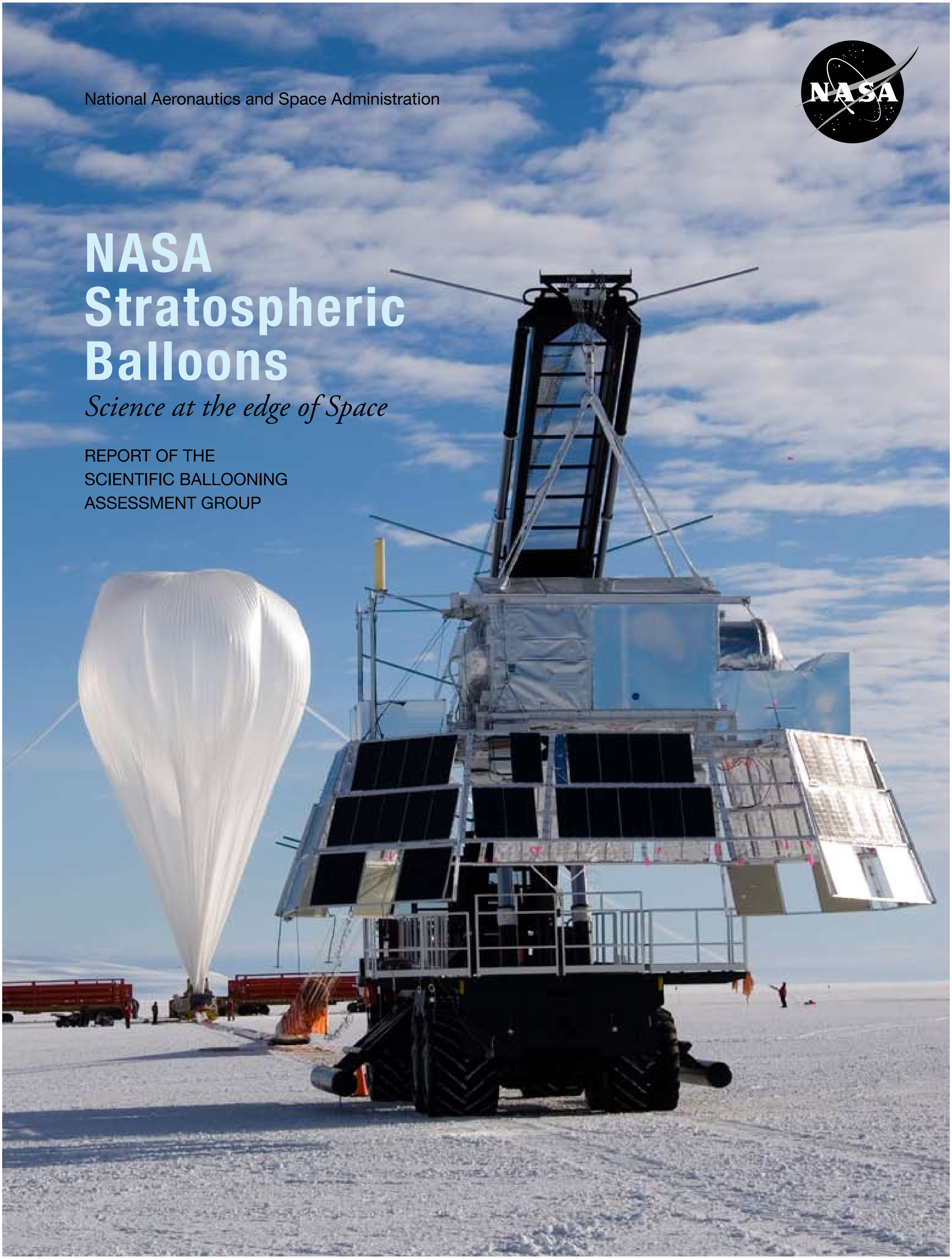
National Aeronautics and Space Administration

NASA Stratospheric Balloons

Science at the edge of Space

REPORT OF THE
SCIENTIFIC BALLOONING
ASSESSMENT GROUP



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Cover Photo:
The Balloon-borne Experiment with Superconducting Spectrometer, BESS Polar II at Williams Field, McMurdo, Antarctica.

Facing Page Photo:
The International Focusing Optics Collaboration for micro-Crab Sensitivity (InFOCµS), a hard x-ray telescope with CdZnTe pixel detector as a focal plane imager.

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January 2010

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The Cosmic Ray Energetics And Mass instrument (CREAM) hangs on the launch vehicle at Williams Field near McMurdo base Antarctica.

Executive Summary

A beautiful sunrise behind a balloon being inflated. Just after sunrise or just before sunset are good launch times.

Balloon-borne science and mission opportunities are more promising than ever in the 50-year history of the balloon program. Long duration and large-area/mass payloads are able to fly in near-space conditions offering exciting opportunities for both development and actual science for many of NASA's highest priority areas for current and future missions. Flights of days to weeks are now routine, and substantial progress has been made in enabling multi-month exposures.

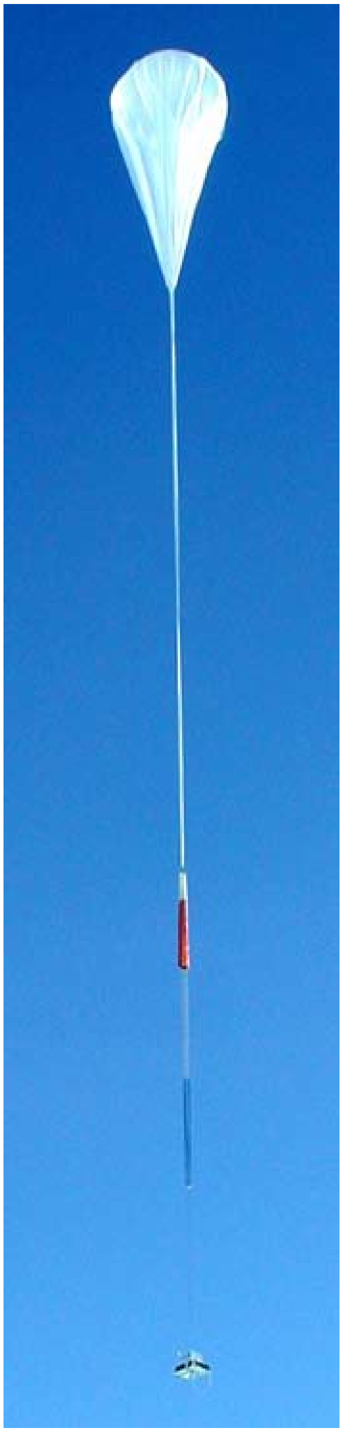
Balloon-borne missions can typically be carried out at less than 10 percent of the cost of a corresponding satellite mission, and on much shorter timescales. The Balloon Program is arguably the most cost effective and scientifically compelling of the various NASA suborbital programs. It provides the most complete and efficient springboard both for instrument development and for the scientists and engineers who will carry out the space-science missions of the future. This springboard has enabled numerous successful space missions, launched the careers of many Principal Investigators, and trained numerous leaders in NASA space and Earth science over the past three decades.

- Instruments carried on high-altitude balloons have produced **important scientific results,** and many more significant results from balloon-borne instruments can be expected in the future.
- Many instruments subsequently used on spacecraft for major astrophysical observations were initially developed with flights on high-altitude balloons, and balloon flights continue to be important for **testing future space-flight instruments.**
- Scientific ballooning is an unexcelled environment in which to **train graduate students and young post-doctoral scientists;** indeed, many leading astrophysicists, including Nobel laureates John Mather and George Smoot, gained invaluable early experience in the balloon program.

In this report, the Scientific Ballooning Assessment Group identifies three high-priority needs to enhance a strong balloon program and enable even greater contributions to NASA's highest priority science over the coming decade:

- **Fund an increased number of more-sophisticated balloon payloads.** Most of the simple experiments have been done. Increased funding is required to train a new generation of Principal Investigators and to build advanced payloads suitable for multiple flights that can exploit the new ballooning capabilities coming online.

- **Complete the current development program of super-pressure balloons (SPB) to enable an operational program of long-duration (≥ 15-day) mid-latitude flights and extend this program to support flights of heavy instruments to altitudes not allowed by the current development.** There is currently a successful program of long-duration (20- to 40-day) flights that take advantage of the continuous sunlight over Antarctica in austral summer; however, not all balloon science can be done in the Polar Regions.



Shortly after launch helium fills only a small fraction of a balloon's volume. At float altitude the helium has expanded and the balloon is nearly spherical. *(See image on page 28.)*

Much of the high priority science accessible to balloon-borne instruments requires long flights at mid-latitudes. The current super-pressure balloon development has the goal of taking 1000 kg instruments to 33.5 km altitude, where much useful science can be done. Extension of the program to develop balloons capable of taking 1000-kg instruments to 38 km would enable an important class of instruments that cannot work effectively at the lower altitudes.

- **Build capability for 100-day flights.** Development of modest trajectory-modification capability to ensure that balloons do not fly over populous areas is important for Ultra-Long-Duration Balloon (ULDB) flights of about 100 days. For a number of investigations, these would be truly competitive with orbital missions, enabling breakthrough science at greatly reduced total cost.

Scientific ballooning has made important contributions to NASA's science program.

It has contributed directly with important science results, and indirectly by serving as a test platform on which instruments have been developed that were subsequently used on NASA spacecraft.

Examples of new science from balloon-borne instruments include early maps of the anisotropies of the Cosmic Microwave Background (CMB), the first identification of antiprotons in the cosmic rays, early detection of gamma-ray spectral lines from supernova 1987A, the first observation of positron-emission lines from the galaxy, early detection of black-hole x-ray transients in the galactic center region, and observations of chlorofluorocarbons (CFCs) and chlorine monoxide radicals in the stratosphere. In November 2008, the Advanced Thin Ionization Calorimeter (ATIC) collaboration reported measurements of high-energy cosmic-ray electrons by an instrument flown three times over Antarctica, displaying a feature in the spectrum that suggests a nearby cosmic-ray source, possibly the signature of annihilation of dark-matter particles. In April 2009, reported results from an Antarctic LDB balloon flight of the Balloon-borne Large Aperture Submillimeter Telescope (BLAST) demonstrated that the submillimeter background light discovered by the Cosmic Background Explorer (COBE) satellite comes from individual galaxies identified by the Spitzer Space Telescope.

Examples abound of spacecraft instrumentation derived from balloon-flights predecessors. All the instruments on the Compton Gamma Ray Observatory (CGRO) were developed from balloon-flight instruments. The design of the Wilkinson Microwave Anisotropy Probe (WMAP) grew out of CMB balloon flights in the late 1980s and 1990s. The detectors on the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) were first developed for balloon-borne instruments. The scintillating fiber trajectory detector for the Cosmic Ray Isotope Spectrometer on the Advanced Composition Explorer (ACE) was demonstrated first in balloon flights. The viability of Cd-Zn-Te (CZT) detectors in space-like environments was first demonstrated on several balloon flights, enabling their use on the highly successful Swift satellite. Several Earth Observing System (EOS)-Aura satellite instruments trace their heritage to balloon-flight devices, as does the Thermal and Evolved Gas Analyzer (TEGA) instrument that flew on the Mars

Polar Lander as part of the Mars Volatile and Climate Surveyor (MVACS) payload. The Mars Science Laboratory will carry a similar instrument.

Balloon-borne instruments will continue to contribute to NASA's objectives.

Prominent examples, who have attested to the importance of the Balloon Program to their career development, include John Mather and George Smoot, winners of 2006 Nobel Prize in Physics.

Investigations on balloons, underway or planned, directly address objectives in NASA's 2007 *Science Plan,* the 2006 plans of the four divisions of NASA's Science Mission Directorate, and the 2004 joint NASA–NSF –DOE *Physics of the Universe—Strategic Plan for Federal Research at the Intersection of Physics and Astronomy.*

Balloon-borne instruments are being developed that will advance the techniques for hard x-ray astronomy envisioned for the Black-Hole Finder Probe (BHFP) and the International X-Ray Observatory (IXO). Planned instruments will also support the objectives of the Inflation Probe (IP), by developing techniques for measuring CMB polarization, making the first CMB polarization measurements, and measuring the foreground that would interfere with CMB observations. Others are laying the groundwork for the Advanced Compton Telescope (ACT) mega-electron volt gamma-ray instrument. A balloon-borne instrument is carrying out a search for neutrinos with energy above 10^{18} eV associated with the interactions of ultra-high-energy cosmic rays with CMB photons. Cosmic-ray instruments on long-duration balloon (LDB) flights are pushing measurements of cosmic-ray composition toward the predicted energy limit of supernova acceleration and to very high nuclear charge. Instruments on LDB balloons are investigating the nature of dark matter through measurements of cosmic-ray antiprotons and a search for antideuterons and are testing baryon asymmetric cosmology through a search for antihelium. High-resolution imaging from balloons can study both the Sun and other astrophysical objects, in optical, as well as other wavelengths. Balloons are well suited to measure the dayside aurora and other ionospheric conditions. For studying the atmosphere of Earth, balloons provide *in situ* validation of remote-sensing spacecraft data, and they provide the possibility of observing detailed processes on much finer spatial and temporal scales. Balloons exploring Venus and Titan have the potential for collecting both in situ atmospheric data and high-resolution geological, geochemical, and geophysical data.

Many scientists with leading roles in NASA were trained in the Balloon Program.

Prominent examples, who have attested to the importance of the Balloon Program to their career development, include John Mather and George Smoot, winners of 2006 Nobel Prize in Physics; Thomas Prince, Professor of Physics at the California Institute of Technology and recently Chief Scientist at the Jet Propulsion Laboratory; and John Grunsfeld, an astronaut who has carried out Hubble Space Telescope (HST) repairs and is a former NASA Chief Scientist.

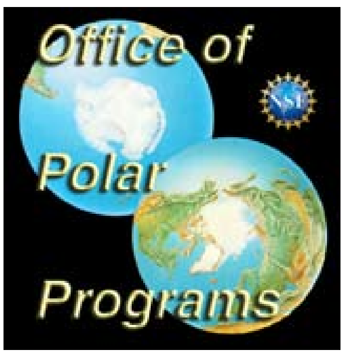
Funding for new instruments under NASA's Supporting Research and Technology line is inadequate.

The Supporting Research and Technology/Research and Analysis (SR&T/R&A) program spends approximately $15M annually supporting scientists to develop balloon instruments and analyze their data. *A strength of this program is that science is selected by peer review, providing opportunity for new ideas to be developed that were*

The Balloon Program, as currently funded, has substantial capability for achieving quality science; however, it is inadequate to pay for important developments.

