed into a light trap that collimates and filters the light to emulate the beam from a collecting telescope and define the aperture stop. An optical relay re-images the aperture stop onto both the MMA and its conjugate optic in the delay-line arm after splitting light 50:50 at beamsplitter-1 (BS1). The light is combined at beamsplitter-2, yielding two output beams known as the bright and dark outputs. The dark output contains the planetary photons, while the bright output contains the stellar photons; both output channels are used for wavefront and amplitude control. The total number of photons is conserved across both channels, allowing realization of a null-control scheme that depends only on the brightness of the target star and is independent of the state of the VNC. This is a significant advantage over other approaches in that it allows rapid control. The angle of separation between the star and planet where the VNC operates is  $2\lambda/D$ , where  $\lambda$  is the wavelength and  $D$  the diameter of the aperture. In visible light this is  $\sim 50$  milliarcseconds for a  $4m$  aperture.

The SFA has been developed by Fiberguide Industries, Inc. (Caldwell, Idaho) under GSFC-funded IRAD and will be shortly tested on the VNT. Additionally, a phase-II SBIR was awarded to Luminix LLC (Torrance, Calif.) to develop a separate waveguide-based approach to the SFA; delivery of the first 1,000-element SFA from Luminix is expected in January 2012. Additionally a second vendor has been awarded a phase-I SBIR for a different lenslet approach to the spatial filter array.

Multiple approaches are possible for achromatic phase shifters, and two approaches have been developed at GSFC with additional approaches under assessment. The first approach was using two dispersive

glass plates and developed by G. Vasudevan (LMCO); the second uses five dispersive glass plates and was developed by (M. Bolcar, Optics Branch, and R. Lyon, Exoplanets and Stellar Astrophysics Laboratory). The third approach is to use a double-rhomb, a technique developed in France for IR achromatic nulling that may be amenable to visible light. However, the fourth approach appears to be the most promising: It is to use customized coatings on the interferometer arms, and a design effort for this is underway. The achromatic phase shifters are not initially needed to achieve and hold narrowband contrast on the VNT but will be needed to broaden the spectral bandpass toward what is required for flight. GSFC in collaboration with



From left: A drawing and image of the Spatial Filter Array and an image of the MMA pupil through SFA. At right is a focal plane image through the SFA, which is the first definitive demonstration that a fiber-based spatial filter array can be made coherent.

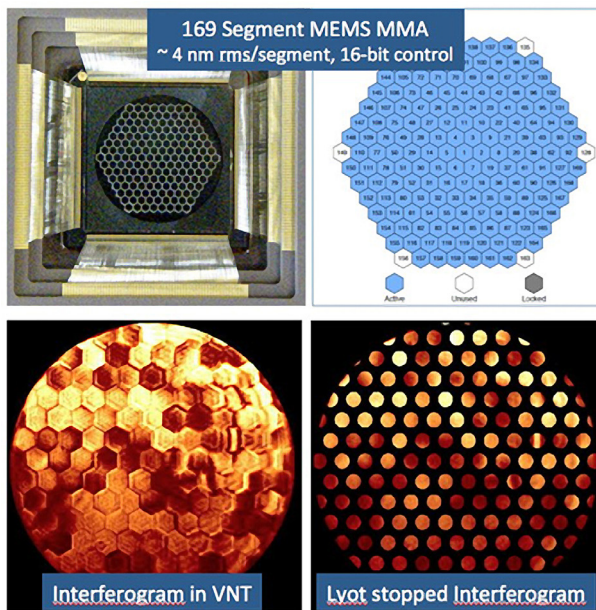
Lockheed-Martin are designing and establishing tolerances for this approach.

The current photon-counting cameras are COTS from Princeton Instruments and utilize E2V's L3 chip. Additional advancement of photon-counting cameras is needed for all coronagraph missions.

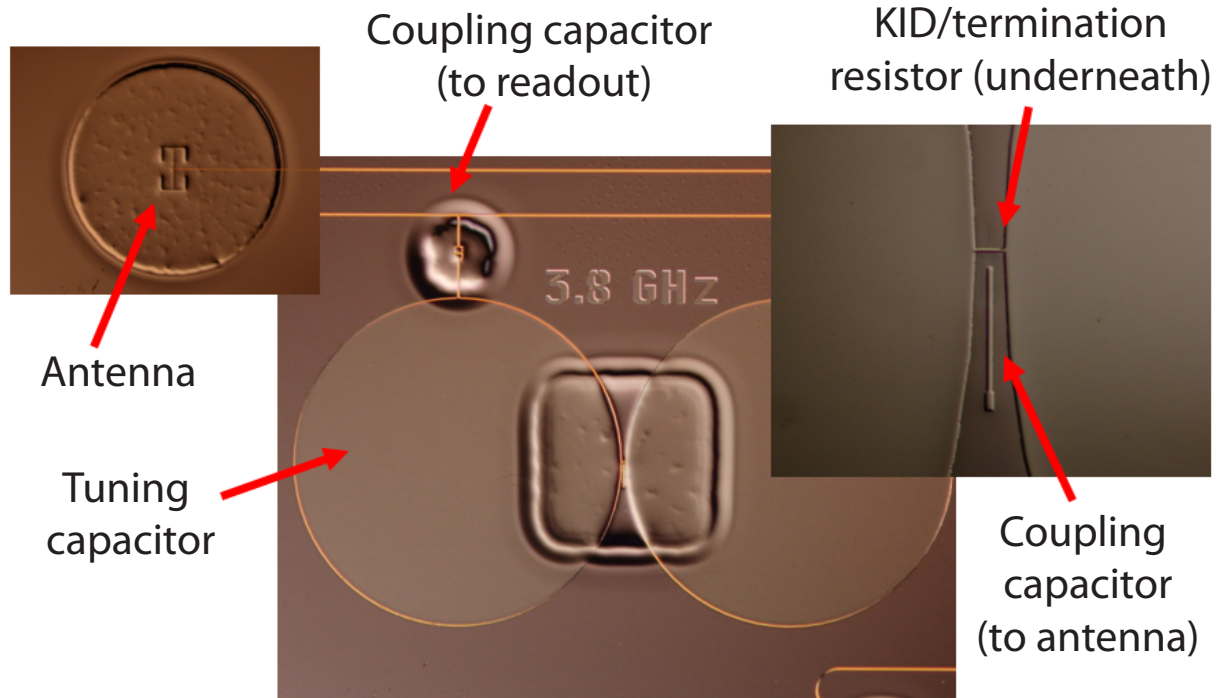
The precision wavefront control is under development at GSFC and lies at the heart of this effort. It is critical to be able to optimally sense and control the

wavefront and amplitude errors, both broad and narrowband, at high enough bandwidth to achieve and hold the contrast by feeding back to the MMA. The stroke of the MMAs, bit depth of the cameras, vibration, thermal drift, coating imperfections, temporal and spatial sampling, quantization, flat fielding, dark current, noise, stray light, approximations and errors in the algorithms, along with other potential effects, all work to corrupt this process. The wavefront control is really a multi-step process that consists of a set of camera calibration algorithms, wavefront sensing algorithms and MMA control algorithms. Wavefront sensing, though, is somewhat of a misnomer because what is important to the science is the contrast. Thus the final control metric is contrast based, and wavefront error is actually an intermediary step, as opposed to converting images to wavefront errors.

The milestones to be achieved under the ongoing TDEM are  $10^8$  narrowband contrast at  $2\lambda/D$  inner working angle by April 2012, and  $10^9$  contrast at  $2\lambda/D$  inner working angle by November 2012. The first milestone requires the MMA, precision WFC, and photon counting, and this milestone is designed to assess the performance of the MMA in a closed loop as driven by the WFC. The second milestone additionally requires the use of the SFA to give greater than a factor of 10 in contrast since it effectively and passively filters the higher spatial frequencies from the wavefront, working in concert with the MMA with one MMA mirrorlet mapped to one optical fiber of the SFA. The third milestone of  $10^9$  in  $> 15\%$  spectral bandpass is still to be negotiated with the technical advisory committee, but we expect this result in mid-2013.



Top: At left is an image of the current MMA, and at right is the valid segment map showing all segments operational. Bottom: At left is an image from the bright output channel; in the control scheme, all the hex-segments are moved to make this image as bright as possible to insure light passes through the dark channel. The image at right shows the bright output channel image as seen through the Lyot stop.



Background-limited microwave kinetic inductance detectors (MKIDs) form the heart of the *Microspec*. The architecture of the antenna-coupled MKIDs is illustrated here. The detectors are fabricated in house in the Detector Development Lab in GSFC.

### Microspec: Integrated Instruments for Submillimeter Spectroscopy

Harvey Moseley and collaborators Dominic Benford, Matt Bradford (JPL), Edward Wollack, Wen-Ting Hsieh, Jack Sadleir, Thomas Stevenson, Negar Ehsan, Kongpop U-Yen, and Jonas Zmuidzinas (Caltech/JPL) are developing fully integrated submillimeter spectrometers based on superconducting transmission lines. The approach will allow the production of spectrometers with resolving powers  $R \sim 1500$ , which are characteristically of order 1.5 meters in scale, on a single 4" wafer. The optical system is fully integrated with its detectors, and thus the entire instrument is mass producible through photolithographic processes. This approach will bring high-performance submillimeter spectroscopy within the reach of Explorer-class space missions by reducing the mass and volume of the optical system and detectors by more than five orders of magnitude.

These advances, combined with rapid progress in cryocoolers, promise to open the submillimeter to spectroscopic investigation. Fine structure lines of abundant elements (C, N, S, Si, Fe, and O) and the

rotational transitions of hydrides are in the mid- and far-infrared spectral bands. The opening of the submillimeter to high-sensitivity spectroscopy allows us to follow the investigation of these lines into the high-redshift universe—much as JWST can follow the discoveries of HST into the higher-redshift universe—and allow us to explore the initial growth of galaxies and the history of element formation.

In FY 2011, development began on a spectrometer with  $R \sim 64$  to demonstrate operation in the 400–600  $\mu\text{m}$  spectral band. The design of the instrument is complete, and masks for its production are in preparation. Tests of this low-resolution spectrometer will demonstrate the operation of all key microwave parts and the suitability of the superconducting materials for the ultimate higher-resolution instrument. These tests are planned to be complete in summer of 2012.

