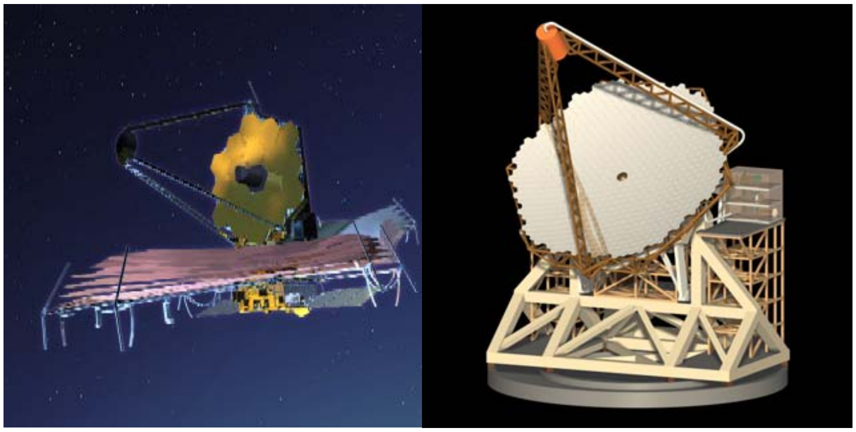
GSMT AND JWST:
Looking Back to the Future of the Universe

History will record that American scientists launched one of humankind's greatest intellectual adventures early in the 20th century. Building giant telescopes that dwarfed their predecessors, astronomers began to wrestle with our ancient, most compelling mysteries: *Where are we? What are we? And where do we come from?* These giant machines of glass and steel, growing decade by decade, revealed a Universe of intimidating size and imponderable age, but more remarkably, one within human understanding.

With an explosion of tools, observations, and ideas building to a crescendo by century's end, astronomers succeeded beyond their expectations: today, we routinely describe the size, age, and contents of a Universe utterly beyond our physical reach. We are mapping our home galaxy, the Milky Way, cataloging and analyzing its stars and following their births and deaths, and discovered a massive black hole at the center of our galaxy, testing our very notions of physical reality by its warping of time and space. We have witnessed our Galaxy and its billion cousins speeding to eventual oblivion in an expanding, accelerating Universe, driven by newly discovered cosmic forces that promise to revolutionize our understanding of fundamental physics.



Two new telescopes, the James Webb Space Telescope (JWST) in space, and the Giant Segmented Mirror Telescope (GSMT) here on Earth, will carry us all the way back—some 13 billion years ago—to witness the actual birth of the first stars and the construction of the first galaxies.

We see now that the history of the Universe is the back story to our own existence. We have met all the major characters in this story, from the trillions of common stars to the exotic massive black holes in galaxy cores that power the phenomenal blasts of quasar light. Now, as the 21st century begins, astronomers prepare to read the final chapter in this great mystery story. They seek to use astronomy's powerful magic—looking out into space to see back in time—to see how our modern Universe came to be. Brought to the threshold of this final step by amazing telescopes—notably the Hubble Space Telescope (HST) and the Keck ground-based telescopes—we examine the feeble light that emerged long ago when the Universe was in its youth. Yet we must go further out, further back.

Two new telescopes, NASA's James Webb Space Telescope (JWST) in space, and the Giant Segmented Mirror Telescope (GSMT) here on Earth, will carry us all the way back, some 13 billion years ago, to witness the actual birth of the first stars, and the construction of the first galaxies. We have reached an ultimate moment in the quest of our origins, one that will never happen again.

Why two telescopes? The JWST will orbit far from Earth, so dark and cold that its sensitivity to the infrared light from the first generation of stars will far exceed what can be done from Earth. The GSMT, with its gigantic mirror and state-of-the-art image-sharpening optics, will spread the light for spectral analysis, revealing the birth rate of the new stars and the swirling of the gas cocoons from which they are emerging. Each will do its special job—just as the Hubble and the Keck telescopes collaborated to lift the veil on the "adolescent" Universe in the 1990s. The JWST will find the first quasars, and the GSMT will use them as beacons to illuminate the hidden gas that feeds their ravenous black holes and their explosive episodes of star birth.