With its current annual budget, the BPO supports about ten to fifteen conventional flights of approximately one-day duration from Palestine, Texas or Ft. Sumner, New Mexico; an annual Antarctic LDB campaign; and an LDB campaign from either Kiruna, Sweden or Alice Springs, Australia. The BPO also supports a development program with the goal of providing a super-pressure balloon (SPB) capable of carrying a 1000-kg instrument to approximately 33.5 km giving little or no day/night altitude variation and ultimately 100-day Ultra-Long-Duration Balloon (ULDB) flights. All of these programs must be preserved but the current BPO budget does not allow the enhanced SPB development, which the Scientific Balloon Assessment Group considers to be of high priority. Also, the current BPO budget would not be adequate for the level of operational funding needed to support a ULDB program.

The Antarctic Long-Duration Balloon program will continue to be a vital part of the Balloon Program.



The National Science Foundation, NSF, Office of Polar Programs.

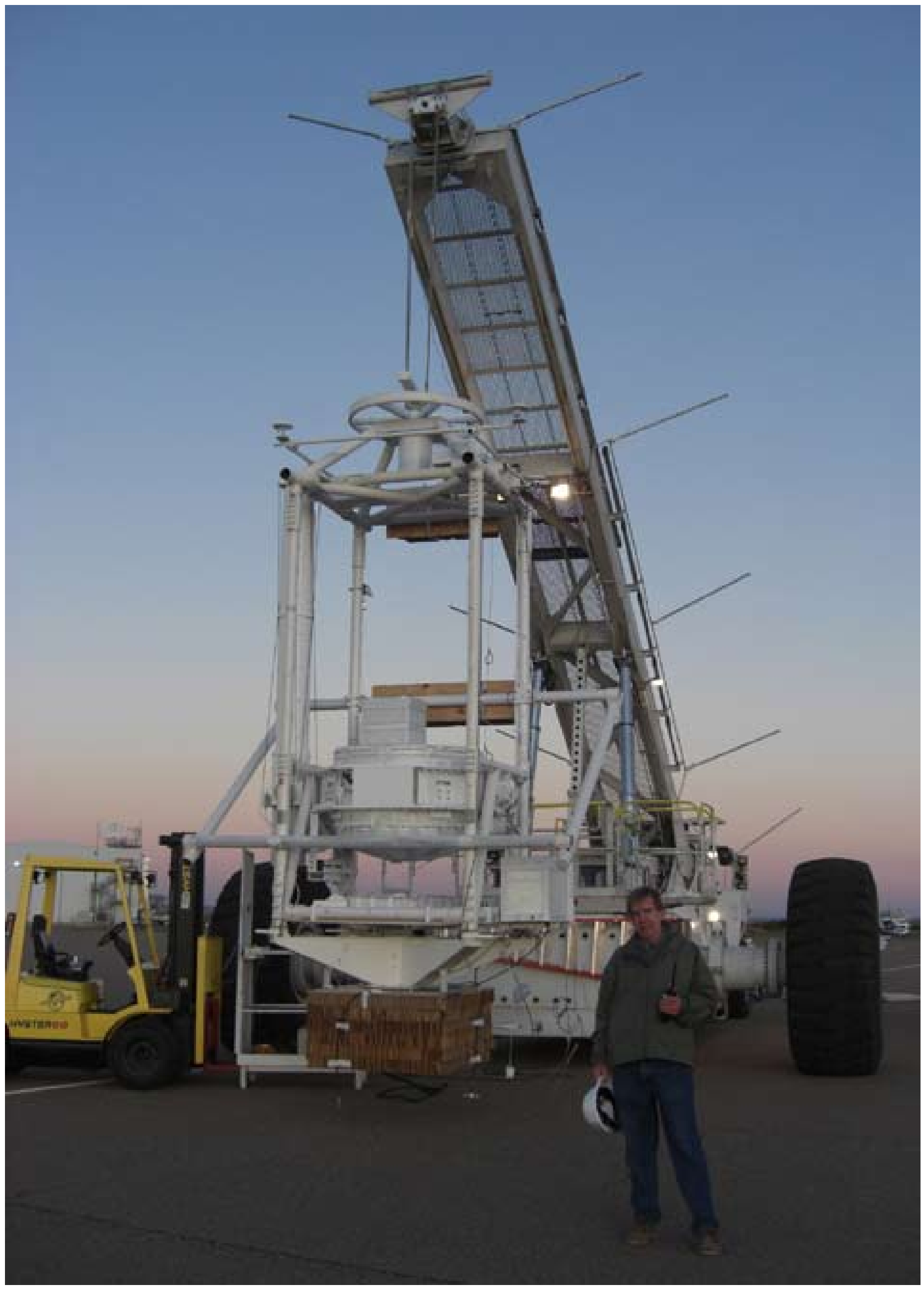
The highly successful LDB program provides flights from Antarctica with durations of two weeks to as much as six weeks. These Antarctic LDB flights have been, and can continue to be, of great importance for cosmic-ray, solar, and submillimeter science. For the past three seasons (2006–07, 2007–08, and 2008–09) superb cooperation among the NASA Balloon Program, the Columbia Scientific Balloon Facility, the National Science Foundation (NSF) Office of Polar Programs, and Raytheon Polar Services Company has enabled three Antarctic launches per season. However, the projection of constrained NSF budgets in coming years, combined with higher fuel prices, will likely impact the operations capability in Antarctica. Continuation of three-launch capability may require additional resources.

Development of Super-Pressure Balloons will open major new capabilities for important science.

Thanks to development spurred by the 2001 Decadal Survey Report, SPB development stands on the threshold of success. Building operational balloon and support systems for moderate altitude (33.5 km) mid-latitude flights is nearly completed. Within three to four years a balloon-borne version of the IP could conduct measurements of the CMB polarization on several mid-latitude flights of approximately fifteen-day duration. Nighttime observing is required for the IP, so Antarctic flights during the austral summer are not useful. Similarly, high-energy x-ray missions, including pathfinder flights for the BHFP, need SPB (and ultimately ULDB) mid-latitude flights to avoid the high backgrounds encountered in LDB flights from polar latitudes. Development of modest trajectory control is key to the full implementation for mid-latitude flights to ensure they do not go over densely populated areas.

The prototype for the BHFP requires large-area/mass hard-x-ray telescopes and long-duration flights at altitudes of about 38 km at mid-latitudes, where the cosmic-ray background flux is relatively low. The current SPB development is targeting a *not foreseen in long-range strategic plans. Rapid response to new scientific developments is afforded by this program.* A major weakness of the SR&T/R&A support is that the funding levels are inadequate for developing many of the sophisticated balloon-borne missions and multi-flight and/or multi-user payloads capable of advancing key elements of NASA's strategic plans, even though these balloon-borne investigations are exceptionally cost effective compared with space-flight investigations. Thus, the current capabilities of the balloon program are underutilized due to inadequate funding of balloon-borne instruments. With expanded balloon capabilities currently under development, this underutilization will be exacerbated unless funding for instruments is increased.

Thanks to development spurred by the 2001 Decadel Survey Report, Super-Pressure Balloon (SPB) development stands on the threshold of success.



ProtoEXIST, a balloon borne instument to develop technology for the Energetic X-ray Imaging Survey Telescope (EXIST) mission. EXIST is a candidate for the Black Hole Finder Probe and will conduct a census of black holes in the known universe.

The SUNRISE solar telescope is ready for launch at Fort Sumner, NM. SUNRISE studies the formation of magnetic structures n the solar atmosphere.

Scientific Ballooning has Made Important Contributions to NASA's Program

Scientific ballooning has contributed significantly to NASA's science program, both directly with science coming from measurements made by balloon-borne instruments, and indirectly by serving as a test platform on which instruments have been developed that were subsequently flown on NASA space missions.

New Science from Balloon-borne Instruments

Following are a few examples of important scientific results from balloons.

The Nature, April 27, 2000 issue highlighted the results of the BOOMERanG flight. Balloon Observations of Millimetric Extragalactic Radiation and Geophysics (BOOMERanG) which showed that the universe is, in fact, flat rather than open or closed.

Cosmic Microwave Background Anisotropy and Intensity Measurements

The most widely recognized use of ballooning at millimeter wavelengths has been the study of the anisotropy in the 2.7 K cosmic microwave background (CMB). Measurements of the anisotropy in the CMB serve as a probe of the state of the universe when it was roughly 300,000 years old. A large number of experiments dating back over thirty years set the stage for the extremely successful measurements of the Balloon Observations of Millimetric Extragalactic Radiation and Geophysics (BOOMERanG) and Millimeter Anisotropy Experiment Imaging Array (MAXIMA) balloon missions in the late 1990's. The final BOOMERanG experiment provided a first glimpse of CMB polarization measurements from balloon platforms. The Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission (ARCADE) has measured the absolute radiometric temperature of the sky as a complement to the differencing measurements from the Wilkinson Microwave Anisotropy Probe (WMAP) and recently reported the discovery of a microwave background brighter than the combined emission of all galaxies in the current Universe.

The Submillimeter Universe Revealed

During a highly successful LDB balloon flight from Antarctica, the Balloon-borne Large Aperture Submillimeter Telescope (BLAST) made detailed large-scale maps of extragalactic and galactic fields. Combined with data from the Spitzer Space Telescope they determined that all of the submillimeter background light first detected by the COsmic Background Explorer (COBE) satellite can be resolved into individual galaxies. In addition to a host of other results, they also determined the epoch when most of the star formation was taking place. Their 40-square-degree galactic map of the Vela star forming region revealed over a thousand star-forming cores enabling a detailed statistical analysis of core lifetimes. (*Nature,* 9 April 2009)

Antiparticles in the Cosmic Rays

The first detection of cosmic antiprotons was made by a magnetic spectrometer flown on a high altitude balloon in 1979. The Isotope Matter-Antimatter Experiment (IMAX) and the Balloon-borne Experiment with a Superconducting Spectrometer (BESS) confirmed this detection in the early 1990's with mass-resolved identification of antiprotons, and the majority of reported cosmic-ray antiprotons have been measured by balloon-borne magnetic spectrometers. Balloon measurements have clearly shown the characteristic secondary antiproton peak from nuclear interactions of primary cosmic rays with the interstellar medium. BESS measurements at the last Solar minimum, when sensitivity to low-energy spectral components is greatest, also suggest the presence of a contribution to the antiproton spectrum by low-energy antiprotons from DM annihilation or PBH evaporation. BESS-Polar recently completed an LDB flight at Solar-minimum, returning a unique dataset that greatly exceeds the statistics on antiprotons below several GeV that the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite instrument will obtain.

Magnetic spectrometers also search for antihelium and heavier antinuclei. The probability for secondary production of anti-helium and heavier anti-nuclei during the interactions of baryons in space is negligible. Thus, the detection of one anti-helium or anti-carbon nucleus would have a profound impact on our understanding of baryon symmetry, a foundation of modern physics, astrophysics and cosmology. The BESS program, with data from conventional and LDB flights, has set the most sensitive upper limit to the existence of cosmological antihelium.

Possible Evidence for Annihilation of Dark-Matter Particles in Space

Data from an Antarctic balloon flight of the Advanced Thin Ionization Calorimeter (ATIC) shows a substantial excess of galactic cosmic-ray electrons at energies of ~300-800 GeV, which may indicate a nearby source of energetic electrons. Such a source could be an astrophysical object, such as a pulsar or micro-quasar, that accelerates electrons to those energies, or the electrons could arise from the annihilation of dark-matter particles (such as a Kaluza-Klein particle with a mass of about 620 GeV). (*Nature,* 20 November 2008)

Beautiful rings of glowing gas from SN 1987a, approximately 160,000 light years away. The rings are lit by ultraviolet radiation. This image is from the HST.

Gamma-Ray Lines from Supernova 1987a

Within a few months of the February 24, 1987 optical discovery of SN1987a in the nearby Large Magellanic Cloud galaxy, the Gamma-Ray Imaging Payload (GRIP) imaged gamma rays from the ejecta of a supernova for the first time. Over the next two years, a highly successful series of payloads was flown from Australia, including GRIP and the Gamma-Ray Imaging Spectrometer (GRIS). Their measurement of gamma-ray lines from freshly produced radioactive nuclei confirmed the basic theory of supernovae. Such a short lead-time from discovery of a new event or phenomenon to making direct observations in wavelengths only observable above the atmosphere was possible within the balloon program. If observations had waited for the typical several-year lead-time for a spacecraft mission, the rapidly fading gamma-ray emission would have been undetectable.

Positron Emission and Black-Hole X-ray Transients from the Galaxy

Production of positrons and their annihilation in the galactic interstellar medium (ISM) is one of the pioneering topics of gamma-ray astronomy. Balloon payloads have led the way in this study, from the initial discovery in the 1970s, to detailed

Today, balloons are used in a comprehensive strategy of ground, suborbital, and space observations to advance our understanding of atmospheric composition.

spectroscopic measurements in the 1990s by GRIS and the High Resolution Gamma-Ray and Hard X-Ray Spectrometer (HIREGS). After three decades of observations, however, the origin of these positrons remains a mystery. Observations made by the Oriented Scintillation Spectrometer Experiment (OSSE) on CGRO and the INTEGRAL SPectrometer (SPI) show that the emission is brightest in the direction of the galactic center, but that the emission is extended, with radius ~4°, as opposed to a dominant black hole in the Galactic Center region as was first speculated. New theories are being explored to explain the bulge/halo positrons. Potential sources include hypernovae from an episode of starburst activity in the bulge, multiple faint point sources (black holes and jets in low mass x-ray binaries), supernova explosions, pulsar winds, and annihilations or decays of (as yet undiscovered) light dark matter particles. Mapping the spatial distribution of this emission remains crucial, and once again today's balloon payloads are leading the way in developing the sensitivity and imaging capabilities to map these annihilations in detail.

Chlorofluorocarbons and Chlorine Monoxide Radicals in the Stratosphere

The primary user of balloons for Earth science research has been NASA's atmospheric chemistry program. Balloon instruments provided the initial observations of key stratospheric species necessary to understand the processes, both human and natural, that impact the abundance of stratospheric ozone. Among these are Chlorofluorocarbons (CFCs) released by human activities and transported into the stratosphere where they are photolyzed and release chlorine. That chlorine reacts with and removes ozone in a catalytic cycle that produces chlorine monoxide radicals (ClO). Balloon-borne observations of the destruction of CFCs and production of ClO confirmed the CFC-Ozone depletion theory. Indeed, the observations of ClO were referred to in Congressional hearings as the "smoking gun." Balloons have also provided observations of all other key chemical species including nitrogen oxides, hydroxyl radicals and an array of source and trace gases. These observations are used both to initialize, and also to test, photochemical models. Measurements made by the Observations of the Middle Stratosphere payload, as part of the Stratospheric Tracers of Atmospheric Transport project, extended the in situ aircraft measurements to much higher altitudes. These observations led to improved understanding of the dynamical processes transporting gases across the tropopause into the upper atmosphere and improved our estimates of the lifetimes of anthropogenic pollutants in the stratosphere. Today, balloons are used in a comprehensive strategy of ground, suborbital, and space observations to advance our understanding of atmospheric composition. They complement Earth observing satellites by providing 1) validation, 2) measurements of species that are not being made from satellites, and 3) measurements at much finer spatial and temporal scales than can be made from space.