A key enabling element for submillimeter spectroscopy in space is the development of detectors with sufficient sensitivity to reach the sensitivity limits set by background photon statistics. For a single-mode input and  $R \sim 1500$ , we will receive only  $\sim 100$  photons per second, so detectors with noise-equivalent powers (NEP)  $\sim 10^{-20}$  W/ $\sqrt{\text{Hz}}$  are required—about a

factor of 20 better than has been achieved to date. Development is underway to produce detectors that will reach the single-photon sensitivity level in the submillimeter. Photon counting offers significant benefits for implementing a practical experiment: Since we are detecting pulses, most of the signal is at high frequencies, making us much less sensitive to low-frequency noise. The system can thus be DC stable without the requirement of reference measurements, resulting in increases in observing speed of as much as a factor of four compared to power detectors.

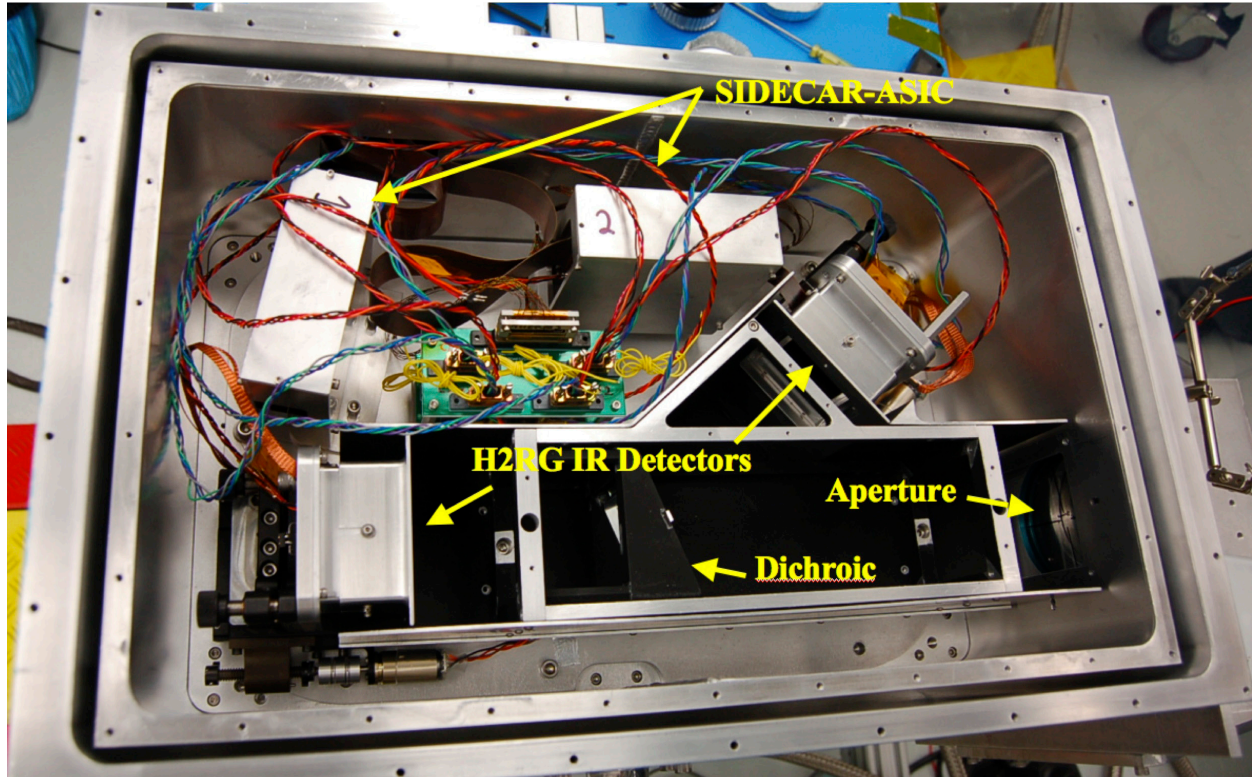
### The Reionization and Transients InfraRed (RATIR) Camera

RATIR is a new optical/infrared imaging camera that will identify high-redshift Gamma-Ray Bursts (GRBs) to probe the early universe, thus shedding light on the first stars and galaxies. The project is a collaboration between UC Berkeley (PI, N. Butler), NASA GSFC (N. Gehrels), and the Universidad Nacional Autónoma de México (UNAM). The GSFC team, led by Alexander Kutyrav and supported by Co-I's O. Fox, G.

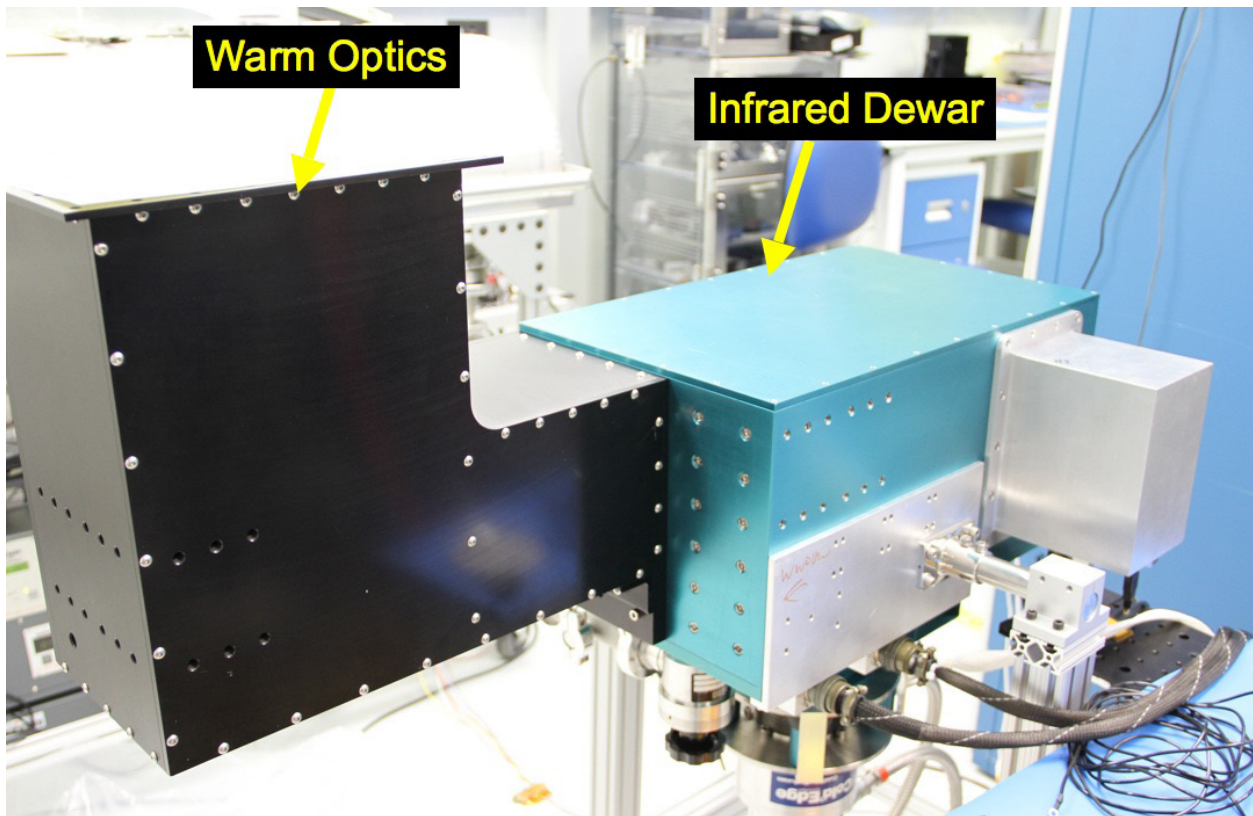
Lotkin, H. Moseley, and D. Rapchun, completed the design, fabrication, and construction of the infrared portion of this camera. (D. Robinson and S. Mathew were formerly part of the team, but have since left for other projects.)

RATIR will provide rapid (on a few minutes' timescale) photometric redshifts (i.e., distances) for all observable GRBs detected by Swift. The primary goal is the rapid identification of very-high-redshift (VHR) bursts and potentially "dark GRBs" that are commonly believed to be at cosmological distances. These GRBs, as well as their afterglows, serve to probe the epoch of reionization and locate the first stars and galaxies. Since GRBs fade quickly, the rapid photometric redshifts are very important for selecting targets for high-resolution spectroscopic follow-up observations with large-aperture telescopes.

While not all GRBs will be at high redshifts, the resulting low-redshift light curves, combined with X-ray/UV observations, will address several open questions, including the nature of "dark GRBs," the global evolution of dust in host galaxies, the cosmic star-formation rate, and the GRB emission mechanism. In



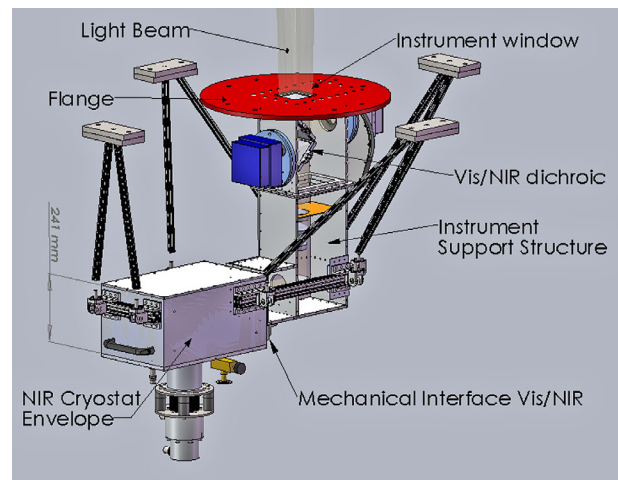
Top view of the RATIR infrared dewar and detector subsystem at NASA Goddard. Two IR cameras ensure rapid multi-color observations for identification of high-redshift GRBs before they fade.



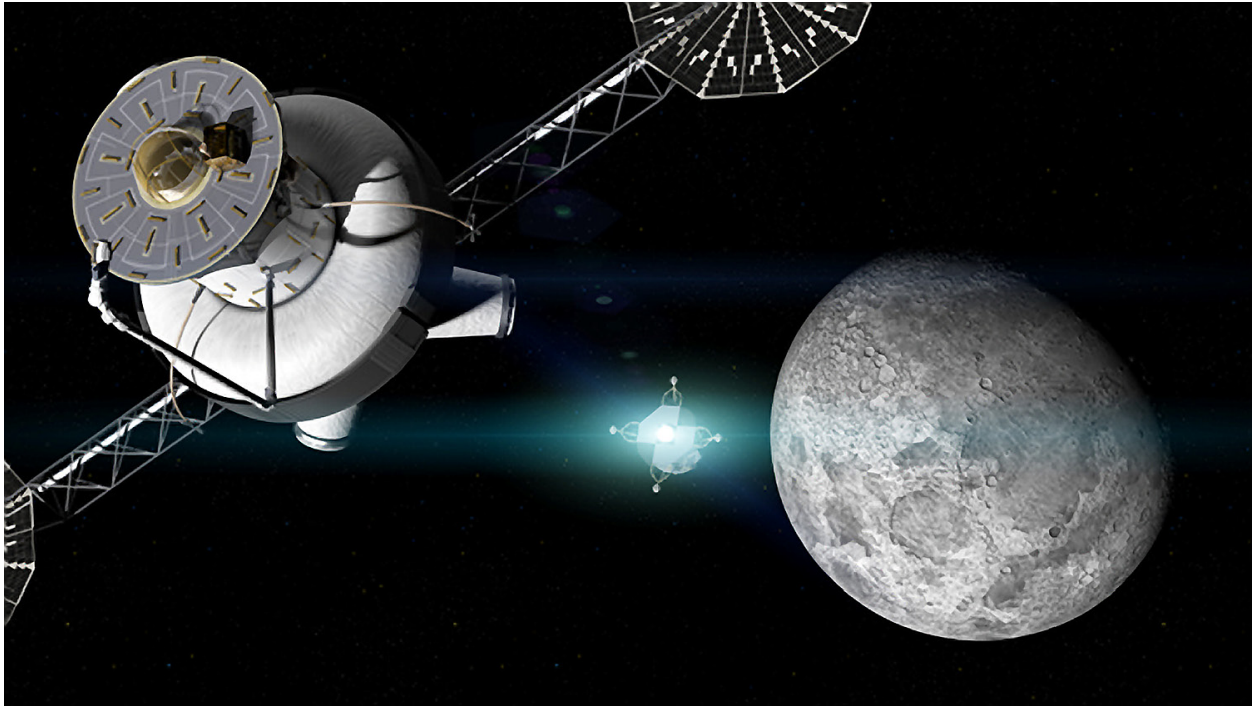
The completed RATIR infrared system at NASA Goddard, which consists of both the cryostat/dewar and warm optics box.

between GRB interrupts, RATIR will support ancillary science that requires systematic long-term monitoring. Ultimately, this work will set the groundwork for future space-based missions, such as JANUS and Lobster X-ray all-sky monitor.

RATIR is a relatively straightforward instrument with several unique advantages that will make it ideal for high-redshift transient photometry. First, the design includes four detector arms (two optical and two near-infrared), capable of making simultaneous measurements. Each arm has two filters, for a total of eight photometric bands. These simultaneous optical and infrared observations allow for the determination of the GRB's photometric redshift from the short-wavelength dropout' caused by the opacity of line-of-sight hydrogen in the intergalactic medium. Second, the camera will be mounted on a **dedicated, fully automated** telescope with quick-response capabilities. Third, the hosting Observatorio Astronomico Nacional of UNAM, located on the Sierra de San Pedro Martir in Baja California, Mexico, is a premiere astronomical site with exceptional seeing quality ( $\leq 0.8$  arcsec), dark skies, and a large number of dark



RATIR's original mechanical design. Incoming light first passes through the visible box, which consists of two dichroics and two CCD cameras with integrated filter wheels. Next, a warm optics box serves as the infrared re-imaging camera. Finally, the light enters the cryostat/dewar, which houses the two cryogenic H2RG infrared detectors, SIDE-CAR ASICs, and JADE Card readout electronics. Struts will provide support between the instrument and telescope.



*One concept for a long-duration human habitation system operating at the Earth-Moon L1 or L2 venue is shown here, shortly after an advanced robotic surface rover has been dispatched to the lunar surface. John Frassanito & Associates*

nights, thus increasing the number of detectable Swift afterglows.

RATIR makes use of existing technology and experience at GSFC, specifically near-infrared camera heritage from projects including Spitzer, HST/WFC3, and JWST. Like JWST, the two near-infrared detectors being used are Teledyne's 2048 x 2048 pixel H2RG arrays and readout will be performed using the SIDECAR (System Image, Digitizing, Enhancing, Controlling, and Retrieving) ASICs (Application-Specific Integrated Circuits).

The project is now in the final stages of construction, with all instrument parts manufactured, assembled, and aligned. A. Kutyrav, D. Rapchun, and O. Fox have tested all components of the camera, including the optics, focus stages, and detector performance. These tests show that all components operate as designed, with detector read noise at ~15 electrons RMS and dark current at 0.1 electron/second. Collaborators at UC Berkeley are implementing their Remote Telescope Software (RTS2) to control the infrared instrument's stages, detectors, and temperature monitors in conjunction with the greater telescope control system. When completed, the infrared camera will be integrated with the visible camera already completed

by Berkeley. RATIR is currently scheduled for commissioning in Spring 2012.

### **Human Operations Beyond Low-Earth Orbit to Assemble and Upgrade Large Optical Systems**

NASA's human space flight program, although with continuing significant uncertainty in its goals and priorities, consistently identifies operations in free space beyond low-Earth orbit (LEO) as a priority. Whether as a staging site for long-duration voyages beyond the Earth-Moon system, supporting human and robotic exploration of the lunar surface, or advancing technologies developed on the International Space Station (ISS), continued human operations in free space have been recommended to NASA for decades as a major enabling capability.

Dr. Harley Thronson continues to lead a small working group of scientists and engineers at Goddard, other NASA centers, and in industry, which has for several years been developing concepts for how equipment and facilities developed for human space flight might be used to achieve other goals. Such work has a long history at Goddard: In the early 1970s, Frank

Cepollina and colleagues persisted in advocating that the space shuttle be adapted to service and upgrade satellites in LEO. This was almost two decades before Cepollina's team used the shuttle to rescue NASA's premier astronomical observatory. Vision and perseverance eventually pays off!

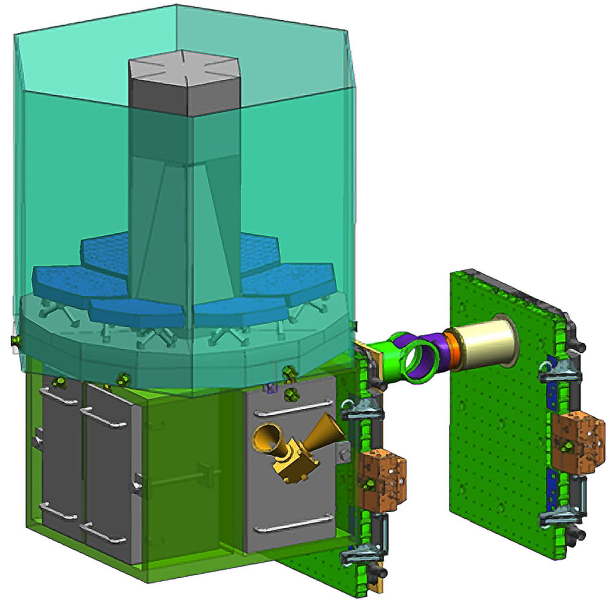
A few years ago, Thronson and his team assessed a concept that used a pair of launch vehicles then under development by the erstwhile Constellation Program. The goal was a mission to take astronauts to the Earth-Moon L1 venue for a two-week upgrade or rescue of a post-JWST observatory in the mid-2020s.

Currently, Thronson's team took on the more ambitious task of designing a long-duration human habitation system for either the L1 or L2 Earth-Moon location. Its primary purpose would be to develop capabilities necessary for safe and comfortable human operations beyond LEO in the 2020s. A major goal for this habitat—dubbed a “Gateway” by its designers—is to support lunar surface operations, either with astronauts or with robots. However, in addition, the capability to repair, assemble and upgrade complex science facilities, including large optical systems, is also under consideration.

### ISS as a Testbed for Future Complex Optical Systems

Large and complex space optical systems that may be launched in the 2020s and 2030s will be necessarily much larger than this decade's James Webb Space Telescope. It is likely, therefore, that such missions will require assembly on orbit and may, in addition, be enhanced by subsequent upgrade and servicing. However, whether such challenging tasks are carried out via robots or astronauts—or a combination of both—the required capabilities do not now exist.

Drs. Harley Thronson and Ken Carpenter are leading a small group of GSFC scientists and engineers that is working with colleagues at the Jet Propulsion Laboratory and NASA Johnson Space Center to assess the International Space Station (ISS) as a long-term testbed to develop the capabilities to use astronauts and robots to enable future very large optics. The Optical Testbed and Integration on ISS Experiment (OpTIIX) entered Phase A study on De-



*The Optical Testbed and Integration on ISS Experiment (OpTIIX) concept is intended to be a 1.4m optical system that will retire the risk of key elements of the robotic assembly and upgrade of future very large telescopes in space. NASA GSFC has overall responsibility for the imaging camera housed within one of the gray orbital replacement units at the base of the segmented telescope assembly.*

ember 1, 2011, and is expected to complete Phase B engineering design at the end of FY2012. The primary goal of OpTIIX, currently proposed for launch to ISS at the end of 2014, is to retire technical risk in complex robotic assembly in space before the 2020 NRC Decadal Survey.

Although significant design work still needs to be carried out, the basic notion is to launch to ISS the components of a modular optical system, including a basic control system and instrument. Robots would then be used to assemble, test and upgrade the system over a few years. The team intends also to explore whether purely autonomous deployment/assembly would be more cost-effective than using external human or robotic agents.

The resulting optical system on ISS would be capable of very limited observations, at least at the start. Even so, the knowledge and experience gained by attempting the construction and servicing of large, precise structures will be essential in enabling very ambitious optical systems in space in future decades.



## 2011 Education and Public Outreach Highlights of NASA's Astrophysics Science Division

It has been an exciting year for ASD's Education and Public Outreach. Despite some personnel changes, our team continued the crucial work of making the Division's astrophysics research and missions exciting and accessible to students, educators, and the general public. We have extensive E/PO projects that align with the Physics of the Cosmos (PCOS) and Cosmic Origins (COR) program offices, and also support NASA astrophysics missions, including Astro-H, GEMS, NICER, JWST, Suzaku, and HEASARC. Additionally, our team leads several grant-funded E/PO projects. Dr. James Lochner (CRESST/USRA) was the ASD EPO Lead until April 2011, when he left for a two-year detail to NASA HQ. Since April, Dr. Amber Straughn (GSFC-665) has been the civil servant

POC for the team, Dr. Koji Mukai (CRESST/USRA) the Acting Lead and Missions and Grants Lead, and Dr. Barbara Mattson (CRESST/USRA) the PCOS/COR Lead. Our team has accomplished much in the past year; here we present some of the highlights.