Spacecraft instrumentation derived from balloon-borne instruments

Balloon payloads funded through the Supporting Research and Technology (SR&T/R&A) program, have enabled prototyping of optics and detectors to extend x-ray and gamma ray measurements to higher energies than are now feasible. Balloon missions provided development and test opportunities for detectors flown on CGRO and for the large silicon strip detector arrays flown on the Fermi Gamma-ray Space Telescope (FGST, formerly called GLAST). Spiderweb bolometers developed for balloon instruments are now flying on the Planck and Herschel space missions. Instruments on the Ramaty High Energy Solar Spectroscopic Imager (RHESSI), Advanced Composition Experiment (ACE), and Earth Observing System (EOS) Aura space missions were originally developed and prototyped on balloon flights. Coded aperture and position sensitive gamma ray imagers tested on balloon flights would be used for the Black Hole Finder Probe (BHFP) mission, and have applications as well for medical imaging and national security. Hard x-ray focusing optics, large-area room-temperature Cd-Zn-Te (CZT) semiconductor arrays, high resolution lanthanum bromide scintillators, and mega-channel data acquisition systems are being developed for the Beyond Einstein program. These technologies are being, and will continue to be flown on balloons as the upcoming Decadal Survey considers the projects they support.

Following are a few examples of instrumentation initially developed for balloon-borne studies that subsequently became a basis for successful spacecraft investigations:

The Wilkinson Microwave Anisotropy Probe (WMAP), artists conception. WMAP was launched in 2001 and has verified the inflation theory of the early universe.

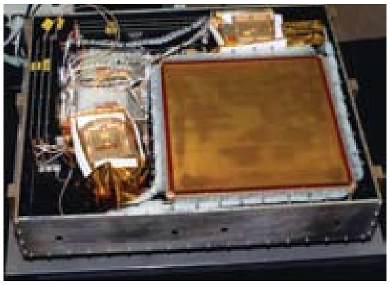
Cosmic Microwave Background Missions

COBE and WMAP measured the CMB to unprecedented accuracies of 10's of micro-Kelvin and provided key confirmation of the Hot Big Bang theory of the origin of the universe. Not only did they require unique detector technology, but they also needed extreme control of systematic errors. The recently launched Planck observatory will extend the anisotropy measurements to smaller angular scale with increased sensitivity. Much of the instrumentation for these missions was developed and tested on balloon platforms.

Ramaty High Energy Solar Spectroscopy Imager (RHESSI) launched in 2002 (artists concept). RHESSI is studying the physics of particle acceleration in solar flares.

Gamma-Ray Spacecraft Observatories

Balloon payloads pioneered the science instruments flown in larger versions on the High Energy Astronomy Observatory (HEAO-C), the Solar Maximum Mission (SMM), CGRO, and INTEGRAL. The currently active Hard X-ray and soft Gamma-ray imaging coded aperture telescopes on the INTEGRAL and Swift missions both had balloon heritage, as did the Hard X-ray Detector on Suzaku/Astro-E2.. Neil Gehrels, PI of Swift reports, "During the development of the CZT array for Swift, three balloon flights were performed to measure the unknown charged-particle induced background in CZT. The flights produced invaluable data on CZT activation and provided the quantitative information needed to design the Swift Burst Alert Telescope (BAT) instrument." Robert Lin, principal investigator (PI) of the currently operating RHESSI reports, "The Balloon program was absolutely essential for the development and testing of the detector and electronics technology for RHESSI." Peter Michelson, PI for the Large Area Telescope (LAT) instrument on the FGST reports, "In 2001 we flew a full engineering prototype of a GLAST LAT telescope module. The balloon flight demonstrated that the instrument trigger, based on signals from the silicon strip tracker, functioned well in a high background environment. This demonstration was critical to the validation of the LAT instrument design."



The scintillating fiber trajectory system in the Cosmic Ray Isotope Spectrometer for the ACE spacecraft. These fibers were first developed for a balloon-flight instrument. Many balloon flights develop technology that is later incorporated into spacecraft.

Galactic Cosmic-Ray Missions

The Cosmic Ray Isotope Spectrometer (CRIS) instrument on the Advanced Composition Explorer (ACE) spacecraft, on orbit since 1997, is measuring the isotopic composition of galactic cosmic rays with unprecedented mass resolution and statistical accuracy. An essential element of the CRIS detector system is the scintillating-optical-fiber hodoscope, which was first demonstrated in balloon-borne cosmic-ray instruments. Similar fiber technology is also being used as a component of the FGST-LAT anti-coincidence shield. A number of balloon-borne magnetic-rigidity spectrometers set the stage and developed the technology for PAMELA, which has been on orbit since June 2006 and has provided ground-breaking measurements of cosmic-ray positrons and antiprotons to high energies. Techniques proven in balloon instruments have benefited the Alpha Magnet Spectrometer (AMS), manifested for launch in September 2010.

Earth Observation

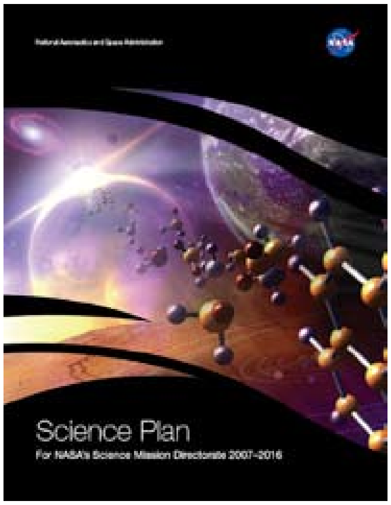
On the current EOS-Aura satellite, the Microwave Limb Sounder (MLS), the Tropospheric Emission Spectrometer (TES), and the High Resolution Dynamics Limb Sounder (HIRDLS) all trace their heritage to instruments that first flew on balloons. Balloon versions of some of the Aura instruments are currently flying as part of the Aura Validation Program.

Planetary Instruments

The Mars Science Laboratory (MSL) will fly a Tunable Laser Spectrometer (TLS) that traces its heritage back to a series of balloon experiments that detected trace gases in Earth's atmosphere using the Balloon-borne Laser In Situ Sensor (BLISS) instrument.

NCT, the Nuclear Compton Telescopes, a Balloon-borne Imaging Gamma Ray Telescope prepares for launch.

Balloon-borne Instruments Will Continue to Contribute to NASA's Objectives



NASA Science Plan for the years 2007 through 2016.

The Science Plan For NASA's Science Mission Directorate 2007-2016, published in January 2007, included plans for each of the four divisions of NASA's SMD – Astrophysics, Earth Science, Heliophysics, and Planetary Science. In early 2004, an interagency working group representing NASA, NSF, and the Department of Energy published *The Physics of the Universe—A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy.* The Scientific Ballooning Assessment Group took those reports as the basis for its work.

In this section, we indicate how investigations on balloons – underway or planned – directly address the objectives established in those reports. We emphasize that the value of ballooning in furthering NASA's science objectives was noted at several places in the *Science Plan.* For example:

In section 3.7 dealing with workforce development:

> The suborbital programs (airplanes, unmanned aerial vehicles (UAVs), rockets, and balloons) and PI-led missions enable students to participate in the entire lifecycle of a science mission from design and construction to flight and data analysis. These hands-on opportunities lead to experiences in problem solving and increased understanding of the systems engineering that is the underpinning of successful science missions.

In the Earth Science chapter, section 4.4.6:

> a comprehensive Earth observing system requires a global, integrated approach combining observations from spacecraft, suborbital platforms such as aircraft and balloons, surface instruments such as carbon-flux towers and ocean buoys, as well as major experiments and field campaigns engaging multiple surface and suborbital measurements, carefully coordinated with satellite observations.

In the Planetary chapter, section 5.4.4:

> Missions to study Venus's atmosphere and Titan's surface will require the development of new concepts of aerial mobility (e.g., balloons, dirigibles, gliders)

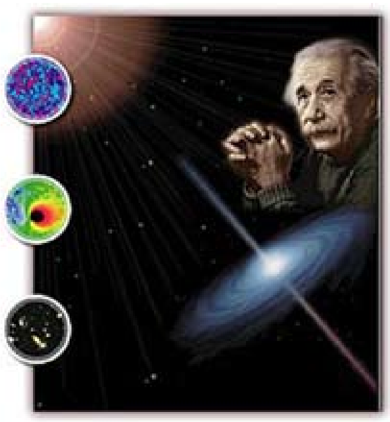
In the Heliophysics chapter, section 6.4.2:

> The LCAS [Low-Cost Access to Space] suborbital program, whose key elements are the sounding rocket and balloon programs, is an essential component of NASA's Heliophysics Research Program. LCAS investigations make cutting-edge science discoveries using state-of-the-art instruments developed in a rapid turnaround environment.

In the Astrophysics chapter, section 7.4.3:

> The Suborbital Program, comprising the sounding rocket and high-altitude balloon programs, provides unique opportunities for high-priority science; detector and instrument development; and training of students, engineers, and future PIs.
>
> Helium-filled balloons … will provide useful flight opportunities for observing campaigns associated with Beyond Einstein and for multiwavelength observing campaigns involving correlated spacecraft and ground observations.
>
> Balloon missions are prototyping optics and detectors to extend x-ray and gamma-ray measurements in space to higher energies than are currently possible.

Beyond Einstein

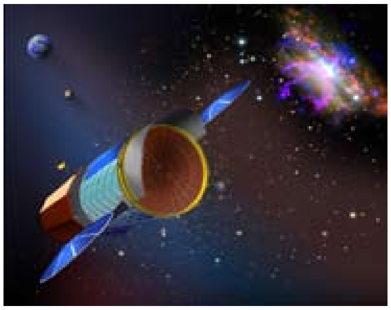


NASA's Beyond Einstein program, a series of space missions that is designed to learn more about three questions left unanswered by Einstein's work: What powered the Big Bang? What happens at the edge of a black hole? What is the mysterious energy responsible for the accelerated expansion of the universe called "dark energy"?

The Beyond Einstein program has been a high priority of the Astrophysics Division. Table 2.2d in the Science Mission Directorate's recent (2007) *Science Plan* summarizes the full suite of two Flagship missions and three Probes. These missions would address three major science objectives: (1) find out what powered the big bang; (2) observe how black holes manipulate space, time, and matter; and (3) identify the mysterious dark energy pulling the universe apart. The two Einstein Great Observatories are: the International X-ray Observatory (IXO), which uses x-ray spectroscopy over the 0.2–80 keV range to follow matter falling into black holes and to study the evolution of the universe; and the Laser Interferometer Space Antenna (LISA), which uses gravitational waves to sense directly the changes in space and time around black holes and to measure the structure of the universe. The three Einstein Probes are: a BHFP to take a census of black holes in the local universe, an Inflation Probe (IP) to detect the imprints left by quantum effects and gravitational waves at the beginning of the Big Bang, and a Dark Energy Probe (DEP) to determine the properties of the dark energy that dominates the Universe.

A 2007 National Academy report *NASA's Beyond Einstein Program: An Architecture for Implementation,* found, "All five mission areas in NASA's Beyond Einstein plan address key questions that take physics and astronomy beyond where the century of Einstein left them." They recommended moving forward first with the DEP and LISA. They also recommended, "NASA should move forward with appropriate measures to increase the readiness of the three remaining mission areas – Black Hole Finder Probe, Constellation-X, and Inflation Probe – for consideration by NASA and the NRC Decadal Survey of Astronomy and Astrophysics." The report also states, "The committee strongly believes that future technology investment is required and warranted in all of the Beyond Einstein mission areas." *Balloon-borne instruments will be essential for this technology development, in particular for developing the large area, high resolution hard x-ray detectors and telescopes needed for IXO (Constellation-X) and the BHFP, and for developing the CMB polarization detectors needed for the IP.* For example, in discussing the technical readiness of IP this report notes, “Investigations of different approaches for modulating the polarization signal may best be done with ground-based and balloon-borne demonstrations.”

International X-ray Observatory



Artists concept of the International X-ray Observatory or IXO, will play a crucial role by detecting the accretion power from their embedded SMBHs (10^7–10^9 solar masses), even when obscured.

The broadband Constellation-X Observatory mission being studied by NASA would use very high sensitivity and fine spectral resolution to study the physics of accreting matter in the extreme gravitational fields near black holes. In parallel, the European Space Agency (ESA), in cooperation with the Japan Aerospace Exploration Agency (JAXA), has been studying a mission with similar goals called the X-ray Evolving Universe Spectrometer (XEUS). A coordination group established by NASA and ESA in May 2008 to explore a joint mission merging Con-X and XEUS proposed a joint study of an International X-ray Observatory (IXO). The plan for that joint study was endorsed during a NASA/ESA bilateral meeting in July 2008. Its observatory class science is broader than the original Constellation-X formulation for the Beyond Einstein Program.

Using high time resolution x-ray spectroscopy, it is possible to track lumps of matter as they fall into a black hole. Since the bulk of the direct energy from these sources comes out in the hard x-ray band, the physics cannot be fully understood without simultaneous hard x-ray measurements. Super-massive black holes (SMBHs) are believed to be at the center of most galaxies and there is direct observational evidence for one at the center of our Milky Way Galaxy. Most of those SMBHs in the local universe are now emitting at low levels, but when they were forming they were luminous, though usually obscured, Active Galactic Nuclei (AGN). Some process turns off the accretion of infalling material and makes the Black Holes nearly invisible except when they occasionally disrupt passing stars, as can be detected with the BHFP mission. The IXO will study nearby dormant SMBHs including our Galactic center in detail, and their luminous progenitors in the early universe.

Since x-rays above ~20 keV can be observed from balloon platforms flying at altitudes above ~120,000 (~36.6 km), a new generation of balloon-borne focusing-optics hard-x-ray telescopes has been flown on balloon missions. In addition to serving as precursors for the upcoming Small Explorer (SMEX) Nuclear Spectroscopic Telescope Array (NuSTAR) and the IXO these balloon-borne hard-x-ray telescopes can also resolve the galactic center region above 20 keV. They will likely observe many smaller Galactic black holes at high sensitivity and spectral resolution. With long-duration flights at mid-latitudes on super-pressure balloons, these telescopes will also enable imaging of the 67 and 78 keV ^{44}Ti line emission from young supernova remnants in our galaxy, thereby probing the innermost regions of nucleosynthesis in supernovae.

Black Hole Finder Probe

The Einstein BHFP mission would “conduct a census of black holes in the universe.” It addresses several of the key science objectives of the Beyond Einstein program, as summarized in section 7.2.2 of the SMD *Science Plan:* The *First Stars* can be studied

The front of ProtoEXIST1, showing the tungsten coded mask, which is essential for imaging at hard x-ray energies over a wide field of view.

through their likely demise as luminous Gamma Ray Bursts (GRBs), detectable with greatly increased sensitivity and spectral coverage by BHFP; the *Formation and Evolution of Galaxies* can be constrained by James Webb Space Telescope (JWST) spectroscopy of distant (out to Pop III) spectra of GRBs precisely located by BHFP to study the evolution of metallicity and galaxy structure over cosmic time; and the *Galaxy-Black Hole Connection* can be directly studied by the BHFP inventory of obscured AGN vs. cosmic redshift. The Energetic X-ray Imaging Survey Telescope (EXIST) and the Coded Aperture Survey Telescope for Energetic Radiation (CASTER) were mission concept studies conducted for the Beyond Einstein Program Assessment Committee (BEPAC). EXIST has been further studied in the subsequent Astrophysics Strategic Mission Study (ASMC) in preparation for the Astro2010 Decadal Survey.

The technology required for BHFP is being developed for balloon flight tests: At altitudes above 120,000 (36.6 km), where the hard x-ray universe becomes directly observable from balloon-borne telescopes, instruments on conventional and LDB flights could demonstrate the large-area fine-pixel CZT and $LaBr_3$ scintillator detectors, multichannel electronics and data acquisition, and fine-grained coded aperture systems that are needed. ProtoEXIST is an example of a payload being developed for flight test of a moderate area BHFP prototype coded aperture array. A follow-up large area (1–2 m^2) telescope with full-BHFP resolution flown on a 30- to 100-day ULDB mission would provide not only a Long-Integration-Time Experiment, but also be a pathfinder for the full BHFP mission. It would also provide a sensitive test of polarization imaging at approximately 100–300 keV, which is key to BHFP measurement of the population of nonthermal black hole jet sources such as Blazars.

At energies above ~600 keV, Compton imaging takes over as the appropriate technique. The Nuclear Compton Telescope (NCT) balloon payload is being developed as a prototype for the Advanced Compton Telescope (ACT) “vision mission” being studied for possible implementation beyond the next decade.

Inflation Probe

The Beyond Einstein IP would seek the imprint of gravitational waves generated by inflation on the relic Cosmic Microwave Background (CMB). These waves should reveal if and how a mysterious “inflation” field stretched and smoothed the universe. The future in this area depends on CMB polarization. The pattern of polarization directions on the sky can be decomposed into “E modes” with no handedness and “B-modes” with handedness. The E-modes are generated from the same dynamics as temperature anisotropies and hence, the same effect that polarizes the atmosphere due to the very anisotropic emission from the Sun. The B-modes are generated by the inflationary gravity waves and by gravitational lensing of the E-modes. The expected magnitude and scales of these effects have been extensively modeled. The expected backgrounds have also been estimated. To put this discussion in perspective, the signal levels expected from CMB polarization are a factor of 10 to 1000 times smaller than the primary CMB anisotropy signals.

Measurement of the CMB polarization, in addition to being a key part of NASA's Beyond Einstein Program, is identified as a priority in *The Physics of the Universe – A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy,* which states, "The three agencies will work together to develop … a roadmap for decisive measurements of both types of CMB polarization … In the near term, ground-based studies from appropriate sites and balloon-borne studies from Antarctica will be required to prove the detector technology and to study the galactic foreground, as well as to exploit CMB radiation polarization as a probe of the universe."

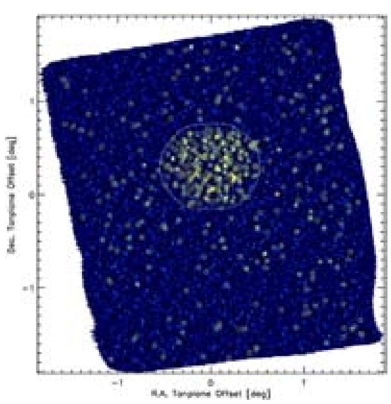
Over the course of a few years, experience in the field should grow to the point where the best space-flight experiment to search for polarization of the CMB can be properly designed.

The search for polarization in the CMB will parallel the way the search for anisotropy in the CMB was carried out. There are currently a number of groups developing balloon-borne instruments with different technologies, frequencies, and observing strategies. These include the E and B Experiment (EBEX), the Primordial Inflation Polarization Explorer (PIPER), and A Large Angular Scale Millimeter-wave Polarimeter (SPIDER). The groups developing them will work to understand the limitations of the technology and systematics that are particular to their techniques. Over the course of a few years, experience in the field should grow to the point where the best space-flight experiment can be properly designed.

Astrophysics Complementing Beyond Einstein

In addition to the Beyond Einstein program, several other astrophysics investigations will address the strategic goal "Discover the origin, structure, evolution, and destiny of the universe."

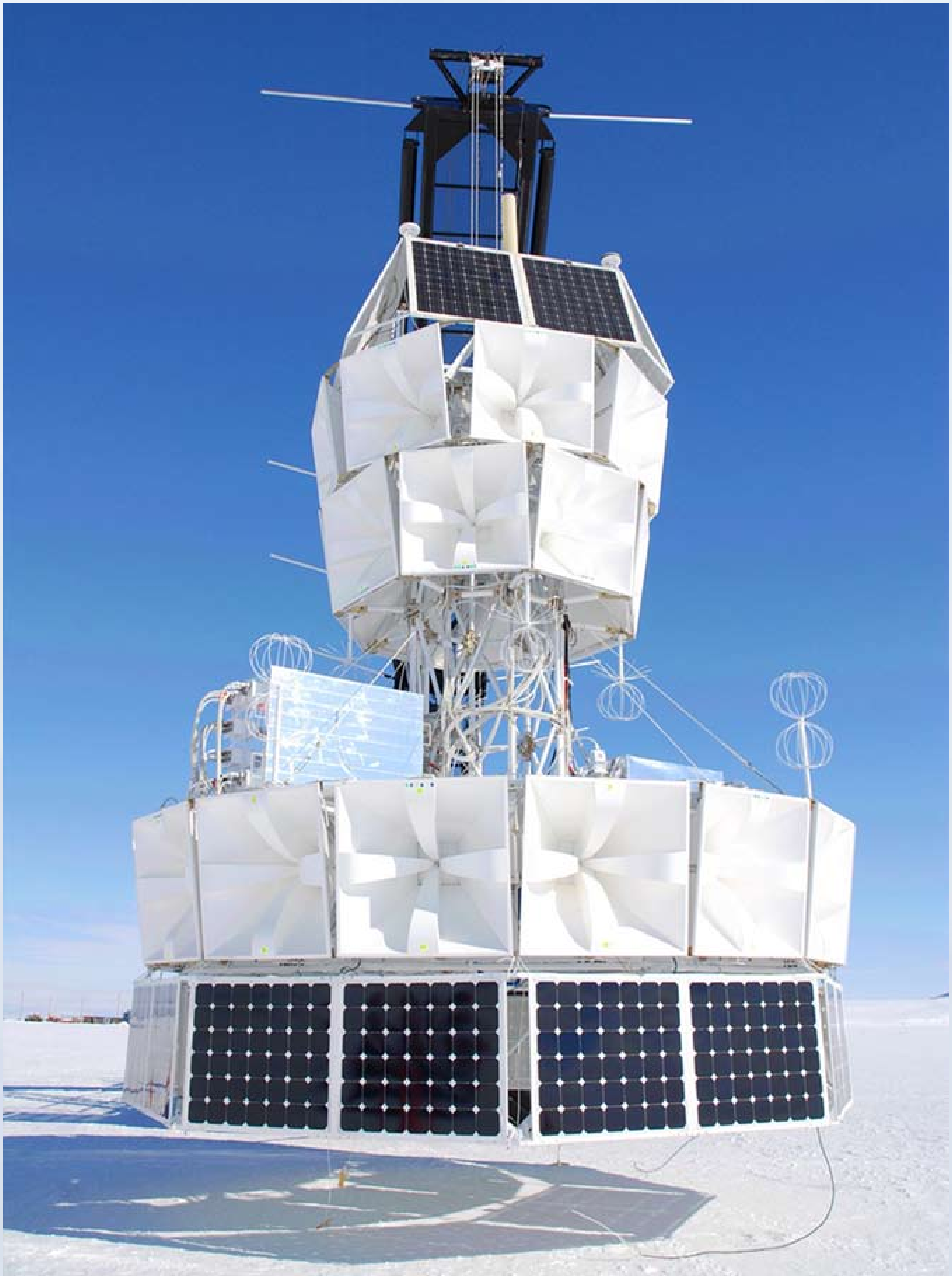
Submillimeter Astrophysics



A map of sources, probably Ultra Luminous Infrared Galaxies, detected by the Ballon-borne, Large Aperture Submillimeter Telescope (BLAST). The full image is an 8.7 square degree field; the inner circle is a 0.8 square degree deep field, which was scanned with increased sensitivity to weak sources.

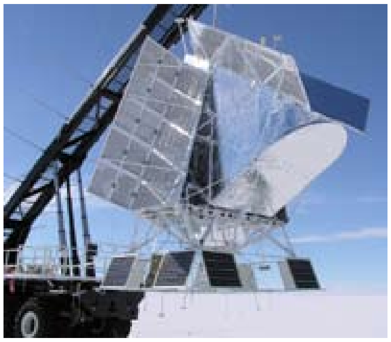
The polarized emission from our own Galaxy in the submillimeter region will provide a wealth of information about its structure, evolution, and dynamics as well as the formation of the first galaxies themselves. Warm (10-50 K) dust is the signature of star formation. Large dense clouds of dust serve as the birthplace of all stars in a galaxy. The star formation process heats the relatively opaque clouds to a temperature where they emit in the submillimeter portion of the spectrum. By studying the clouds, the origin of stars and solar systems can be understood. While these measurements are very powerful in their own right, they would also help scientists characterize the galaxy as a foreground for the Einstein Inflation Probe.

The Balloon-borne Large Aperture Telescope (BLAST) met all of these goals with two LDB flights, one from Sweden and on in Antarctica. Unfortunately, the payload was destroyed after landing at the end of the Antarctic flight. Were it not for the strong working relationship between NASA and the NSF Office of Polar Programs everything would have been lost. As it was, the data and a few key components of the experiment were recovered. While the data from the Antarctic flight are still being analyzed, the initial results indicate it was a great success. While BLAST was much smaller than a



The ANtarctic Impulsive Transient Antenna (ANITA) preparing for its successful August 2005 flight. ANITA will search for pulses of radio emission from neutrinos penetrating the Antarctic ice.

large ground-based telescope, the increased sensitivity at balloon altitudes meant that it could quickly survey large areas of the sky. To put this in perspective, in one 50-h survey, BLAST should be able to find one hundred times more submillimeter galaxies than the ground-based Submillimeter Common-User Bolometer Array (SCUBA) instrument has seen in several years. This makes it a very attractive tool for astronomers who need large surveys or follow-up in the submillimeter region. The BLAST "near-satellite" sensitivity and its ability to spend up to several hundred hours on a single patch of sky would make it a flexible and multipurpose space instrument for a relatively modest investment; however, it would also be possible to fly a larger (2.5-3 m) aperture version on ULDB vehicles making it a true submillimeter observatory.



The Balloon-borne Large Aperture Telescope (BLAST).

The future of submillimeter astronomy from balloons lies with polarization measurements, which have two key goals. First, it is postulated that galactic magnetic fields have a strong effect of on star formation. The same magnetic fields would polarize the submillimeter emission from the star forming regions. Hence, a polarized version of the BLAST payload would have almost the perfect resolution for studying this tantalizing effect. Secondly, the same kind of polarized emission on galactic scales could turn out to be a significant, if not limiting, foreground for the Inflation Probe mission. A small polarized submillimeter balloon payload could map out a large region of sky to address this question. While the PLANCK satellite should make this measurement at millimeter wavelengths, additional data at shorter wavelengths would be invaluable and achieved at relatively low cost.

Extremely High-Energy Neutrinos

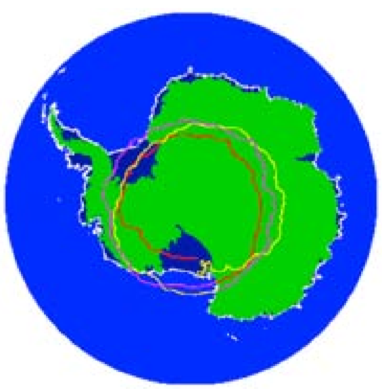
Science Plan, section 7.2.1 includes as one of its prime objectives probing "the Extremes of Spacetime" such as Black Holes. In the jets and accretion disks near Massive Black Holes, almost certain to be the engines for Active Galactic Nuclei, bulk particle acceleration is an observational fact, and neutrino emission is an inevitable consequence of the decay of pions produced in the colliding matter. These black holes are expected to produce neutrinos with energies of the order of 10^{14}–10^{19} eV. Constraints on neutrino fluxes from such sources will also constrain their role in the origin of the highest energy cosmic rays.

Science Plan, section 7.2.2 in addressing "the Galaxy-Black Hole Connection" notes the need to understand "the most powerful cosmic rays." The highest-energy cosmic rays (>10^{19} eV) originate almost by definition in the most extreme astrophysical environments possible with no accepted theory for their production. The neutrinos from interactions of these cosmic rays with the microwave background would be an important probe of those extreme environments and their source evolution history. In fact, a lack of detection of such neutrinos at the levels now predicted in conservative models would have profound consequences, forcing a reevaluation of the fundamental understanding of the highest-energy cosmic rays.

The very low flux and low interaction probability of the highest-energy (>10^{18} eV) neutrinos require enormous detector volumes. Balloons offer a unique capability at these energies, not achievable with either ground-based instruments or instruments in spacecraft, of monitoring a million square kilometers of Antarctic ice for bursts of coherent GHz radio emission coming from the electromagnetic cascade that develops when a neutrino interacts with the ice. The ANtarctic Impulsive Transient Antenna (ANITA) instrument successfully achieved its first balloon Antarctic balloon flight during the December 2006 – January 2007 austral summer and a second flight in December 2008 – January 2009. It complements ground-based instruments, such as IceCube, under construction at the U.S. Amundsen-Scott South Pole Station. Those instruments have smaller detector areas and thus are sensitive to neutrinos of lower energy, up to approximately 10^{16} eV, where the flux is higher.

High-Energy Cosmic Rays

Question 6 in The Physics of the Universe is "How do cosmic accelerators work and what are they accelerating?" Understanding supernovae – the energy they release, the nuclei they synthesize, and the cosmic rays they accelerate – is essential to the goals of the Cycles of Matter and Energy theme. The rigidity dependence of the process leads to a characteristic change in elemental composition between the limiting energies for protons and iron, respectively ~10^{14} and ~26×10^{14} eV. The Advanced Cosmic-ray Composition Experiment for Space Science (ACCESS) was given high priority in the 2001 NRC decadal study "Astronomy and Astrophysics in the New Millennium" to look for this characteristic signature, which would associate a limit to supernova acceleration with the "knee" feature around 10^{15} eV seen in extensive air shower data for the all-particle spectrum.