Two of our team members received prestigious awards in 2011. Sara Mitchell (Syneren Technologies) received an Exceptional Public Service Medal as part of the 2011 NASA Honor Award. Sarah Eyer mann (Syneren Technologies) received the Robert H. Goddard Award for Exceptional Achievement in Outreach for her involvement in the Afterschool Universe program.

This year, our team completed the major task of developing and beginning implementation of the



*More than 3,000 middle-school students gather to learn about JWST at the Sept. 2011 American Institute of Aeronautics and Astronautics meeting in Long Beach, Calif. This was the first time all the major JWST partners (Goddard, STScI, and Northrop Grumman) participated in a joint outreach booth.*

EPO plan for Physics of the Cosmos and Cosmic Origins. This effort was led by Lochner and Mattson. The plan maps out the E/PO efforts for PCOS and COR through FY2016, representing a broad portfolio of activities with programs for all audiences: formal education, informal education and outreach. In addition to continuing implementation of some of our very successful programs, such as *Big Explosions and Strong Gravity* and *Blueshift*, the plan outlines several exciting new programs that are currently being developed.

The *Afterschool Universe* (AU; PI Anita Krishnamurthi (Afterschool Alliance)) program had another successful year, now having certified many trainers who are in turn running training workshops around the country themselves. AU is an out-of-school time astronomy program for middle-school students. For the first half of 2011, Mitchell and Eyermann performed extensive follow-up to a large train-the-trainer event they conducted in Dec. 2010. In July, Sarah and Sara conducted an intensive two-day training workshop at Goddard for AU. The workshop drew 44 participants total, many from local organizations as well as attendees from Texas, New York, Indiana, and other states. In addition to the workshops, the AU program also has a video component. Sarah and Sara have recorded, edited, and released a total of ten videos featuring activities from the program. The videos were released on YouTube and the Goddard SVS website.

*Family Science Night*, a two-hour program for middle school students and their families that was piloted at the GSFC Visitor's Center in 2010, moved into its final year in 2011 with the program disseminated to other facilitators around the country. In July, Mitchell co-facilitated four 90-minute workshops about the Family Science Night program at the Department of Education's 21st Century Community Learning Centers Summer Institute in National Harbor, Maryland. The workshops were at capacity and drew interested potential partners from around the country.

Also in July, Eyermann, Mattson, Mitchell, and intern Faith Tucker presented workshops for several hundred visiting teachers in the Education Office's PA3 program. The workshops covered spectroscopes and the composition of the universe. JWST also had activities and hands-on demos at this event. Additionally, Tucker and Mattson presented a three-hour workshop to teachers at the Goddard Education Re-

source Center on "Your Cosmic Connection to the Elements" as part of the ERC's Summer of Innovation programming for teachers.

The JWST E/PO team saw the successful completion in 2011 of the first year's partnership with the RealWorld/InWorld Engineering Design Challenge (partnering with the National Institute of Aerospace, USA Today, and LearnIt TeachIt) for 9–12 grade students. In the Real World challenge, the students use the engineering design process to solve a real-life engineering problem. Selected RealWorld teams are mentored InWorld by college engineering students in a virtual world setting. Over 700 students participated in the 2010–2011 school year. Due to the success of the first-year partnership, JWST continued for a second year with RWIW, with the program expanded to junior high school students as well. Throughout the year, GSFC scientists and engineers presented to students InWorld. Todd Toth (GSFC Ed. Office/IPA), Maggie Masetti (Adnet), and Straughn were partners in this program. In addition to RWIW, the JWST E/PO team also helped coordinate and participate in educational events surrounding the JWST 0Full Scale Model at Baltimore's Inner Harbor, and numerous other outreach events across the country. JWST continues to have a significant social media presence, with almost 24,000 Facebook "likes," 19,000 Twitter followers, and 180,000 total YouTube video views.

ASD's social media presence, led by Barbara Mattson, continues to expand and attract new followers. Innovative use of Twitter, Facebook, and NASA Blueshift (podcast + blog) have taken the E/PO work of the Division to broad, diverse audiences. These different outlets are coordinated and utilized in many ways, including contests with astrophysics E/PO-themed giveaways. Just this year, our Facebook page has grown from 2,500 to > 9,500 "likes," and Twitter followers from 310 to > 2,400. More than being just the Division blog, Blueshift continues to have a loyal following due to its unique content. For example, in May, Mitchell and Masetti hosted a filming team from the food-humor blog "Fancy Fast Food" at Goddard. They interviewed a variety of Goddard employees about their work and cooked a space-themed meal in the Building 34 kitchen. In July, Blueshift coordinated the release of a video and accompanying social media content from the collaboration. The project was also featured in *Goddard View*.

## HEASARC Education and Public Outreach

The HEASARC E/PO program continues to fulfill its mission of bringing high-energy astronomy and cosmology to teachers and their students. The E/PO program was led by Dr. Jim Lochner (USRA) until May 2011, when he left for a 2-year detail at NASA Headquarters; in his absence, Dr. Barbara Mattson (CRESST/USRA) now leads the program.

In 2011, the HEASARC continued to distribute the Cosmic Times materials through educator workshops at local, regional, and national teacher conferences. Notably, Lochner presented the materials at the Biennial NASA Educator Resource Center (ERC) Network meeting. The NASA ERCs distribute NASA resources across the country, and the leaders of these centers often run their own workshops on NASA materials. Presenting in this venue ensured that the ERC directors are well versed in all that Cosmic Times has to offer.

The 2010 evaluation of the “New Media for Cosmic Times” project revealed that the most significant learning opportunities occur when students are allowed to produce their own videos rather than watching other student-produced works. In response to this, Mattson is collaborating with two area high school teachers to create a lesson plan entitled “Universe Mash-up,” which will walk teachers through using media clips and images to help their students create short video or audio pieces related to Cosmic Times topics.

Science updates to the Imagine the Universe! web pages continued throughout 2011. Under the supervision of Mattson and Lochner, intern Kate Carroll (UMD) revised about half of the science pages, incorporating input from experts within the ASD.

As part of his Education and Public Outreach for Earth and Space Sciences (EPOESS) grant, Lochner, with the assistance of Meredith Gibb (Syneren Technologies), produced in 2011 the 15th edition of the Imagine the Universe! DVD-ROM, featuring the websites for Imagine and StarChild as well as the 2010 collection of Astronomy Pictures of the Day. The guest website on the 15th edition DVD was a selection of



*Cover of the 15th edition of the Imagine the Universe! DVD-ROM*

educational pages from the James Webb Space Telescope website. In addition, Lochner worked with our evaluator, Dr. Allyson Walker (Cornerstone Evaluation Associates), to develop a survey for the users of the 15th edition DVD. This survey explores in detail how DVD recipients use the resources on the DVD; survey responses will be solicited through early 2012.

Mattson took over as PI on Lochner’s EPOESS grant while he is on detail at NASA HQ. In 2011, preparations began to produce the 16th edition of the Imagine the Universe! DVD-ROM. This 16th edition DVD will include the usual sites: Imagine the Universe!, StarChild, and the 2011 collection of Astronomy Picture of the Day. This time the guest site will be Afterschool Universe, an ASD E/PO initiative aimed at providers of afterschool programs. The guest site was chosen based on the 2010 DVD user survey, which suggested out-of-school-time activity providers as an additional audience to target in future editions of the DVD.



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**2011 Publications**

1. PSRs J0248+6021 and J2240+5832: Young pulsars in the northern Galactic plane. Discovery, timing, and gamma-ray observations. Theureau, G., Parent, D., Cognard, I., et al. *Astron. Astrophys.*, 525 A94 (2011), doi: 10.1051/0004-6361/201015317
2. K-shell photoionization of Na-like to Cl-like ions of Mg, Si, S, Ar, and Ca. Witthoeft, M.C.; Garcia, J.; Kallman, T.R., et al. *Astrophys. J. Suppl. Ser.* 192 (2011) 7 doi: 10.1088/0067-0049/192/1/7
3. Hubble Space Telescope WFC3 early release science: Emission-line galaxies from infrared grism observations. Straughn, A.N., Kuntschner, H., Kummel, M., et al. *Astron. J.* 141 (2011) 14, doi: 10.1088/0004-6256/141/1/14
4. Fermi-LAT search for pulsar wind nebulae around gamma-ray pulsars. Ackermann, M., Ajello, M., Baldini, L., et al. *Astrophys. J.* 726 (2011) 35 doi: 10.1088/0004-637X/726/1/35
5. Atomic decay data for modeling the Al K lines. Palmeri, P., Quinet, P., Mendoza, C., et al. *Astron. Astrophys.* 525 A59 (2011), doi: 10.1051/0004-6361/201014779
6. First radar observations in the vicinity of the plasmopause of pulsed ionospheric flows generated by bursty bulk flows. Frissell, N.A., Baker, J.B.H., Ruohoniemi, J.M., et al. *Geophys. Res. Lett.* 38 (2011) L01103, doi: 10.1029/2010GL045857
7. XMM-Newton observations of MBM 12: More constraints on the solar wind charge exchange and local bubble emissions. Koutroumpa, D., Smith, R.K., Edgar, R.J., et al. *Astrophys. J.* 726 (2011) 91, doi: 10.1088/0004-637X/726/2/91
8. System parameters, transit times, and secondary eclipse constraints of the exoplanet systems HAT-P-4, TrES-2, TrES-3, and WASP-3 from the NASA EPOXI mission of opportunity. Christiansen, J.L., Ballard, S., Charbonneau, D., et al. *Astrophys. J.* 726 (2011) 94, doi: 10.1088/0004-637X/726/2/94
9. Constraints on the cosmic-ray density gradient beyond the solar circle from Fermi gamma-ray observations of the third galactic quadrant. Ackermann, M., Ajello, M., Baldini, L., et al. *Astrophys. J.* 726 (2011) 81, doi: 10.1088/0004-637X/726/2/81
10. Three millisecond pulsars in Fermi LAT unassociated bright sources. Ransom, S.M., Ray, P.S., Camilo, F., et al. *Astrophys. J. Lett.* 727 (2011) L16, doi: 10.1088/2041-8205/727/1/L16
11. Erratum: "Disentangling the origin and heating mechanism of supernova dust: Late-time Spitzer spectroscopy of the Type II In SN 2005ip" (2010, ApJ, 725, 1768). Fox, O.D., Chevalier, R.A., Dwek, E., et al. *Astrophys. J.* 727 (2011) 61, doi: 10.1088/0004-637X/727/1/61
12. The hot horizontal-branch stars in  $\omega$  Centauri. Moehler, S., Dreizler, S., Lanz, T., et al. *Astron. Astrophys.* 526 A136 (2011), doi: 10.1051/0004-6361/201015020
13. The abundance of iron-peak elements and the dust composition in  $\eta$  Carinae: Manganese. Bautista, M.A., Melendez, M., Hartman, H., et al. *Mon. Not. Roy. Astron. Soc.* 410 (2011) 2643, doi: 10.1111/j.1365-2966.2010.17642.x
14. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Sky maps, systematic errors, and basic results. Jarosik, N., Bennett, C.L., Dunkley, J., et al. *Astrophys. J. Suppl. Ser.* 192 (2011) 14, doi: 10.1088/0067-0049/192/2/14

15. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Galactic foreground emission. Gold, B., Odegard, N., Weiland, J.L., et al. *Astrophys. J. Suppl. Ser.* 192 (2011) 15, doi: 10.1088/0067-0049/192/2/15
16. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Power spectra and WMAP-derived parameters. Larson, D., Dunkley, J., Hinshaw, G., et al. *Astrophys. J. Suppl. Ser.* 192 (2011) 16, doi: 10.1088/0067-0049/192/2/16
17. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Are there cosmic microwave background anomalies? Bennett, C.L., Hill, R.S., Hinshaw, G., et al. *Astrophys. J. Suppl. Ser.* 192 (2011) 17, doi: 10.1088/0067-0049/192/2/17
18. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Cosmological interpretation. Komatsu, E., Smith, K. M., Dunkley, J., et al. *Astrophys. J. Suppl. Ser.* 192 (2011) 18
19. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Planets and celestial calibration sources. Weiland, J.L., Odegard, N., Hill, R.S., et al. *Astrophys. J. Suppl. Ser.* 192 (2011) 19, doi: 10.1088/0067-0049/192/2/19
20. Measuring the sizes, shapes, surface features and rotations of solar system objects with interferometry. Li, J.Y., Kuchner, M.J., Allen, R.J., et al. *Icarus* 211 (2011) 1007, doi: 10.1016/j.icarus.2010.11.017
21. Electron-impact excitation of H-like Cr, Mn, Fe, Co, and Ni for applications in modeling X-ray astrophysical sources. Malespin, C., Ballance, C.P., Pindzola, M.S., et al. *Astron. Astrophys.* 526 A115 (2011), doi: 10.1051/0004-6361/201016132
22. When a standard candle flickers. Wilson-Hodge, C.A., Cherry, M.L., Case, G.L., et al. *Astrophys. J. Lett.* 727 (2011) L40, doi: 10.1088/2041-8205/727/2/L40
23. The supersoft X-ray phase of Nova RS Ophiuchi 2006. Osborne, J.P., Page, K.L., Beardmore, A.P., et al. *Astrophys. J.* 727 (2011) 124, doi: 10.1088/0004-637X/727/2/124
24. The origin of dust in the early universe: Probing the star formation history of galaxies by their dust content. Dwek, E., and Cherchneff, I. *Astrophys. J.* 727 (2011) 63, doi: 10.1088/0004-637X/727/2/63
25. The lack of diffuse, non-thermal hard X-ray emission in the Coma Cluster: the Swift Burst Alert Telescope's eye view. Wik, D.R., Sarazin, C.L., Finoguenov, A., et al. *Astrophys. J.* 727 (2011) 119, doi: 10.1088/0004-637X/727/2/119
26. Search for gravitational waves associated with the August 2006 timing glitch of the Vela pulsar. Abadie, J., Abbott, B.P., Abbott, R., et al. *Phys. Rev. D* 83, 042001 (2011), doi: 10.1103/PhysRevD.83.042001
27. On the volatile enrichments and heavy element content in HD189733b. Mousis, O., Lunine, J.I., Petit, J.M., et al. *Astrophys. J.* 727 (2011) 77, doi: 10.1088/0004-637X/727/2/77
28. Insights into the high-energy gamma-ray emission of Markarian 501 from extensive multifrequency observations in the Fermi era. Abdo, A.A., Ackermann, M., Ajello, M., et al. *Astrophys. J.* 727 (2011) 129, doi: 10.1088/0004-637X/727/2/129
29. Three-year Swift-BAT survey of active galactic nuclei: Reconciling theory and observations? Burlon, D., Ajello, M., Greiner, J., et al. *Astrophys. J.* 728 (2011) 58, doi: 10.1088/0004-637X/728/1/58

30. Polycyclic aromatic hydrocarbon emission within Ly $\alpha$  blobs. Colbert, J.W., Scarlata, C., Teplitz, H., et al. *Astrophys. J.* 728 (2011) 59, doi: 10.1088/0004-637X/728/1/59
31. Gamma-ray flares from the Crab Nebula. Abdo, A.A., Ackermann, M., Ajello, M., et al. *Science* 331 (2011) 739, doi: 10.1126/science.1199705
32. Radio and gamma-ray constraints on the emission geometry and birthplace of PSR J2043+2740. Noutsos, A., Abdo, A.A., Ackermann, M., et al. *Astrophys. J.* 728 (2011) 77, doi: 10.1088/0004-637X/728/2/77
33. Submillimetre galaxies reside in dark matter haloes with masses greater than  $3 \times 10^{11}$  solar masses. Amblard, A., Cooray, A., Serra, P., et al. *Nature* 470 (2011) 510, doi: 10.1038/nature09771
34. Erratum: “The first Fermi Large Area Telescope catalog of gamma-ray pulsars” (2010, ApJS, 187, 460). *Astrophys. J. Suppl. Ser.* 193 (2011) 22, doi: 10.1088/0067-0049/193/1/22
35. Suzaku observation of the LINER NGC 4102. Gonzalez-Martin, O., Papadakis, I., Braitto, V., et al. *Astron. Astrophys.* 527 A142 (2011), doi: 10.1051/0004-6361/201016097
36. Discovery of the nearby long, soft GRB 100316D with an associated supernova. Starling, R.L.C., Wiersema, K., Levan, A.J., et al. *Mon. Not. Roy. Astron. Soc.* 411 (2011) 2792, doi: 10.1111/j.1365-2966.2010.17879.x
37. Uncovering obscured active galactic nuclei in homogeneously selected samples of Seyfert 2 galaxies. LaMassa, S.M., Heckman, T.M., Ptak, A., et al. *Astrophys. J.* 729 (2011) 52, doi: 10.1088/0004-637X/729/1/52
38. The Atacama Cosmology Telescope: A measurement of the cosmic microwave background power spectrum at 148 and 218 GHz from the 2008 Southern survey. Das, S., Marriage, T.A., Ade, P.A.R., et al. *Astrophys. J.* 729 (2011) 62, doi: 10.1088/0004-637X/729/1/62
39. Views from EPOXI: Colors in our solar system as an analog for extrasolar planets. Crow, C.A., McFadden, L.A., Robinson, T., et al. *Astrophys. J.* 729 (2011) 130, doi: 10.1088/0004-637X/729/2/130
40. The Gemini NICI planet-finding campaign: Discovery of a substellar L dwarf companion to the nearby young M dwarf Cd–35 2722. Wahhaj, Z., Liu, M.C., Biller, B.A., et al. *Astrophys. J.* 729 (2011) 139, doi: 10.1088/0004-637X/729/2/139
41. Detection of a spectral break in the extra hard component of GRB 090926A. Ackermann, M., Ajello, M., Asano, K., et al. *Astrophys. J.* 729 (2011) 114, doi: 10.1088/0004-637X/729/2/114
42. Possible charge-exchange X-ray emission in the Cygnus Loop detected with Suzaku. Katsuda, S., Tsunemi, H., Mori, K., et al. *Astrophys. J.* 730 (2011) 24, doi: 10.1088/0004-637X/730/1/24
43. The Swift serendipitous survey in deep XRT GRB fields (SwiftFT). I. The X-ray catalog and number counts. Puccetti, S., Capalbi, M., Giommi, P., et al. *Astron. Astrophys.* 528 A122 (2011), doi: 10.1051/0004-6361/201015560
44. The Hubble Space Telescope Wide Field Camera 3 early release science data: Panchromatic faint object counts for 0.2–2  $\mu\text{m}$  wavelength. Windhorst, R.A., Cohen, S.H., Hathi, N.P., et al. *Astrophys. J. Suppl. Ser.* 193 (2011) 27, doi: 10.1088/0067-0049/193/2/27