Trajectory of the CREAM instrument December 1, 2009 to January 10, 2010, the most recent three-orbit flight over Antarctica, this one lasting almost 37 days.

The Cosmic Ray Energetics and Mass (CREAM) instrument has 25% of the geometric acceptance of ACCESS and similar science objectives. It was developed for the ULDB demonstration mission and has now flown on four LDB flights. The maiden flight of CREAM circumnavigated the South Pole three times during a 42-day record-breaking flight in December 2004 and January 2005. A cumulative exposure of 70 days within 13 months was achieved when the second flight completed its 28-day journey in January 2006 after twice circumnavigating the South Pole. The total exposure reached 118 days with a 29-day flight ending in January 2008 and a 19-day flight ending in January 2009. The fifth flight of CREAM was launched December 1, 2009, and added 37 more days of exposure. Future flights would extend the CREAM energy reach to higher energies.

The CREAM measurements provide a bridge to connect the voluminous, high quality satellite data at energies three to four decades below the "knee" (~10^{15}eV) with the ground-based air shower measurements extending at least five orders of magnitude above the knee. The energy reach of CREAM overlaps ground based air shower measurements for about an order of magnitude below the "knee."

Antiparticles in the Cosmic Rays

The BESS instrument measures cosmic-ray particles and antiparticles to study the early universe and cosmic-ray processes. In December 2004 and again in 2007 the BESS-Polar spectrometer completed successful Antarctic flights. The 2004 flight lasted 8½ days and the 2007 flight, during solar minimum, yielded more than 24 days of data from a 30-day flight. Its search for an excess of low-energy antiprotons could provide evidence for the existence of primordial black holes dating from the creation of the universe. Antiproton excess could also result from annihilation of neutralinos or other dark matter particles trapped in the gravitational field of our galaxy. While no anti-helium has been discovered in the cosmic radiation, the BESS-Polar flights will set new limits, lower by a factor of approximately 20 compared to prior experiments. The presence of anti-helium in the cosmic radiation would provide evidence for a baryon-symmetric cosmology.

While no anti-helium has been discovered in the cosmic radiation, the BESS-Polar flights will set new limits, lower by a factor of approximately 20 compared to prior experiments.

The BESS instrument had nine conventional ~1-day balloon flights between 1993 and 2002 with the objective of measuring the spectra of light nuclei, including antiparticles. The BESS-Polar instrument has increased sensitivity at low energies. Its geometric acceptance (~0.3 m^2 sr) is similar to that of the Alpha Magnetic Spectrometer (AMS) planned for the International Space Station, and much greater than any prior balloon-borne magnet spectrometer. Excellent particle identification is achieved with its advanced superconducting magnet and sophisticated particle detectors.

Cosmic Rays Heavier than Iron

The Trans-Iron Galactic Element Recorder (TIGER) instrument flew twice over Antarctica, in December 2001 – January 2002 and again two years later, accumulating a total of fifty days of data on the elemental composition of the rare cosmic rays with atomic number greater than 26. Its excellent charge resolution gave the first precise abundance measurements of elements with atomic number up to 34, and provided new data supporting a model of galactic cosmic-ray origin in groups of young massive stars (OB associations). A four-times larger version of this instrument, Super-TIGER, has been approved for development, leading to an Antarctic flight in December 2012. This new instrument will extend our precise knowledge of the cosmic-ray elemental composition substantially further up the periodic table. TIGER is also a prototype for one instrument being studied for future space flight as one of the Astrophysics Strategic Mission Concept Studies.

Gamma-Ray Lines

A new generation of compact Compton telescopes now under development will provide dramatic improvements in sensitivity for gamma-ray astrophysics. The ACT, a Vision Mission concept utilizing these technologies, is being designed to study radioactive nuclei produced in stellar explosions, which then seed new generations of stars and the evolution of planetary systems. ACT would address Cycles of Matter and Energy objectives and NASA's exploration priorities. Prototype Compton telescopes are now under development for conventional and LDB payloads. Looking forward to ultra long-duration balloon (ULDB) exposures, these instruments would greatly improve the currently coarse images of ^{26}Al (1.809 MeV) emission from novae and massive stars, allowing their distribution to be measured in the galaxy. Perhaps most exciting, a large-area ULDB ACT mission would allow pathfinder measurements of the expected ^{56}Ni (0.847 MeV) emission from Type Ia supernovae in nearby clusters of galaxies (e.g., Virgo). This, in turn, would constrain both the physics and evolution of these fundamental, but poorly understood, probes of distance scale and dark energy in the universe, in addition to providing otherwise unattainable information about the mechanisms of heavy nuclei production in supernovae.

The technology required to detect and characterize potentially habitable worlds is enormously challenging, and no single mission can provide all the measurement capablilities.

Search for planets around other stars

The NASA Science Plan for 2007 – 2016 includes in section 7.2.4, "Exploring New Worlds," "The technology required to detect and characterize potentially habitable worlds is enormously challenging, and no single mission can provide all the measurement capabilities." Stratospheric balloon-borne telescopes are potential platforms for the discovery and characterization of exoplanets. The technical challenge is to achieve the necessary dynamic range in the immediate neighborhood of a targeted star. Meeting this challenge depends primarily on the design of the light-suppressing element in the telescope and the quality of seeing in Earth's stratosphere.

There are at least four competing designs that incorporate internal occulters, with expected contrast ratios of ~10^{-10} close to the star. These designs, in historical order, are shaped pupil, band-limited mask, pupil mapping, and vortex mask. In principle, any of these could be used as an internal coronagraph, and could be used to detect exoplanets.

Wavefront distortion ("seeing") in the stratosphere is mild compared to seeing at ground-based sites; indeed it is similar to the imaging conditions in space. There are no direct measurements of stratospheric seeing, but there are two lines of evidence that it is good enough for exoplanet observations. First, theoretical predictions of wavefront distortion by the free atmosphere, based on satellite observations of stars occulted by Earth's limb, suggest that exoplanet contrasts of 10^{-10} should be readily achievable. Second, experimental measurements of the local gondola-induced air turbulence have been instrument-limited to less than 1/1000 wave rms, which corresponds to a contrast of 10^{-8} or less. This is an acceptably good upper limit, given that there are about twenty known exoplanets that have angular separations accessible to balloon-borne coronagraphs (i.e., greater than 0.1 arcsec) and expected planet/star contrast values in the range 10^{-9} to 10^{-8}, i.e., potentially bright enough to stand out against a speckle background.

Heliophysics

Recent advances in observing the Sun and its extended atmosphere, coupled with equally impressive advances in theory and modeling, have initiated a new era of quantitative understanding of solar phenomena and the diverse physical processes that underlie them. The joint Japan/US/UK Hinode mission exemplifies this new solar physics. Hinode observations of unprecedented spatial resolution reveal the intricacies of the vector magnetic field in quantitative detail, and simultaneously record the dynamics of the upper layers of the solar atmosphere where energetic photons, particles, and magnetic fields arise.

NASA's 2007 Science Plan for the Science Mission Directorate outlines key research objectives for Heliophysics in the coming decade. Planned and future balloon missions will contribute uniquely to several of the Specific Research Focus Areas outlined in that report:

- Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms

- Understand the plasma processes that accelerate and transport particles

- Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments

- Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment

- Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events

High-Resolution Imaging

High-resolution observations, especially when carried out with quantitative measurements of magnetic fields, flows, and thermal properties of the solar atmosphere, are necessary to address long-standing problems of solar physics including: heating of the solar chromosphere and corona, acceleration of the solar wind, initiation and release of energy in solar flares and coronal mass ejections.

The Solar Bolometric Imager (SBI) shown here is an innovative, balloon-borne solar telescope that can take images in light integrated over nearly the entire solar spectrum.

Many of these most important issues in solar physics center on physical processes that take place at very small scales within the solar atmosphere. Although Hinode provides a dramatic advance in resolution, it still represents a compromise: its 50-cm aperture does not allow full resolution of crucial scales in the solar atmosphere such as the density scale height. The recently flown Sunrise balloon mission, with its large 1-m aperture and ultraviolet capability, provides the first ever observations that resolve the scale height in the solar photosphere. The use of a balloon platform offers significant advantages. Sunrise is realized at a tiny fraction of the cost of an equivalent orbital mission, and allows for the possibility of changes in its instrumentation on subsequent flights. Sunrise will explore measurement of the magnetic field vector in the solar chromosphere where extrapolation of the measured field into the solar corona becomes more tractable. Furthermore, the mission will employ new lightweight mirror technology that could be used in future large-aperture orbiting solar telescopes.

Imaging the Sun in the Ultraviolet

High altitude balloons offer access to some ultraviolet wavelengths not visible from the ground. The Sunrise telescope will take advantage of the transmission window at 220 nm at float altitudes of 30-40 km. At somewhat higher altitudes it is possible that one may observe very interesting solar spectral emission lines below 200 nm. Small payloads of limited weight at very high altitudes could benefit from development of multiple-payload missions and modular pointing infrastructure, as recommended by the whitepaper report of the Low-Cost Access to Near Space (LCANS) Workshop held in Boulder, CO in April, 2007.

Other Balloon Opportunities for Solar Observing

Other solar science opportunities proposed for the next decade include a new approach to high-energy x-ray imaging of the Sun. A high-energy x-ray and gamma-ray imaging instrument could provide fifty times RHESSI's sensitivity to gamma-ray lines from solar flares. It would contribute to the Focus Area of understanding the plasma processes that accelerate and transport particles. If the x-ray and gamma-ray imager and a telescope with new neutron detection technology were mounted together on a ULDB platform, the science return for a high-energy flare mission would be comparable to that of a small Explorer at a small fraction of the cost.

Earth's Magnetosphere

Strategic goal 3.2 of the 2006 NASA Strategic Plan is, "Understand the Sun and its effects on Earth and the solar system." Subgoal 3B.3 looks to "Progress in developing the capability to predict the extreme and dynamic conditions in space in order to maximize the safety and productivity of human and robotic explorers." In particular, the Radiation Belt Storm Probes Mission (RBSP) will "improve the understanding of how solar storms interact with and change the particles, fields, and radiation in Earth's Van Allen radiation belts and atmosphere." A top priority for RBSP is, "differentiating among competing processes affecting the precipitation and loss of radiation particles"

BARREL 2009/2010 Antarctic Balloon campaign logo.

In December 2007 NASA awarded a grant for the Balloon Array for Radiation-belt Relativistic Electron Losses (BARREL), which will launch a series of relatively small (300,000 cu ft) balloons in Antarctica on a daily basis. Each series of launches will produce a ring of detectors around the South Pole to monitor precipitating electrons, thereby complementing simultaneous observations with the RBSP satellites. Balloons provide an ideal platform for measuring radiation belt electron precipitation, with two major advantages over the more traditional spacecraft measurements:

(1) They provide a nearly stationary platform, making it possible to separate spatial and temporal variations in precipitation, which is observed to last from minutes to hours at a single location. A spacecraft in low Earth orbit flies through the radiation belt region in a few minutes, and may be in a precipitation region for

only tens of seconds, so detailed temporal analysis is not possible. Balloons provide the only method for studying this temporal variation. The temporal modulation on timescales from seconds to minutes already observed from balloons is still not understood. The lack of temporal-spatial ambiguity in balloon measurements also allows the spatial extent of a precipitation region to be measured, which is critical for determining the total loss rate.

(2) They measure only those particles that are truly being lost to the atmosphere. The electron loss cone is that part of the angular distribution of particles that will be lost to the atmosphere. At the equator, the loss cone is only a few degrees wide, so spacecraft particle detectors cannot resolve it. This is especially true at MeV energies, where it is difficult to construct detectors with sufficient collimation, and scattering in the detectors blurs the angular measurement. Low-altitude spacecraft such as the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX), do better since they measure a larger fraction of particles that mirror at lower altitude; however, they still must separate the trapped and precipitation populations in their measurements, which can be difficult. Balloons naturally measure only the precipitating particles, making it easier to quantify the electron loss rate.

Earth Observations

Current Balloon Contributions

Most Earth science disciplines do not use balloon platforms. Instead, they prefer aerial observations with controlled flight paths of aircraft, which also have the ability to go to specific locations. Balloons have been used for studies of stratospheric chemistry, where control of flight paths is less critical and access to the stratosphere is most important. Balloons provide *in situ* validation of data from spacecraft to address a number of questions from the *NASA Science Plan for Earth Science* for studying the atmosphere of Earth (e.g., Earth Science Questions, Table 4.1: How is atmospheric composition changing? How do atmospheric trace constituents respond to and affect global environmental change? How will future changes in atmospheric composition affect ozone, climate and global air quality?) They also provide the possibility of observing detailed processes on much finer spatial and temporal scales than orbiting spacecraft.

The Atmospheric Composition focus area in the Science Plan (Section 4.2.1) acknowledges the importance of suborbital observations: "Understanding atmospheric composition in the Earth system requires an integrated approach including a hierarchy of space-based, suborbital, and pathfinder observations, …". Currently, multi-instrument balloon payloads are making critical validation measurements for the Earth Observing System (EOS) Aura satellite. These include recent winter measurements in Kiruna, Sweden to sample the polar vortex under extreme temperature and composition conditions, as well as both remote sensing and in situ instruments at mid-latitudes.

Only a small fraction of a balloon's volume is filled with helium on the ground. The helium expands as the balloon rises, so at float altitude the balloon is fully inflated and nearly spherical.

Balloons are also being used as a platform for flights of newly developed instruments to advance their Technical Readiness Level (TRL). For example, the Far Infra Red Spectroscopy of the Troposphere (FIRST) instrument was developed under NASA's Instrument Incubator Program.

Ultra-Long Duration Balloons, ULDBs, could provide a platform for making some of the critical measurements that cannot be accommodated from space.

Potential Contributions with Super-Pressure Balloons

The recent NRC Decadal Survey for Earth Science called for fifteen high priority new missions for the period through 2025. However, current NASA budget profiles *(Science Plan, Section 4.3.3)* project a capability of 8-9 new missions over that time period. Super-Pressure Balloons flying for ~100 days (ULDB) could provide a platform for making some of the critical measurements that cannot be accommodated from space. In addition, they could provide measurements for which there are no planned satellites.

One of the high-priority Decadal Survey missions is the Climate Absolute Radiance and Refractivity Observatory (CLARREO), which would provide spectrally resolved radiation measurements. Measurements of Earth's radiation budget (i.e., the balance between incoming and outgoing radiation) are of critical importance to understanding climate change. NASA has made Earth Radiation Budget (ERB) measurements from a series of satellites for several decades. Satellites are an ideal platform for making such long-term measurements. but it is critically important to have consistency between successive satellites (and instruments) to ensure a reliable long-term record. ULDB flights could provide this invaluable complement to the satellite instruments. Balloon instruments can be precisely and accurately calibrated to National Institute of Standards and Technology (NIST)-traceable standards before and after flights, and can provide a calibration (or transfer) standard between successive satellites. This carefully intercalibrated data set would be very valuable for addressing changes in the incoming and outgoing radiation over decadal time scales.

NASA's Tropical Rainfall Measuring Mission (TRMM) satellite carries a Lightning Imaging Sensor (LIS), which has made some significant discoveries including the fact that there is virtually no lightning over oceans; however TRMM will be ending and the future series of NOAA weather satellites [i.e., the National Polar-Orbiting Operational Environmental Satellite System (NPOESS)] will not carry lightning sensors. Nevertheless, the measurement has considerable value for precipitation research. ULDB would operate at almost an ideal altitude—above all weather, but close enough to thunderstorms to provide a close-up view rather than the 8-km-average smeared view provided by LIS and other satellite sensors. In addition, ULDB instruments could observe the full temporal development of a lightning storm, as opposed to the snapshot taken by a satellite that races past and is gone for 90 min. Sprites and other electrical phenomena occurring above a thunderstorm, only discovered in the 1990s, would also be ideally observed from a ULDB. Aircraft dare not approach closely and cannot fly high enough or long enough to gather much data.

Atmospheric composition has been the Earth science research area that has made use of balloons over the past two decades. The EOS Aura spacecraft is providing most of the atmospheric composition measurements needed by that community. However, the next atmospheric composition mission to provide such complete coverage (including polar regions such as the Antarctic ozone hole) is late in the Decadal Survey queue. ULDB flights could provide a means to fill any gap between missions in addition to providing continuous coverage of the recovery of stratospheric ozone over the coming decades.

One critical measurement for the Earth Surface and Interior focus area that cannot be made from space is of the Crustal Magnetic Field *(Earth Science Decadal Survey, pg 8-30).* Such a measurement could be made from ULDB flights, which could address questions such as: What are the natures of the upper, middle, and lower crust? How is the South Atlantic magnetic anomaly changing? What is the sub-ice circulation in polar regions? What are the stratospheric/atmospheric processes with magnetic signatures? Measurements from stratospheric balloons would enable processes in the crust to be measured directly and would complement those from aircraft and satellites.

Changes in ice sheets are an important factor both as a contributor to, and as an indicator of, climate change. Another near term Decadal Survey mission is ICESAT II, a lidar mission to map the surface topography of ice sheets. While satellites can easily measure surface topography, measuring the depth (or volume) from space is much more challenging. ULDB with trajectory modification capability would be ideal platforms for carrying ice-penetrating radar to map ice volume. As long as the ULDB could be kept over the ice sheet, the exact trajectory would not matter much, as long as the whole ice sheet is eventually mapped. Changes in ice sheet volume between mappings spaced 5–10 years apart would allow us to estimate outflow glacier flux and determine the relative importance of outflow glaciers vs. precipitation-melting balance in controlling ice sheet volume.

Ground-penetrating radar is revolutionizing the study of water resources underground. In the past, these could only be studied and mapped using boreholes. Now, similar mapping can be achieved for far lower cost and with far greater accuracy using ground-penetrating radar, sometimes dragged on sleds across remote areas not served by roads. ULDB could carry such radars and provide far wider mapping at even lower cost. Freshwater availability is a critical societal issue to which these measurements could contribute.

Balloons, particularly ULDB, could also serve as a platform for the Venture class of missions identified in the Earth Science Decadal Survey.

Solar-System Observations

Balloons can contribute to planetary exploration in two very different ways. Observations from balloons flying in Earth's atmosphere are uniquely suited to a number of planetary science questions. Balloons can also be a platform in the atmosphere of other planets. Although development of balloon missions on other planets is outside the scope of NASA's Balloon Program, this program has expertise that can be a valuable resource for both planning exo-Earth missions and demonstrating some of their critical technologies.

Planetary Observations from Earth's Stratosphere

Unlike space-based telescopes, balloon-borne platforms are inexpensive enough to be dedicated to specific projects, such as long spectral exposures of faint solar system targets.

Stratospheric balloon-borne telescopes have unique advantages in the context of Solar-System observations. Unlike ground-based telescopes, balloon-borne telescopes have diffraction-limited point spread functions, access to certain UV and IR spectral regimes, and the ability to image objects close to the direction of the Sun. Unlike space-based telescopes, balloon-borne platforms are inexpensive enough to be dedicated to specific projects, such as long spectral exposures of faint solar system targets.

The most recent Solar System Decadal Survey (Priority Questions for Solar System Exploration 2003-2013: The Basis for an Integrated Exploration Strategy) lists "12 Key Scientific Questions" that derive from four cross-cutting themes. Here we list four examples that showcase the ability of stratospheric balloon-borne telescopes to address key solar system questions.

(1) One cross-cutting theme is "The First Billion Years of Solar System History." With their ability to look at objects near the Sun with low levels of scattered light, stratospheric telescopes are uniquely capable of obtaining IR spectra and images of Sun-grazing comets. Comets, particularly long-period comets making their first solar encounters, are likely to be pristine reservoirs that formed in the early solar nebula. The ability to observe them from a space-like environment as they outgas near the Sun is an important capability of balloon-borne telescopes.

(2) A second theme is "Volatiles and Organics: The Stuff of Life." The most effective way to study volatiles and organics throughout the solar system is by infrared spectroscopy, as most organic molecules have their strongest spectral features in the 1 to 10 μm regime. Amino-acid precursors such as ammonia, HCN, or methanol have fundamental spectral features near 5 microns, a region that is difficult to observe because of low solar flux and high thermal backgrounds. Stratospheric instruments have transparent access to this entire spectroscopic window. With lower thermal backgrounds and virtually no column of water, a balloon-borne spectrograph could survey the faint, frost covered objects in the near- and mid-IR to look for the spectral signatures of important organic molecules.

(3) In the third theme, "The Origin and Evolution of Habitable Worlds," one key question is "Why did the terrestrial planets differ so dramatically in their evolution?". This question can be addressed in part by observations of Venus and Mars. Balloon-borne telescopes are particularly well-suited to observe Venus, an object that is close to the Sun, in UV and IR wavelengths that will track clouds in Venus's atmosphere, map the distributions of trace constituents (like water vapor), and map the abundance

of SO2. Balloon-borne telescopes will easily surpass HST observations in spatial resolution, since HST can only observe Venus when it is far from the Sun (and therefore a smaller disk than at its inferior conjunction).

Balloons have the potential of collecting in situ atmospheric data and high-resolution geological, geochemical, and geophysical data.

(4) The fourth theme is "Processes: How Planetary Systems Work." On Mars, Triton, Pluto, and (we expect) countless Kuiper-Belt Objects, a surface frost constituent and the primary atmospheric constituent are in vapor pressure equilibrium. Stratospheric telescopes are well suited to study the interacting surfaces and atmospheres of these objects, via infrared spectroscopy of their surfaces (including the 4.28 μm nitrogen frost feature that is blocked by Earth's atmosphere) and by observing stellar occultations to assess the atmospheric vertical profiles. Balloons can be deployed over water and land to acquire occultation light curves.

Planetary Ballooning

The 2006 roadmap for Solar System Exploration includes under the general question "How did the Solar System evolve to its current diverse state?" the objectives "Determine how the processes that shape planetary bodies operate and interact," "Understand why the terrestrial planets are so different from one another," and "Learn what our Solar System can tell us about extra-solar planetary systems." Balloon missions can contribute to these objectives by addressing the specific goals of carrying out multidisciplinary comparative studies of planetary atmospheres, surfaces, interiors, and satellites. For example, they can perform studies of Venus' atmospheric chemistry and surface/atmosphere interactions.

Collection of *in situ* atmospheric data and high-resolution geological, geochemical, and geophysical data is best done using an aerial platform. The ability to collect data near the surface, and embedded in the boundary layer, complements orbital observations, and provides much greater coverage than surface rovers. Progress on many science issues would be enabled by even sparse low-altitude data, because of the unique vantage point they provide. For exploration of Venus and Titan balloons have the potential of collecting *in situ* atmospheric data and high-resolution geological, geochemical, and geophysical data.

The 2006 roadmap for Solar System Exploration, in a section "Technologies for *In Situ* Exploration" notes that, "Many of the missions in this Roadmap require direct access to the atmosphere and surface of planets and satellites. This is achieved through the use of planetary probes, landers, and mobile surface and aerial platforms." Further this planetary Roadmap anticipates "that the deployment and inflation of balloon systems for the proposed Titan Explorer (TE) and Venus Mobile Explorer (VME) missions would be straightforward, with the descent providing ample time for completing these operations." Under the section on "Planetary Mobility" the report states, "The thick atmospheres of Titan and Venus enable buoyant vehicles that are much less susceptible to being immobilized by surface obstacles or surfaces with low bearing strengths. Aerial vehicles can also travel over much greater distances with less energy consumption. They would provide local imaging, as well as chemical and mineralogical sampling, at multiple sites for both the proposed VME and TE."

NASA's Space Exploration Policy

The radiation environment in the polar stratosphere is similar to that found on the way to, or at, the Moon or Mars. Balloons offer an ideal platform for Radiation Research.

In preparing for sending humans on missions to the Moon and Mars, NASA recognizes the vital importance of research on radiation health and radiation protection. The NASA Radiation Research Program aims to develop the scientific basis for the protection of human crewmembers from space radiation. Long-duration balloon flights over Antarctica, are capable of exposing a variety of materials and radiation monitors to weeks of cosmic radiation. The radiation environment in the polar stratosphere is similar to that found on the way to, or at, the Moon or Mars, so balloons offer an ideal platform for this Radiation Research Program.

Piggy back dosimeters have been flown on several balloon-borne cosmic-ray payloads including ATIC, TRACER, TIGER and CREAM. The data collected thus far support the idea of using high altitude balloon flights for studies of radiation shielding. The background radiation needs to be measured during the flight to improve the fidelity of the exposure. The Linear Energy Transfer (LET) spectra and directionality are similar to those calculated for interplanetary space. This study will continue with more flights. Repeated flights will help sort out the impact of the secondary particle contribution which depends on the flight path, float altitude and its variation, and the primary payload configuration.

The Advanced Thin Ionization Calorimeter, ATIC, measured cosmic-ray proton and helium spectra up to more than 10^{14} eV and electrons to nearly 10^{12} eV.

"A balloon payload is effectively a satellite on a string, much cheaper, with the possibility for servicing after flight. A student has the opportunity to work on every phase of such a payload."

Dr. John C. Mather,
Senior Astrophysicist, Nobel Laureate

"The first balloon-borne CMB experiment -- three flights of the cooled 3-mm receiver -- proved that cooled receivers could be made sufficiently well to use them on COBE."

Dr. George F. Smoot,
Astrophysicist, Nobel Laureate

"The NASA Balloon Program was critical to my development as a scientist, both in graduate school and as a junior faculty member at Caltech."

Dr. Thomas A. Prince,
Chief Scientist at JPL

"The NASA scientific ballooning program provided me with the complete and quintessential scientific experience, going from concept to hardware, observations, and scientific analysis of the results—all in the time frame of a few years.

Dr. John M. Grunsfeld
Astronaut and former Chief Scientist

Many Scientists with Leading Roles in NASA were Trained in the Balloon Program

The National Research Council Committee recommends that NASA increase its investment in proven programs such as high-altitude balloon campaigns, which provide ample opportunity for hands-on flight development experience at a relatively low cost of failure.

The Science Plan notes (section 3.7) that a goal of SMD programs is to "Strengthen NASA and the Nation's future workforce."

The National Research Council's Committee on Meeting the Workforce Needs for the National Vision for Space Exploration, its 2007 report, *Building a Better NASA Workforce: Meeting the Workforce Needs for the National Vision for Space Exploration,* noted (Finding 6), "Involvement in providing development and educational opportunities, especially hands-on flight and vehicle development opportunities, will pay future dividends not only by encouraging larger numbers of talented students to enter the field, but also by improving the abilities of incoming employees." The report also states (Recommendation 6) "The committee recommends that NASA increase its investment in proven programs such as sounding rocket launches, aircraft-based research, and high-altitude balloon campaigns, which provide ample opportunities for hands-on flight development experience at a relatively low cost of failure."

Many of the leading scientists in NASA's programs today—both NASA employees and scientists at universities—received their early training in the Balloon Program. Four outstanding examples are John Mather, George Smoot, Thomas Prince, and John Grunsfeld.

Dr. John C. Mather, Senior Astrophysicist at NASA's Goddard Space Flight Center, and Dr. George F. Smoot, Professor of Physics at the University of California—Berkeley, shared the 2006 Nobel Prize in Physics for their leadership of the COBE satellite mission.

Dr. Mather, who is now the Senior Project Scientist for the James Webb Space Telescope, attests to the importance of ballooning in his career:

> The Cosmic Background Explorer satellite (COBE) sprang directly from my thesis work at UC Berkeley on the cosmic background radiation. It started with ground-based measurements, progressed to a balloon payload (now on display at the Air and Space Museum), and then, only months after completing my Ph.D., I organized a team to propose the COBE satellite. A balloon payload is effectively a satellite on a string, much cheaper, with the possibility for servicing after flight. A student has the opportunity to work on every phase of such a payload, from scientific concept to mission design, construction, integration, test, flight, and data analysis, or, as luck had it my case, to after-the-fact failure analysis of the first flight. Such experience is worth its weight in gold to enable new generations of leaders for NASA science and engineering. In addition, ballooning is essential to learn what can be done at low cost before we are justified in moving projects into space.

Prof. Smoot describes the importance of ballooning to his career and to the development of that Nobel-Prize-Winning COBE investigation.

> Beginning in 1970 I was involved in a series of balloon-borne experiments—superconducting magnetic spectrometers for cosmic-ray physics, gamma rays and searches for antimatter. After that we had a series of CMB instruments—first U2 aircraft and then balloon-borne—that related directly and indirectly to COBE. The first balloon-borne CMB experiment—three flights of the cooled 3-mm receiver—proved that cooled receivers could

> be made sufficiently well to use them on COBE to make the COBE DMR CMB anisotropy maps and later the WMAP maps. The factor of two in sensitivity gained by cooling was crucial in the discovery of anisotropies. We continued ballooning with the MAX (Millimeter-wave Anisotropy eXperiment) which found anisotropy on intermediate angular scales. Then MAXIMA (MAX Imaging Array), along with sister experiment BOOMERANG, found the first acoustic peak in the CMB anisotropy and thus that the Universe has a flat geometry. These were absolutely critical for (1) training people, (2) developing and proving techniques and technology, as well as convincing the conservative space systems management that they had heritage, reliability, and efficacy.