45. Recent advances in the determination of atomic parameters for modeling K lines in cosmically abundant elements Quinet, P., Palmeri, P., Mendoza, C., et al. *J. Electron Spectrosc. Relat. Phenom.* 184 (2011) 170, doi: 10.1016/j.elspec.2010.12.027
46. A new frequency-luminosity relation for long gamma-ray bursts? Ukwatta, T.N., Dhuga, K.S., Morris, D.C., et al. *Mon. Not. Roy. Astron. Soc.* 412 (2011) 875, doi: 10.1111/j.1365-2966.2010.17944.x
47. The recent star formation in NGC 6822: An ultraviolet study. Efremova, B.V., Bianchi, L., Thilker, D.A., et al. *Astrophys. J.* 730 (2011) 88, doi: 10.1088/0004-637X/730/2/88
48. The first Fermi multifrequency campaign on BL Lacertae: Characterizing the low-activity state of the eponymous blazar. Abdo, A.A., Ackermann, M., Ajello, M., et al. *Astrophys. J.* 730 (2011) 101, doi: 10.1088/0004-637X/730/2/101
49. The Arcade 2 instrument. Singal, J., Fixsen, D.J., Kogut, A., et al. *Astrophys. J.* 730 (2011) 138, doi: 10.1088/0004-637X/730/2/138
50. PTF 10fq: A luminous red nova in the spiral galaxy Messier 99. Kasliwal, M.M., Kulkarni, S.R., Arcavi, I., et al. *Astrophys. J.* 730 (2011) 134, doi: 10.1088/0004-637X/730/2/134
51. Erratum: "Multi-wavelength observations of the flaring gamma-ray blazar 3C 66a in 2008 October" (2011, ApJ, 726, 43). Abdo, A.A., Ackermann, M., Ajello, M., et al. *Astrophys. J.* 731 (2011) 77, doi: 10.1088/0004-637X/731/1/77
52. Modeling the oxygen K absorption in the interstellar medium: An XMM-Newton view of Sco X-1. Garcia, J., Ramirez, J.M., Kallman, T.R., et al. *Astrophys. J. Lett.* 731 (2011) L15, doi: 10.1088/2041-8205/731/1/L15
53. Large-scale shock-ionized and photoionized gas in M83: The impact of star formation. Hong, S., Calzetti, D., Dopita, M.A., et al. *Astrophys. J.* 731 (2011) 45, doi: 10.1088/0004-637X/731/1/45
54. Detection of brown dwarf like objects in the core of NGC 3603. Spezzi, L., Beccari, G., De Marchi, G., et al. *Astrophys. J.* 731 (2011) 1, doi: 10.1088/0004-637X/731/1/1
55. A fast X-ray disk wind in the transient pulsar IGR J17480-2446 in Terzan 5. Miller, J.M., Maitra, D., Cackett, E.M., et al. *Astrophys. J. Lett.* 731 (2011) L7, doi: 10.1088/2041-8205/731/1/L7
56. Probing the nature of short Swift bursts via deep INTEGRAL monitoring of GRB 050925. Sakamoto, T., Barbier, L., Barthelmy, S.D., et al. *J. Adv. Space Res.* 47 (2011) 1346, doi: 10.1016/j.asr.2010.08.004
57. The Atacama Cosmology Telescope: Extragalactic sources at 148 GHz in the 2008 survey. Marriage, T.A., Juin, J.B., Lin, Y.T., et al. *Astrophys. J.* 731 (2011) 100, doi: 10.1088/0004-637X/731/2/100
58. The first gamma-ray outburst of a narrow-line Seyfert 1 galaxy: The case of PMN J0948+0022 in 2010 July. Foschini, L., Ghisellini, G., Kovalev, Y.Y., et al. *Mon. Not. Roy. Astron. Soc.* 413 (2011) 1671, doi: 10.1111/j.1365-2966.2011.18240.x
59. HerMES: SPIRE emission from radio-selected active galactic nuclei. Seymour, N., Symeonidis, M., Page, M.J., et al. *Mon. Not. Roy. Astron. Soc.* 413 (2011) 1777, doi: 10.1111/j.1365-2966.2011.18253.x
60. A Herschel resolved far-infrared dust ring around HD 207129. Marshall, J.P., Lohne, T., Montesinos, B., et al. *Astron. Astrophys.* 529 A117 (2011), doi: 10.1051/0004-6361/201116673



61. The Atacama Cosmology Telescope: Cosmology from galaxy clusters detected via the Sunyaev-Zel'dovich effect. Sehgal, N., Trac, H., Acquaviva, V., et al. *Astrophys. J.* 732 (2011), doi: 10.1088/0004-637X/732/1/44
62. Discovery of two millisecond pulsars in Fermi sources with the Nançay radio telescope. Cognard, I., Guillemot, L., Johnson, T.J., et al. *Astrophys. J.* 732 (2011) 47, doi: 10.1088/0004-637X/732/1/47
63. A search for additional planets in five of the exoplanetary systems studied by the NASA EPOXI mission. Ballard, S., Christiansen, J.L., Charbonneau, D., et al. *Astrophys. J.* 732 (2011) 41, doi: 10.1088/0004-637X/732/1/41
64. Electromagnetic counterparts to black hole mergers. Schnittman, J.D. *Class. Quantum Gravity* 28 (2011) 094021, doi: 10.1088/0264-9381/28/9/094021
65. Wide-field Infrared Survey Explorer observations of young stellar objects in the Western Circinus molecular cloud. Liu, W.M., Padgett, D.L., Leisawitz, D., et al. *Astrophys. J. Lett.* 733 (2011) L2, doi: 10.1088/2041-8205/733/1/L2
66. Fermi Large Area Telescope detection of bright gamma-ray outbursts from the peculiar quasar 4C +21.35. Tanaka, Y.T., Stawarz, Ł., Thompson, D.J., et al. *Astrophys. J.* 733 (2011) 19, doi: 10.1088/0004-637X/733/1/19
67. The rapid X-ray variability of NGC 4051. Vaughan, S., Uttley, P., Pounds, K.A., et al. *Mon. Not. Roy. Astron. Soc.* 413 (2011) 2489, doi: 10.1111/j.1365-2966.2011.18319.x
68. Precise gamma-ray timing and radio observations of 17 Fermi gamma-ray pulsars. Ray, P.S., Kerr, M., Parent, D., et al. *Astrophys. J. Suppl. Ser.* 194 (2011) 17, doi: 10.1088/0067-0049/194/2/17
69. Earth as an extrasolar planet: Earth model validation using EPOXI Earth observations. Robinson, T.D., Meadows, V.S., Crisp, D., et al. *Astrobiology* 11 (2011) 393, doi: 10.1089/ast.2011.0642
70. Discovery of millisecond pulsars in radio searches of southern Fermi Large Area Telescope sources. Keith, M.J., Johnston, S., Ray, P.S., et al. *Mon. Not. Roy. Astron. Soc.* 414 (2011) 1292, doi: 10.1111/j.1365-2966.2011.18464.x
71. Development of embedded heatsinking layers for compact arrays of X-Ray TES microcalorimeters. Finkbeiner, F.M., Bailey, C.N., Bandler, S.R., et al. *IEEE Trans. Appl. Supercond.* 21 (2011) 223, doi: 10.1109/TASC.2010.2091237
72. Development of a real-time pulse processing algorithm for TES-based X-Ray microcalorimeters. Tan, H., Hennig, W., Warburton, W.K., et al. *IEEE Trans. Appl. Supercond.* 21 (2011) 276, doi: 10.1109/TASC.2010.2082473
73. Strong new constraints on the extragalactic background light in the near- to mid-infrared. Orr, M.R., Krennrich, F., Dwek, E. *Astrophys. J.* 733 (2011) 77, doi: 10.1088/0004-637X/733/2/77
74. Search for gravitational waves from binary black hole inspiral, merger, and ringdown. Abadie, J., Abbott, B.P., Abbott, R., et al. *Phys. Rev. D.* 83 (2011) 122005, doi: 10.1103/PhysRevD.83.122005
75. The radio-2 mm spectral index of the Crab Nebula measured with GISMO. Arendt, R.G., George, J.V., Staguhn, J.G., et al. *Astrophys. J.* 734 (2011) 54, doi: 10.1088/0004-637X/734/1/54

76. Observations of the young supernova remnant RX J1713.7-3946 with the Fermi Large Area Telescope. Abdo, A.A., Ackermann, M., Ajello, M., et al. *Astrophys. J.* 734 (2011) 28, doi: 10.1088/0004-637X/734/1/28
77. Interpretation of the Arcade 2 absolute sky brightness measurement. Seiffert, M., Fixsen, D.J., Kogut, A., et al. *Astrophys. J.* 734 (2011) 6, doi: 10.1088/0004-637X/734/1/6
78. Exozodiacal dust levels for nearby main-sequence stars: A survey with the Keck Interferometer Nuller. Millan-Gabet, R., Serabyn, E., Mennesson, B., et al. *Astrophys. J.* 734 (2011) 67, doi: 10.1088/0004-637X/734/1/67
79. Arcade 2 observations of galactic radio emission. Kogut, A., Fixsen, D.J., Levin, S.M., et al. *Astrophys. J.* 734 (2011) 4, doi: 10.1088/0004-637X/734/1/4
80. Arcade 2 measurement of the absolute sky brightness at 3-90 GHz. Fixsen, D.J., Kogut, A., Levin, S., et al. *Astrophys. J.* 734 (2011) 5, doi: 10.1088/0004-637X/734/1/5
81. Search for gravitational wave bursts from six magnetars. Abadie, J., Abbott, B.P., Abbott, R., et al. *Astrophys. J. Lett.* 734 (2011) L35, doi: 10.1088/2041-8205/734/2/L35
82. Fermi Large Area Telescope observations of two gamma-ray emission components from the quiescent sun. Abdo, A.A., Ackermann, M., Ajello, M., et al. *Astrophys. J.* 734 (2011) 116, doi: 10.1088/0004-637X/734/2/116
83. Detection of high-energy gamma-ray emission during the X-ray flaring activity in GRB 100728A. Abdo, A.A., Ackermann, M., Ajello, M., *Astrophys. J. Lett.* 734 (2011) L27, doi: 10.1088/2041-8205/734/2/L27
84. X-ray illumination of the ejecta of Supernova 1987A. Larsson, J., Fransson, C., Ostlin, G., et al. *Nature* 474 (2011) 484, doi: 10.1038/nature10090
85. The second Swift Burst Alert Telescope gamma-ray burst catalog. Sakamoto, T., Barthelmy, S.D., Baumgartner, W.H., *Astrophys. J. Suppl. Ser.* 195 (2011) 2, doi: 10.1088/0067-0049/195/1/2
86. The problem of inertia in Friedmann universes. Sultana, J., Kazanas, D. *Int. J. Mod. Phys. D* 20 (2011) 1205, doi: 10.1142/S0218271811019384
87. The Primordial Inflation Explorer (PIXIE): A nulling polarimeter for cosmic microwave background observations. Kogut, A., Fixsen, D.J., Chuss, D.T., et al. *J. Cosmol. Astropart. Phys.* 7 (2011) 025, doi: 10.1088/1475-7516/2011/07/025
88. Hubble and Spitzer space telescope observations of the debris disk around the nearby K dwarf HD 92945. Golimowski, D.A., Krist, J.E., Stapelfeldt, K.R., et al. *Astron. J.* 142 (2011) 30, doi: 10.1088/0004-6256/142/1/30
89. Heterogeneity in short gamma-ray bursts. Norris, J.P., Gehrels, N., Scargle, J.D. *Astrophys. J.* 735 (2011) 23, doi: 10.1088/0004-637X/735/1/23
90. Evidence for dark energy from the cosmic microwave background alone using the Atacama Cosmology Telescope lensing measurements. Sherwin, B.D., Dunkley, J., Das, S., et al. *Phys. Rev. Lett.* 107 (2011) 021302, doi: 10.1103/PhysRevLett.107.021302