Without the next generation of instrumentalists, practical knowledge about how to work in endangered technical areas will be lost, greatly reducing the probability of success and diminishing U.S. leadership.

Both Dr. Thomas A. Prince, Professor of Physics at the California Institute of Technology and Dr. John M. Grunsfeld, NASA Astronaut, earned their doctoral degrees with dissertations that reported results of cosmic-ray investigations carried out on balloons.

Prof. Prince, an accomplished researcher in gamma-ray astronomy, served as Chief Scientist at JPL from 2001 to 2006 and is the NASA Mission Scientist for LISA, one of the two Beyond Einstein great observatories. He captures the value of the Balloon Program for training of scientists:

> The NASA Balloon Program was critical to my development as a scientist, both in graduate school and as a junior faculty member at Caltech. I can't imagine a better scientific training for experimental space science than the experience of building and launching a science payload on a balloon. You directly experience all the important steps: design to cost, schedule, weight, and power constraints; quality control and risk management; field operations; and reduction and analysis of data. The impact of the NASA Balloon Program goes far beyond the demonstration of technology and the direct science data that are produced—the scientists who 'cut their teeth' in the NASA Balloon Program are very often the leaders of today's NASA space science missions and programs.

Dr. Grunsfeld is an astronaut who has been in space five times, including three missions to repair and upgrade the Hubble Space Telescope. He served recently as Chief Scientist at NASA Headquarters. He also attests to the value of the balloon program:

> In my career as a scientist, astronaut, and as NASA's Chief Scientist, I often reflect back on the strength of the foundation upon which I was trained. As an undergraduate and as a graduate student I had the great fortune to perform experiments in high-energy astrophysics using high-altitude balloons as a platform for access to space. The NASA scientific ballooning program provided me with the complete and quintessential scientific experience, going from concept to hardware, observations, and scientific analysis of the results—all in the time frame of a few years. The rich environment that NASA's sub-orbital program supports not only enables top quality science, but is also crucial as a training

In a February 2005 report, the National Research Council Committee to Assess Progress Toward the Decadal Vision in Astronomy and Astrophysics noted, "Instrument builders are particularly critical to the health of the field. Without the next generation of instrumentalists, practical knowledge about how to work in endangered technical areas (such as high-energy astrophysics) will be lost, greatly reducing the probability of success and diminishing U.S. leadership." This statement by the committee further underscores the importance of the Balloon Program.

The Balloon Program has Substantial Capability for Achieving Quality Science

Description of Balloons in Use and Envisioned

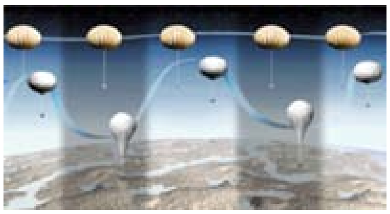
The scientific balloon program uses helium-filled polyethylene balloons of large volume, typically between about 0.3 and 1.1 million cubic meters (10–40 million cubic feet). Crews of the Columbia Scientific Balloon Facility (CSBF) based in Palestine, TX launch the balloons from various sites around the world. The balloons float in the stratosphere for periods ranging from about a day to over a month, following trajectories imposed by the wind at the float altitude. On radio command, the flights are terminated over an appropriate location, and the instruments parachute to the ground and are recovered for possible future flight.

A balloon has just been released (right) and moments later lifts the instrument payload off the launch vehicle (left). In the left-hand photo the parachute hangs from the bottom of the balloon, with the instrument payload hanging below the parachute.

"Conventional" balloon flights last on the order of a day, and the balloon support system is based on line-of-sight communications. These balloons are usually launched from the CSBF home base in Palestine, TX; from Ft. Sumner, NM; or Alice Springs, Australia; and their payloads are recovered typically within several hundred miles of the launch site. Special campaigns have launched from Alaska and Sweden. LDB flights have durations from about two weeks to more than a month. They use the same balloons employed for conventional flights, but a more sophisticated over-the-horizon communication system. They may be launched in Sweden for recovery in northern Canada or Alaska, or from the McMurdo base in Antarctica and recovered within a few hundred miles of McMurdo after traveling around the South Pole once, twice, or even three times. Pending approval for overflight, the flights launched from Sweden could continue over Russia, or flights could be launched from Fairbanks, AK, and recovered in northern Canada after flying westward around the world. These balloons may also be launched in Australia for recovery in that country or for trans-Pacific flight with recovery in South America.

Typically, stratospheric scientific balloons have carried one- to two-ton instruments to float altitudes of about 36.5–39.5 km (120,000 to 130,000 ft), where the residual atmospheric pressure is in the range of approximately 4.5 to 3 millibars (mbar). (Sea level pressure is approximately 1 bar, i.e., 1000 mbar.) Recently a 200-kg instrument was successfully flown on a 1.7 million cubic meter (60 million cubic foot) balloon to an altitude of 49 km, where the residual atmosphere is less than 1 mbar.

Balloons that have been used to date for both conventional and LDB flights are "zero-pressure," meaning that they are vented near the bottom to the outside, so the balloon pressure is in equilibrium with the atmospheric pressure at that point (zero differential pressure). Only a small fraction of the balloon's volume is filled with helium on the ground, since the helium expands as the balloon rises. Excess helium flows out the vents as the balloon reaches its fully inflated float altitude. After floating during a day, at night there is a cooling of the helium and consequent shrinking of the balloon volume, which causes the balloon to sink to a very much lower altitude. To reduce the altitude variation, ballast is dropped at sunset. Limitations on the amount of ballast that can be carried limit the number of sunsets a balloon can survive and the extent to which the diurnal altitude variation can be reduced. The longest duration LDB flights are flown during local summer over Antarctica or in the Arctic, where continuous sunlight permits the balloon to keep altitude without need to drop ballast.



Conventional zero-pressure balloons loose altitude dramatically at sunset. Even over Antarctica in December, when the sun never sets, the altitude of zero-pressure balloons varies in response to the daily variation of sun angle and in response to varying amounts of high cold clouds below the balloon. (green and magenta lines). Super-pressure balloons maintain constant altitude, essentially independent of external heat input (dark blue line).

Super-Pressure Balloons (SPB), capable of maintaining essentially constant volume day and night and thus to float at nearly constant altitude without need for dropping ballast, are currently under development. These balloons are sealed and designed to withstand slight differential pressure. They are inflated with enough helium to fill the volume at the coldest temperatures, and they have enough strength to hold that helium when sunlight heats it. SPB offer two advantages. First, they would permit LDB flights of one- to two-week durations at any latitude—say from Australia to South America—without diurnal altitude variation. Second, they would permit ULDB flights circumnavigating the globe at any latitude and lasting of the order of a hundred days. The current SPB development program is leading to 0.6 million cubic meter (22 million cubic foot) balloons capable of carrying 1000 kg instruments to an altitude of about 33.5 km (110 kft).

Multiple Payloads

The balloon program has a long history of payloads sharing resources. Most new balloon payloads are large collaborations involving multiple institutions. These collaborations frequently include international partners who make substantial contributions: BOOMERanG, BLAST, BESS, HEFT, and InFOCμS to name a few. Balloon collaborations can build enduring relationships that have been the foundation of collaborations on larger space missions such as GRO and INTEGRAL/SPI. In this respect, balloon payloads provide excellent training for large missions, which are collaborative ventures by necessity. The NASA investment in a new payload is frequently amortized over many flights and multiple PIs. Recovery of the payload is the key. Components of payloads are frequently reused and new payloads are almost never entirely new. This continuity in technology is an important part of the NASA corporate knowledge.

The carrying capacity of balloons makes sharing a flight practical, and shared science goals make sharing advantageous. Piggyback flights are often integrated and flown in short timeframes, demonstrating the balloon carrier's ability to support technology flights quickly. Ballooning has a long history of rideshares, many of them arranged by the Balloon Program Office. An example is the series of flights that led to the development of BARREL (Balloon Array for Radiation-

Balloon experiments are well suited to inexpensive hands-on student training projects that can foster student excitement in aerospace and science careers.

belt Relativistic Electron Loss). Predecessors to BARREL were flown as piggybacks on LDB flights in both the Arctic and Antarctic. Similarly, ANITA-Lite, a prototype of the ANITA detector system, flew as piggyback on a TIGER Antarctic LDB flight three years before the first ANITA flight. Additionally, an engineering test flight of prototype detectors for the Gamma Ray Polarimeter Experiment (GRAPE) and the CASTER missions were flown as a piggyback payload on a planned mission within eight weeks of contacting the Balloon Program. This kind of BPO support is exceedingly useful for the development of future balloon-based investigations that will keep the balloon program healthy and relevant.

NASA's stratospheric chemistry program has a long history of multi-instrument payloads with combinations of remote sensing instruments (e.g., the JPL Remote gondola flying recently for Aura validation) or a suite of in situ instruments (the Observations of the Middle Stratosphere in situ payload). Both of these combine instruments from multiple institutions on a single gondola in order to provide collocated and simultaneous measurements.

In some cases, standard platforms have been designed for multiple payloads, allowing the possibility of flying lightweight, inexpensive experiments without the complication of designing a custom ballooncraft interface for each payload. Deep Space Test Bed (DSTB) is an example of a ballooncraft designed to provide repeated flight opportunities for measurements of galactic cosmic-ray composition and energy spectra. It has provided experimental validation of radiation transport codes used to protect astronauts from space radiation, to test the radiation shielding effectiveness of spacecraft construction materials, and to develop and test new radiation monitoring instrumentation.

Balloon experiments are also well suited to inexpensive hands-on student training projects that can foster student excitement in aerospace and science careers. They teach both science and project management skills, and they help address workforce development issues. Since 2006, the NASA Balloon Program has collaborated with Louisiana State University to provide the High Altitude Student Platform (HASP) as an annual conventional balloon flight designed to provide students with a near-space flight opportunity to perform technology testing or make scientific measurements. The HASP platform is designed to carry up to twelve student payloads to an altitude of about 36 kilometers with flight durations of about twenty hours using a small-volume, zero-pressure balloon. The standard mechanical, power, and communication interface for the student payloads based on a flight-tested design. It simplifies integration, allows the student payloads to be fully exercised, and minimizes platform development and operation costs. In addition, HASP is lightweight with simple mission requirements, thereby allowing maximum flexibility in the launch schedule. Since 2006, over thirty university payloads have flown on HASP. They have included experiments to study the cosmic-ray flux, test rocket nozzle designs, measure the thermal characteristics of the balloon, evaluate an accelerometer-based inertial guidance system, and perform remote imaging.

Funding of the Balloon Program Office

The Balloon Program Office (BPO) at the Wallops Flight Facility of Goddard Space Flight Center manages NASA's balloon flight operations via a competitively selected support contractor. The BPO currently contracts with the New Mexico State University for management of the CSBF, which carries out the launches and flight operations, including flights launched both at the CSBF home site in Palestine, TX, and at remote sites. The BPO also carries out a research and development program to advance the capabilities of scientific ballooning.

The relatively short time required for development of balloon-flight instruments makes ballooning an ideal place for training graduate students and young scientists.

With its current annual budget of approximately $25M, the BPO supports ten to fifteen conventional domestic flights (approximately one-day duration from Palestine, TX; or Ft. Sumner, NM), one polar LDB campaign (annual flights over Antarctica), and an LDB campaign from either Kiruna, Sweden or from Alice Springs, Australia. Each of these LDB campaigns has the capability for two to three balloon flights.

The recent budget of the BPO has also supported the development of super-pressure balloons. This technology project is a phased development of super-pressure capability starting with relatively small balloons, and scheduled to lead to balloons large enough to carry a 1-ton instrument to 33.5 km by 2011–2012.

The Scientific Ballooning Assessment Group does not see reason for any changes in the program of the BPO for conventional flight operations, given the constraints of its budget. The Assessment Group notes, however, that this budget is barely adequate for supporting this program, and, as outlined in the Findings below, this report sees a need for enhanced funding to bring the super-pressure balloon technology to fruition to support a greatly enhanced science program.

Funding of Scientific Instruments

The scientific instruments flown by the Balloon Program are developed by investigators funded under NASA's Supporting Research and Technology (SR&T/R&A) program. The annual funding for development of instruments and analysis of data is approximately $15M. Investigations are selected by peer review of proposals submitted in response to annual Research Opportunities in Space and Earth Sciences (ROSES). The typical time from selection of a new instrument for development to the first balloon flight of the instrument is three to five years, depending on its complexity. The relatively short time required for development of balloon-flight instruments makes ballooning an ideal place for training graduate students and young scientists.

A serious weakness of the SR&T/R&A support is that the funding levels are inadequate for developing some of the sophisticated balloon-borne missions most capable of advancing key elements of NASA strategic plans. As a result, the number of highly rated payloads that can be supported has declined, and there are many more highly rated balloon-borne investigations proposed than will fit into the current budget.

The Assessment Group has not attempted to prioritize among the large number of potential balloon investigations. Indeed, a significant strength of the balloon program is that science is selected by peer review, providing opportunity for new ideas to be developed that were not foreseen in long-range strategic plans or roadmaps.

Findings

There is Need for Reliable Funding of New Balloon-Borne Instruments

Some proposed Long Duration Balloon, LDB, instruments are ambitious enough to be treated like small missions rather than SR&T/R&A investigations.

NASA's LDB capabilities have matured over the past two decades, opening a new era of scientific ballooning. The LDB vehicle has become a reliable platform for achieving significant amounts of observing time in a near-space environment. This capability makes the LDB platform a particularly cost-effective vehicle for NASA's scientific return. But recent years have seen a significant decrease in the number of balloon-flight instruments funded for development, in spite of the substantial number of highly rated investigations proposed. The viability of the balloon program depends on there being a steady stream of orders to the balloon manufacturer, and flights for the CSBF launch crew. The Scientific Ballooning Assessment Group considers assurance of adequate funding for new balloon-borne instrumentation to be of extremely high priority.

There are significant scientific opportunities that are enabled by these increased balloon capabilities. Given the improved balloon capabilities, the natural evolution of scientific payloads is towards increasingly more sophisticated and expensive instruments. Supporting enough payloads to satisfy the scientific proposal pressure is already beyond the scope of the current SR&T/R&A program. Furthermore, some proposed LDB instruments are ambitious enough to be treated like small missions rather than SR&T/R&A investigations. However, no viable means for funding large complex LDB payloads currently exists—because of the large gap between the current levels of suborbital payload support in the SR&T/R&A program and the Explorer program. A middle level competitive program could address this large gap, and it would represent a viable avenue for supporting future balloon missions. Such a program would allow NASA to utilize fully the mature LDB launch capability and a future ULDB capability, for optimal science returns.

Completion and Extension of Super-Pressure Balloon Development Will Enable Important New Science Capability

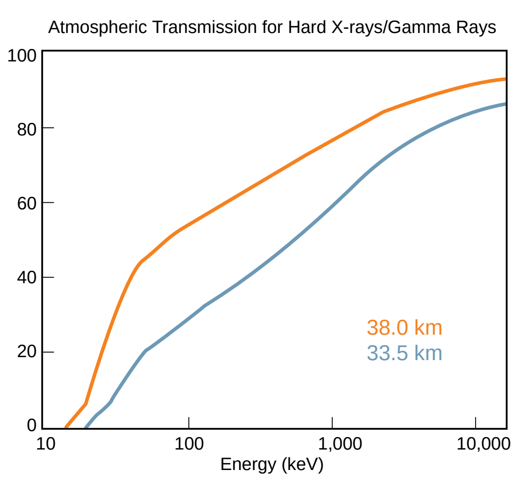
Super-Pressure Balloons: The Path to Future Science

To realize the science available from balloon-borne missions and telescopes, the Scientific Ballooning Assessment Group places high priority on completing as rapidly as possible the current development of a reliable super-pressure balloon SPB. Such a balloon maintains nearly constant altitude by maintaining fixed balloon volume (by positive internal pressure) throughout its flight. Conventional "zero-pressure" balloons, on the other hand, decrease in volume after sunset and then sink to lower altitudes unless ballast (a finite resource limiting flight duration) is dropped from the balloon prior to sunset. As recognized and recommended by the 2001 Astronomy and Astrophysics Decadal Survey, this capability would make balloon science truly competitive, and in some cases arguably superior, to orbital missions for some areas of investigation.

The development of such a balloon has been underway for several years, and over the past year NASA has achieved promising new breakthroughs in understanding the requirements for successful SPB fabrication and deployment. These advances were confirmed by the successful completion on February 20, 2009 of a 54-day test flight of a seven-million-cubic-foot SPB. *[and by the time we send this to press we may be able to add here something about the test flight of a larger SPB scheduled for launch in mid-June from Sweden.]* With these successes, it is likely that within a few years 1-ton science payloads could be flown for ~15-day mid-latitude flights between Australia and South America.

A viable SPB opens doors to new science. First, and foremost, it would enable LDB flights from *mid-latitudes,* not just the current LDB program from Antarctic and Arctic latitudes. For several high-priority science programs directly in support of the Beyond Einstein Program, namely theIP and BHFP, an SPB is essential. For the IP technology, and *possibly even a balloon borne version of the ultimate mission,* mid-latitude LDB is required in order to ensure night-time coverage of the sky. The sensitive bolometer type detectors needed for IP simply cannot tolerate the high and changing thermal load of daytime Sun. For the BHFP technology as well as preliminary black hole surveys on timescales not now possible with Swift, the mid-latitude capability is essential to avoid the high background rates encountered at polar latitudes as well as provide coverage of the full sky.

In addition to enabling LDB flights at mid-latitudes, super-pressure balloons are required for ultra-long-duration flights of the order of 100-day duration. In virtually every scientific area described in previous sections of this report, the scientific return is greatly enhanced by increased flight duration, permitting astrophysicists and solar and planetary astronomers longer-integration time for observation of weak sources, ability to survey more sources, and ability to observe temporal variations. They also permit Earth scientists to monitor extended temporal and spatial variations of Earth's atmosphere. Just as the extension of ballooning from conventional one- or two-day flights to LDB flights of two to six weeks opened doors to previously unrealized scientific capability, the extension from LDB flights of a few weeks to ULDB flights of a few months would expand scientific opportunities for a fraction of the cost of spaceflight missions.



Extension of the SPB Development Program

The currently planned SPB development program is leading to balloons capable of carrying an instrument weighing approximately 1 ton to an altitude of about 33.5 km. At that altitude, many of the investigations described earlier in this report can be successfully carried out; however, for measurement of gamma rays and hard x-rays, that altitude is inadequate. At 38 km, the atmospheric transmission is at least 40% for x-ray energies above 30 keV, while at 33.5 km, 40% transmission occurs only above 200 keV. At 33.5 km, the transmission at 30 keV is only 10%; to achieve signal-tonoise at this altitude comparable to that achievable at the higher altitude would require integration for a period sixteen times longer.

Because of this atmospheric attenuation, time spent below about 36.5 km is quite ineffective. Summer flights in Polar Regions, which provide long durations above 36.5 km with zero-pressure balloons, are not useful for these instruments because the charged-particle flux of cosmic rays is an undesirable background. These instruments are generally flown at mid-latitudes where the geomagnetic field excludes many of the cosmic rays that reach instruments near the poles. At mid-latitudes, the day/night variation of balloon altitude is inescapable for long-duration flights using zero-pressure balloons. Thus, an LDB flight on a zero-pressure balloon from Australia to South America spends roughly half the time at altitudes too low for useful measurements of gamma rays or x-rays. Consequently, a high priority for the gamma-ray and hard-x-ray investigations supportive of the Beyond Einstein Program is the extension of the super-pressure balloon development to reach 38-km altitudes with those instruments, which have typical weight of about one ton.

At the present time, there is no funding for development of trajectory modification capability, but this capability is needed for reliable 100-day ULDB flights at most latitudes.

Long Duration Flights Need Modest Trajectory-Modification Capability.

The ability to modify the trajectory of a balloon, even if limited to steering the balloon a few degrees off the direction that the winds are carrying it, would be necessary to utilize fully the capabilities of super-pressure balloons. Hundred-day flights would circumnavigate the globe more than once. Such ULDB flights at any other than polar latitudes would face the possibility of premature cut-down if winds were carrying the balloon toward a heavily populated area, where safety requirements can prohibit overflight. With the capability of modifying a balloon's trajectory, flight controllers could steer flights away from such areas.

At the present time there is no funding for development of trajectory modification capability, but this capability is needed for reliable 100-day ULDB flights at most latitudes.

Modest trajectory modification would also be useful for LDB flights over Antarctica. Those flights of zero-pressure balloons take advantage of the stratospheric winds that carry the balloons around the pole in about two weeks. There have now been several Antarctic flights of approximately thirty-day duration, one traveled three times around the Pole for a duration of 42 days and the record Antarctic flight lasted 54 days. Many of the instruments flown over Antarctica would benefit from the longer duration afforded by a two- or three-revolution flight. Some flights, however, are not permitted to fly around more than once because a northerly component to the (generally westward) winds at float altitude sometimes makes it likely that the balloon would drift off the continent if left to float for a second or third revolution, making recovery of the instrument impossible. Two- or three-revolution flights could be assured if it were possible to steer the flight trajectory a few degrees off the direction that the winds are carrying the balloon.

In Addition to the Highest-Priority Needs Described in the Findings Above, the Assessment Group Identified Other Desirable Improvements.

The ANITA instrument after landing with the Bassler recovery aircraft in the background.

Reliable payload recovery

Payload recovery and relatively inexpensive reflight are critical for the balloon program. These twin capabilities make much higher instrument risk on an individual flight acceptable, which encourages the development of cutting edge technology and allows broader participation by students in balloon payloads.

Reliable automatic separation of the payload from a parachute at touchdown is crucial for minimizing damage to instruments after landing, and the successes of new separation hardware since late 2007 suggest that this issue has been resolved. Another development that could help to minimize instrument damage on landing would be use of a system like the guided parachutes developed for military air drops, which could permit placing the payload at a safe landing site, even in populated areas. A guided parachute could reduce the risks of high-speed landings due to high surface winds by flying into the wind at touchdown.

Antarctica poses special problems for recovery of instruments after balloon flights. Currently, recovery of Antarctic LDB balloon payloads requires use of relatively small NSF Twin Otter aircraft that must be shared with other NSF Antarctic programs at a time of peak activity. The strain on aircraft availability has become more apparent in the past three seasons with the increase from two to three balloon flights each season. Provision of a dedicated aircraft at McMurdo would cost approximately $0.5M annually. The cost of a typical LDB payload is at least $5M, and many are planning for multiple flights. The availability of an aircraft capable of recovering large payloads and dedicated to the balloon program would improve the probability of timely recovery of instruments, permitting prompt refurbishment and upgrading for later flights.

Three-Flight Capability in Antarctica

The Antarctic LDB campaign was established with an open-ended Memorandum of Understanding (MOU) in 1988 between the NASA Office of Space Science and the NSF Office of Polar Programs. That MOU provided for "one campaign about every other year," but in fact, the program has averaged about two flights per year. In September 2003, this NASA/NSF cooperation was extended until 2009 with a Memorandum of Agreement (MOA) that envisioned one to two flights per year, with the possibility of adding a third flight. NASA agreed to pay the incremental costs associated with adding a third flight. A new 2009 MOA extends essentially this same relationship until 2013.

The Assessment Group strongly favors making three Antarctic flights per year a permanent capability. During December 2006 – January 2007 there were in fact, for the first time, three successful launches at McMurdo, and three flights were again successfully launched in the 2007-08 and the 2008-09 seasons; however the two existing preparation facilities are inadequate for three instruments. Unavoidable interference occurs when two instruments must share the same payload facility during pre-flight preparation. A one-time expenditure of approximately $1M would enable construction of a third instrument-preparation facility and associated infrastructure. In addition, the annual incremental cost for conducting the third flight is approximately $1M.

Most investigations currently being flown in the Antarctic would work equally well in the Arctic.

Expanded Arctic Capability

Other things being equal, most investigations currently being flown in the Antarctic would work equally well in the Arctic. Increased funding for Arctic operations would permit three Arctic LDB flights each year. These flights would be competitive with Antarctic flights if negotiations with Russia to permit overflight of that nation's territory were successfully concluded.

Mid-Latitude Operational Scenarios

Expansion of LDB flights to mid-latitudes, with both the current zero-pressure balloons and the future super-pressure balloons, enables many scientific investigations that require launch locations other than Antarctica. Mid-latitude flights are crucial for nighttime observing, full-sky coverage, and reduced gamma ray backgrounds. Given the demand for such launch capabilities, a number of operational issues need to be resolved, including viable launch sites, balloon paths, safety analyses, and recovery options.

Touchdown for the Far Infrared Spectroscopy of the Troposphere (FIRST) experiment, in June 2005, after a successful flight. FIRST measures the radiation of the Earth in the 10–100 μ regime.

Acronyms

ACCESS	Advanced Cosmic-ray Composition Experiment for Space Science
ACE	Advanced Composition Explorer
ACT	Advanced Compton Telescope
AGN	Active Galactic Nuclei
AMS	Alpha Magnetic Spectrometer
ANITA	ANtarctic Impulsive Transient Antenna
ARCADE	Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission
ASMC	Astrophysics Strategic Mission Study
ATIC	Advanced Thin Ionization Calorimeter
BARREL	Balloon Array for Radiation-belt Relativistic Electron Losses
BEPAC	Beyond Einstein Program Assessment Committee
BESS	Balloon-borne Experiment with a Superconducting Spectrometer
BHFP	Black Hole Finder Probe
BHFP	Black-Hole Finder Probe
BLAST	Balloon-borne Large Aperture Submillimeter Telescope
BLISS	Balloon-borne Laser In Situ Sensor
BOOMERanG	Balloon Observations of Millimetric Extragalactic Radiation and Geophysics
CASTER	Coded Aperture Survey Telescope for Energetic Radiation
CFC	Chlorofluorocarbons
CGRO	Compton Gamma Ray Observatory
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CMB	Cosmic Microwave Background
COBE	Cosmic Background Explorer
CREAM	Cosmic Ray Energetics and Mass
CRIS	Cosmic Ray Isotope Spectrometer
CSBF	Columbia Scientific Balloon Facility
CZT	Cadmium-Zinc-Telluride
DEP	Dark Energy Probe
DM	Dark Matter
DOE	Department of Energy (US)
EBEX	E and B Experiment
EOS	Earth Observing System
ERB	Earth Radiation Budget
EXIST	Energetic X-ray Imaging Survey Telescope
FGST	Fermi Gamma-ray Space Telescope
FIRST	Far Infra-Red Spectroscopy of the Troposphere
GRB	Gamma Ray Burst

GRIP	Gamma-Ray Imaging Payload
GRIS	Gamma-Ray Imaging Spectrometer
HEAO-C	High Energy Astronomy Observatory
HIRDLS	High Resolution Dynamics Limb Sounder
HIREGS	High Resolution Gamma-Ray and Hard X-Ray Spectrometer
HST	Hubble Space Telescope
ICESat	Ice, Cloud, and land Elevation Satellite
IMAX	Isotope Matter-Antimatter Experiment
INTEGRAL	International Gamma-Ray Astrophysics Laboratory
IP	Inflation Probe
IP	Inflation Probe
IR	Infrared
ISM	Interstellar Medium
IXO	International X-Ray Observatory
JAXA	Japan Aerospace Exploration Agency
JWST	James Webb Space Telescope
LAT	Large Area Telescope
LCANS	Low-Cost Access to Near Space
LDB	Long-Duration Balloon
LET	Linear Energy Transfer
LIS	Lightning Imaging Sensor
LISA	Laser Interferometer Space Antenna
MAX	Millimeter-wave Anisotropy eXperiment
MAXIMA	Millimeter Anisotropy Experiment Imaging Array
MLS	Microwave Limb Sounder
MSL	Mars Science Laboratory
MVACS	Mars Volatile and Climate Surveyor (MVACS)
NASA	National Aeronautics and Space Administration
NCT	Nuclear Compton Telescope
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NRC	National Research Council
NSF	National Science Foundation
NuSTAR	Nuclear Spectroscopic Telescope Array
OSSE	Oriented Scintillation Spectrometer Experiment
PAMELA	Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics
PBH	Primordial Black Hole
PI	Principal Investigator
PIPER	Primordial Inflation Polarization Explorer
R&A	Research and Analysis

RBSP	Radiation Belt Storm Probes Mission
RHESSI	Ramaty High Energy Solar Spectroscopic Imager
rms	Root-Mean-Squared
ROSES	Research Opportunities in Space and Earth Sciences
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SCUBA	Submillimeter Common-User Bolometer Array
SMBH	Super-Massive Black Hole
SMEX	Small Explorer
SMM	Solar Maximum Mission
SPB	Super-Pressure Balloons
SPI	INTEGRAL SPectrometer
SPIDER	Scale Millimeter-wave Polarimeter
SR&T	Supporting Research and Technology
TE	Titan Explorer
TEGA	Thermal and Evolved Gas Analyzer
TES	Tropospheric Emission Spectrometer
TIGER	Trans-Iron Galactic Element Recorder
TLS	Tunable Laser Spectrometer
TRL	Technical Readiness Level
TRMM	Tropical Rainfall Measuring Mission
UAV	Unmanned Aerial Vehicle
ULDB	Ultra-Long-Duration Balloon
UV	Ultraviolet
VME	Venus Mobile Explorer
WMAP	Wilkinson Microwave Anisotropy Probe
XEUS	X-ray Evolving Universe Spectrometer

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