91. Detection of the power spectrum of cosmic microwave background lensing by the Atacama Cosmology Telescope. Das, S., Sherwin, B.D., Aguirre, P., et al. *Phys. Rev. Lett.* 107 (2011) 021301, doi: 10.1103/PhysRevLett.107.021301
92. The Spitzer-Wise survey of the ecliptic poles. Jarrett, T.H., Cohen, M., Masci, F., et al. *Astrophys. J.* 735 (2011) 112, doi: 10.1088/0004-637X/735/2/112
93. The origin of variability of the intermediate-mass black-hole ULX system HLX-1 in ESO 243-49. Lasota, J.P., Alexander, T., Dubus, G., et al. *Astrophys. J.* 735 (2011) 89, doi: 10.1088/0004-637X/735/2/89
94. Discovery and evolution of the new black hole candidate Swift J1539.2-6227 during its 2008 outburst. Krimm, H.A., Tomsick, J.A., Markwardt, C.B., et al. *Astrophys. J.* 735 (2011) 104, doi: 10.1088/0004-637X/735/2/104
95. The Atacama Cosmology Telescope: Detection of Sunyaev-Zel'dovich decrement in groups and clusters associated with luminous red galaxies. Hand, N., Appel, J.W., Battaglia, N., et al. *Astrophys. J.* 736 (2011) 39, doi: 10.1088/0004-637X/736/1/39
96. Measuring the optical properties of astrophysical dust analogues: Instrumentation and methods. Rinehart, S.A., Benford, D.J., Cataldo, G., et al. *Appl. Optics* 50 (2011) 4115, doi: 10.1364/AO.50.004115
97. Discovery of high-energy gamma-ray emission from the binary system PSR B1259-63/LS 2883 around periastron with Fermi. Abdo, A.A., Ackermann, M., Ajello, M., et al. *Astrophys. J. Lett.* 736 (2011) L11, doi: 10.1088/2041-8205/736/1/L11
98. Components of the extragalactic gamma-ray background. Stecker, F.W., Venters, T.M. *Astrophys. J.* 736 (2011) 40, doi: 10.1088/0004-637X/736/1/40
99. Astronomy: A census of the Carina complex. Gull, T. R. *Nature* 475 (2011) 460, doi:10.1038/475460a
100. The dust properties of two hot R Coronae Borealis stars and a Wolf-Rayet central star of a planetary nebula: In search of a possible link. Clayton, G.C., De Marco, O., Whitney, B.A., et al. *Astron. J.* 142 (2011) 54, doi: 10.1088/0004-6256/142/2/54
101. The dark current and hot pixel percentage of James Webb Space Telescope 5  $\mu\text{m}$  cutoff HgCdTe detector arrays as functions of temperature. Rauscher, B.J., Lindler, D.J., Mott, D.B., et al. *Publ. Astron. Soc. Pac.* 123 (2011) 953, doi: 10.1086/661663
102. Physical conditions of the interstellar medium of high-redshift, strongly lensed submillimetre galaxies from the Herschel-ATLAS. Valtchanov, I., Virdee, J., Ivison, R.J., et al. *Mon. Not. Roy. Astron. Soc.* 415 (2011) 3473, doi: 10.1111/j.1365-2966.2011.18959.x
103. Note: Vector reflectometry in a beam waveguide. Eimer, J.R., Bennett, C.L., Chuss, D.T., et al. *Rev. Sci. Instrum.* 82 (2011) 086101, doi: 10.1063/1.3622522
104. Real-time detection and rapid multiwavelength follow-up observations of a highly subluminous Type II-P supernova from the Palomar Transient Factory survey. Gal-Yam, A., Kasliwal, M.M., Arcavi, I., et al. *Astrophys. J.* 736 (2011) 159, doi: 10.1088/0004-637X/736/2/159
105. Probing the GC-LMXB connection in NGC 1399: A wide-field study with the Hubble Space Telescope and Chandra. Paolillo, M., Puzia, T.H., Goudfrooij, P., et al. *Astrophys. J.* 736 (2011) 90, doi: 10.1088/0004-637X/736/2/90

106. Polarized emission from SiO masers in IK Tauri. Cotton, W.D., Ragland, S., Danchi, W.C. *Astrophys. J.* 736 (2011) 96, doi: 10.1088/0004-637X/736/2/96
107. Fermi Large Area Telescope observations of Markarian 421: The missing piece of its spectral energy distribution. Abdo, A.A., Ackermann, M., Ajello, M., et al. *Astrophys. J.* 736 (2011) 131, doi: 10.1088/0004-637X/736/2/131
108. Far-ultraviolet number counts of field galaxies. Voyer, E.N., Gardner, J.P., Teplitz, H.I., et al. *Astrophys. J.* 736 (2011) 80, doi: 10.1088/0004-637X/736/2/80
109. A 5  $\mu\text{m}$  image of Beta Pictoris b at a sub-Jupiter projected separation: Evidence for a misalignment between the planet and the inner, warped disk. Currie, T., Thalmann, C., Matsumura, S., et al. *Astrophys. J. Lett.* 736 (2011) L33, doi: 10.1088/2041-8205/736/2/L33
110. Comparison of signals from gravitational wave detectors with instantaneous time-frequency maps. Stroer, A., Blackburn, L., Camp, J. *Class. Quantum Gravity* 28 (2011) 155001, doi: 10.1088/0264-9381/28/15/155001
111. A new TeV binary: The discovery of an orbital period in HESS J0632+057. Bongiorno, S.D., Falcone, A.D., Stroh, M., et al. *Astrophys. J. Lett.* 737 (2011) L11, doi: 10.1088/2041-8205/737/1/L11
112. Constraints on dark matter models from a Fermi LAT search for high-energy cosmic-ray electrons from the Sun. Ajello, M., Atwood, W.B., Baldini, L., et al. *Phys. Rev. D* 84 (2011) 032007, doi: 10.1103/PhysRevD.84.032007
113. Support for temporally varying behavior of the Pioneer anomaly from the extended Pioneer 10 and 11 doppler data sets. Turyshev, S.G., Toth, V.T., Ellis, J., et al. *Phys. Rev. Lett.* 107 (2011) 081103, doi: 10.1103/PhysRevLett.107.081103
114. Beating the spin-down limit on gravitational wave emission from the Vela pulsar. Abadie, J., Abbott, B.P., Abbott, R., et al. *Astrophys. J.* 737 (2011) 93, doi: 10.1088/0004-637X/737/2/93
115. Relativistic jet activity from the tidal disruption of a star by a massive black hole. Burrows, D.N., Kennea, J.A., Ghisellini, G., et al. *Nature* 476 (2011) 421, doi: 10.1038/nature10374
116. The Cosmic Origins Spectrograph: On-orbit instrument performance. Osterman, S., Green, J., Froning, C., et al. *Astrophys. Space Sci.* 335 (2011) 257, doi: 10.1007/s10509-011-0699-5
117. Simultaneous multi-wavelength campaign on PKS 2005-489 in a high state. Abramowski, A., Acero, F., Aharonian, F., et al. *Astron. Astrophys.* 533 A110 (2011), doi: 10.1051/0004-6361/201016170
118. New young star candidates in the Taurus-Auriga region as selected from the Wide-field Infrared Survey Explorer. Rebull, L.M., Koenig, X.P., Padgett, D.L., et al. *Astrophys. J. Suppl. Ser.* 196 (2011) 4, doi: 10.1088/0067-0049/196/1/4
119. K-shell photoionization of nickel ions using R-matrix. Witthoef, M.C., Bautista, M.A., Garcia, J., et al. *Astrophys. J. Suppl. Ser.* 196 (2011) 7, doi: 10.1088/0067-0049/196/1/7
120. A new limit on Planck scale Lorentz violation from gamma-ray burst polarization. Stecker, F.W. *Astropart Phys.* 35 (2011) 95, doi: 10.1016/j.astropartphys.2011.06.007
121. Uncovering the spectral energy distribution in active galaxies using high-ionization mid-infrared emission lines. Melendez, M., Kraemer, S.B., Weaver, K.A., Mushotzky, R.F. *Astrophys. J.* 738 (2011) 6, doi: 10.1088/0004-637X/738/1/6

122. Star and dust formation activities in AzTEC-3, a starburst galaxy at  $z=5.3$ . Dwek, E., Staguhn, J.G., Arendt, R.G., et al. *Astrophys. J.* 738 (2011) 36, doi: 10.1088/0004-637X/738/1/36
123. Sky localization of complete inspiral-merger-ringdown signals for nonspinning massive black hole binaries. McWilliams, S.T., Lang, R.N., Baker, J.G., Thorpe, J.I. *Phys. Rev. D* 84 (2011) 064003, doi: 10.1103/PhysRevD.84.064003
124. Herschel Detects a Massive Dust Reservoir in Supernova 1987A. Matsuura, M., Dwek, E., Meixner, M., et al. *Science* 333 (2011) 1258, doi: 10.1126/science.1205983
125. Fermi Large Area Telescope observations of the active galaxy 4C+55.17: Steady, hard gamma-ray emission and its implications. McConville, W., Ostorero, L., Moderski, R., et al. *Astrophys. J.* 738 (2011) 148, doi: 10.1088/0004-637X/738/2/148
126. Fermi and Swift gamma-ray burst afterglow population studies. Racusin, J.L., Oates, S.R., Schady, P., et al. *Astrophys. J.* 738 (2011) 138, doi: 10.1088/0004-637X/738/2/138
127. The Atacama Cosmology Telescope: Cosmological parameters from the 2008 power spectrum. Dunkley, J., Hlozek, R., Sievers, J., et al. *Astrophys. J.* 739 (2011) 52, doi: 10.1088/0004-637X/739/1/52
128. Star formation in 30 Doradus. De Marchi, G., Paresce, F., Panagia, N., et al. *Astrophys. J.* 739 (2011) 27, doi: 10.1088/0004-637X/739/1/27
129. Recovering Swift-XRT energy resolution through CCD charge trap mapping. Pagani, C., Beardmore, A.P., Abbey, A.F., et al. *Astron. Astrophys.* 534 A20 (2011), doi: 10.1051/0004-6361/201117660
130. Host galaxy properties of the Swift Bat ultra hard X-ray selected active galactic nucleus. Koss, M., Mushotzky, R., Veilleux, S., et al. *Astrophys. J.* 739 (2011) 57, doi: 10.1088/0004-637X/739/2/57
131. Development of tiled imaging CZT detectors for sensitive wide-field hard X-ray surveys to EXIST. Grindlay, J., Hong, J., Allen, B., et al. *Nucl. Instrum. Methods Phys. Res. Sect. A-Accel. Spectrom. Detect. Assoc. Equip.* 652 (2011) 671, doi: 10.1016/j.nima.2010.09.160
132. Mergers of black-hole binaries with aligned spins: Waveform characteristics. Kelly, B.J., Baker, J.G., Boggs, W.D., et al. *Phys. Rev. D* 84 (2011) 084009, doi: 10.1103/PhysRevD.84.084009
133. First detections of the [N II] 122  $\mu\text{m}$  line at high redshift: Demonstrating the utility of the line for studying galaxies in the early universe. Ferkinhoff, C., Brisbin, D., Nikola, T., et al. *Astrophys. J. Lett.* 740 (2011) L29, doi: 10.1088/2041-8205/740/1/L29
134. Burst and persistent emission properties during the recent active episode of the anomalous X-ray pulsar 1E 1841–045. Lin, L., Kouveliotou, C., Gogus, E., et al. *Astrophys. J. Lett.* 740 (2011) L16, doi: 10.1088/2041-8205/740/1/L16
135. A Very Large Array search For 5 GHz radio transients and variables at low galactic latitudes. Ofek, E.O., Frail, D.A., Breslauer, B., et al. *Astrophys. J.* 740 (2011) 65, doi: 10.1088/0004-637X/740/2/65
136. X-ray polarization signature of warm absorber winds in AGN. Dorodnitsyn, A., Kallman, T. *Astrophys. Space Sci.* 336 (2011) 245, doi: 10.1007/s10509-011-0656-3
137. X-ray flare candidates in short gamma-ray bursts. Margutti, R., Chincarini, G., Granot, J., et al. *Mon. Not. Roy. Astron. Soc.* 417 (2011) 2144, doi: 10.1111/j.1365-2966.2011.19397.x

138. Imaging X-ray Polarimeter for Solar Flares (IXPS). Hosack, M., Black, J.K., Deines-Jones, P., et al. *Exp. Astron.* 32 (2011) 101, doi: 10.1007/s10686-011-9254-1
139. DXL: A sounding rocket mission for the study of solar wind charge exchange and local hot bubble X-ray emission. Galeazzi, M., Chiao, M., Collier, M.R., et al. *Exp. Astron.* 32 (2011) 83, doi: 10.1007/s10686-011-9249-y
140. The radio/gamma-ray connection in active galactic nuclei in the era of the Fermi Large Area Telescope. Ackermann, M., Ajello, M., Allafort, A., et al. *Astrophys. J.* 741 (2011) 30, doi: 10.1088/0004-637X/741/1/30
141. Discovery and mass measurements of a cold, 10 earth mass planet and its host star. Muraki, Y., Han, C., Bennett, D.P., et al. *Astrophys. J.* 741 (2011) 22, doi: 10.1088/0004-637X/741/1/22
142. Proximity effects and nonequilibrium superconductivity in transition-edge sensors. Sadleir, J.E., Smith, S.J., Robinson, I.K., et al. *Phys. Rev. B* 84 (2011) 184502, doi: 10.1103/PhysRevB.84.184502
143. V344 Lyrae: A touchstone SU UMa cataclysmic variable in the Kepler field. Wood, M.A., Still, M.D., Howell, S.B., et al. *Astrophys. J.* 741 (2011) 105, doi: 10.1088/0004-637X/741/2/105
144. Gamma-ray and parsec-scale jet properties of a complete sample of blazars from the MOJAVE program. Lister, M.L., Aller, M., Aller, H., et al. *Astrophys. J.* 742 (2011) 27, doi: 10.1088/0004-637X/742/1/27
145. Fermi detection of a luminous gamma-ray pulsar in a globular cluster. Freire, P.C.C., Abdo, A.A., Ajello, M., et al. *Science* 334 (2011) 1107, doi: 10.1126/science.1207141
146. A cocoon of freshly accelerated cosmic rays detected by Fermi in the Cygnus Superbubble. Ackermann, M., Ajello, M., Allafort, A., et al. *Science* 334 (2011) 1103, doi: 10.1126/science.1210311
147. The interplanetary network supplement to the HETE-2 gamma-ray burst catalog. Hurley, K., Atteia, J.L., Barraud, C., et al. *Astrophys. J. Suppl. Ser.* 197 (2011) 34, doi: 10.1088/0067-0049/197/2/34
148. The first hundred brown dwarfs discovered by the Wide-field Infrared Survey Explorer (WISE). Kirkpatrick, J.D., Cushing, M.C., Gelino, C.R., et al. *Astrophys. J. Suppl. Ser.* 197 (2011) 19, doi: 10.1088/0067-0049/197/2/19
149. Planck early results. XV. Spectral energy distributions and radio continuum spectra of northern extragalactic radio sources. Aarokoski, J., Ade, P.A.R., Aghanim, N., et al. *Astron. Astrophys.* 536 A15 (2011), doi: 10.1051/0004-6361/201116466
150. Herschel discovery of a new class of cold, faint debris discs. Eiroa, C., Marshall, J.P., Mora, A., et al. *Astron. Astrophys.* 536 L4 (2011), doi: 10.1051/0004-6361/201117797
151. Carbon fiber reinforced polymer dimensional stability investigations for use on the Laser Interferometer Space Antenna mission telescope. Sanjuan, J., Preston, A., Korytov, D., et al. *Rev. Sci. Instrum.* 82 (2011) 124501, doi: 10.1063/1.3662470
152. CANDELS: The Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey—the Hubble Space Telescope observations, imaging data products, and mosaics. Koekemoer, A.M., Faber, S.M., Ferguson, H.C., et al. *Astrophys. J. Suppl. Ser.* 197 (2011) 36, doi: 10.1088/0067-0049/197/2/36
153. The nature and cause of spectral variability in LMC X-1. Ruhlen, L., Smith, D.M., Swank, J.H. *Astrophys. J.* 742 (2011) 75, doi: 10.1088/0004-637X/742/2/75

154. Probing the star formation history and initial mass function of the  $z \sim 2.5$  lensed galaxy SMM J163554.2+661225 with Herschel. Finkelstein, K.D., Papovich, C., Finkelstein, S.L., et al. *Astrophys. J.* 742 (2011) 108, doi: 10.1088/0004-637X/742/2/108
155. Extreme emission-line galaxies in CANDELS: Broadband-selected, starbursting dwarf galaxies at  $z > 1$ . van der Wel, A. Straughn, A.N., Rix, H.W., et al. *Astrophys. J.* 742 (2011) 111, doi: 10.1088/0004-637X/742/2/111
156. Constraining dark matter models from a combined analysis of Milky Way satellites with the Fermi Large Area Telescope. Ackermann, M., Ajello, M., Albert, A., et al. *Phys. Rev. Lett.* 107 (2011) 241302, doi: 10.1103/PhysRevLett.107.241302
157. The identification of the X-ray counterpart to PSR J2021+4026. Weisskopf, M.C., Romani, R.W., Razzano, M., et al. *Astrophys. J.* 743 (2011) 74, doi: 10.1088/0004-637X/743/1/74
158. Imaging the time evolution of Eta Carinae's colliding winds with HST. Gull, T.R., Madura, T.I., Groh, J.H., Corcoran, M.F. *Astrophys. J. Lett.* 743 (2011) L3, doi: 10.1088/2041-8205/743/1/L3
159. Images of the extended outer regions of the debris ring around HR 4796 A. Puccetti, S., Capalbi, M., Giommi, P., et al. *Astrophys. J. Lett.* 743 (2011) L6, doi: 10.1088/2041-8205/743/1/L6
160. The second catalog of active galactic nuclei detected by the Fermi Large Area Telescope. Ackermann, M., Ajello, M., Allafort, A., et al. *Astrophys. J.* 743 (2011) 171, doi: 10.1088/0004-637X/743/2/171
161. Radiative efficiency and thermal spectrum of accretion onto Schwarzschild black holes. Noble, S.C., Krolik, J.H., Schnittman, J.D., Hawley, J.F. *Astrophys. J.* 743 (2011) 115, doi: 10.1088/0004-637X/743/2/115
162. Pulsar pair cascades in magnetic fields with offset polar caps. Harding, A.K., Muslimov, A.G. *Astrophys. J.* 743 (2011) 181, doi: 10.1088/0004-637X/743/2/181
163. Observations of energetic high magnetic field pulsars with the Fermi Large Area Telescope Parent, D., Kerr, M., den Hartog, P.R., et al. *Astrophys. J.* 743 (2011) 170, doi: 10.1088/0004-637X/743/2/170
164. HST-COS observations of hydrogen, helium, carbon, and nitrogen emission from the SN 1987A reverse shock. France, K., McCray, R., Penton, S.V., et al. *Astrophys. J.* 743 (2011) 186, doi: 10.1088/0004-637X/743/2/186
165. Chandra phase-resolved X-ray spectroscopy of the Crab Pulsar. Weisskopf, M.C., Tennant, A.F., Yakovlev, D.G., et al. *Astrophys. J.* 743 (2011) 139, doi: 10.1088/0004-637X/743/2/139
166. A CANDELS WFC3 grism study of emission-line galaxies at  $z \sim 2$ : A mix of nuclear activity and low-metallicity star formation. Trump, J.R., Weiner, B.J., Scarlata, C., et al. *Astrophys. J.* 743 (2011) 144, doi: 10.1088/0004-637X/743/2/144
167. Directional Limits on Persistent Gravitational Waves Using LIGO S5 Science Data. Abadie, J., Abbott, B.P., Abbott, R., et al. *Phys. Rev. Lett.* 107 (2011) 271102, doi: 10.1103/PhysRevLett.107.271102
168. Spectral cross-calibration of the Konus-Wind, the Suzaku/WAM, and the Swift/BAT data using gamma-ray bursts. Sakamoto, T., Pal'Shin, V., Yamaoka, K., et al. *Publ. Astron. Soc. Jpn.* 63 (2011) 215
169. Merging black holes. Centrella, J., Baker, J., Kelly, B., van Meter, J. *Contemp. Phys.* 52 (2011) 1, doi: 10.1080/00107514.2010.520908







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