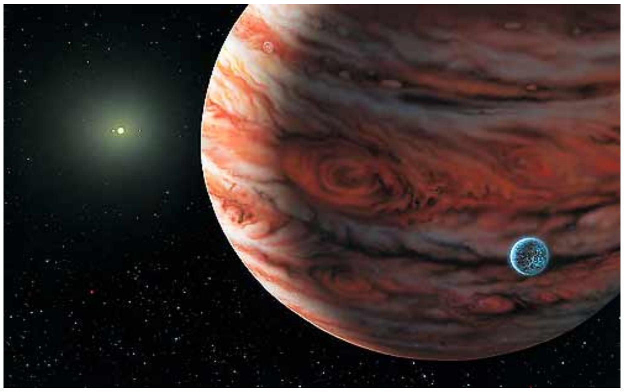
Already science programs have been constructed for these two ambitious new facilities. The concordance of the plans for each to explore the birth of the modern Universe might seem a case of duplication or repetition. Not at all. The detailed programs complement each other; indeed, they require the capabilities of both the JWST and the GSMT to reach a full understanding of how the Universe of stars and galaxies into which humankind was born came to be.

In the dense early Universe, galaxy mergers like the one shown in this Hubble image (right) were frequent and accompanied by violent star formation. JWST will detect these distant galaxies and GSMT will reveal their formation processes, as depicted in the simulation on the left.

The pursuit of this grand goal began here in the U.S.—our scientists must lead the final push. The JWST is well underway at NASA, but the GSMT will require a collaboration of private, state, and federal funding unprecedented in scope and difficulty. Particularly challenging will be the task of bringing the GSMT into operation while the JWST is alive in space. Having the two facilities available simultaneously will significantly enhance what they can accomplish. The U.S. needs to hold its traditional lead in this historic research and coordinate the world-wide effort to finish this extraordinary episode in our intellectual journey.

The GSMT will outlive the JWST, just as the Keck telescopes will survive the Hubble. Fortunately for astronomers, just as the book on the birth of the modern Universe begins to close, the story of the birth of stars, planets, and life beyond Earth is just beginning. Not only will the GSMT solve the riddles of galaxy birth, the extraordinary sharpness and depth of GSMT's images will be revolutionary for studies of star birth and how it leads to the formation of planets.

Not surprisingly, next on NASA's list of major astronomical observatories is the Terrestrial Planet Finder (TPF), a telescope specially constructed for the extraordinarily difficult job of detecting planets as small as Earth around the few hundred stars nearest our Sun. The GSMT will have remarkable, unique capabilities to study the formation of stars, observing how they assemble and how their birth leaves behind a disk of dust and ice that will build their families of planets. Its breakthrough capabilities will provide us with the clearest pictures of stars as they are born. In addition, GSMT will allow us to detect giant planets around nearby stars, the perfect complement for the TPF's search for Earth-sized planets around the same stars. Both will be needed to find true analogues to our own solar system—giant planets on stable orbits guarding the existence of vulnerable Earth-like worlds in the "habitable zone"—where life can begin and flourish. The TPF will be the GSMT's partner after JWST has retired.



Artist's conception of the planetary system orbiting the nearby star 55 Cancri as seen from a Jupiter-like planet, at a distance approximate to that of Jupiter from our own Sun. GSMT will be able to analyze the light from this planet, determine its chemical composition, and infer the mechanism by which it formed. NASA's Terrestrial Planet Finder will enlarge the sample for GSMT analysis.

- **An investment for the long-term, GSMT is essential to maintaining U.S. leadership in science, engineering, and technology.**

A Giant Segmented Mirror Telescope

Synergy with the James Webb Space Telescope

July 15, 2005

Dr. Garth Illingworth
UC, Santa Cruz
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Santa Cruz, CA 95064

Dear Garth,

I am pleased to submit the following report: "A Giant Segmented Mirror Telescope: Synergy with the James Webb Space Telescope" to the Astronomy and Astrophysics Advisory Committee in response to the following charge:

"The two highest-ranked programs in the Astronomy and Astrophysics Survey Committee Decadal Survey were a 30-m class ground-based telescope, GSMT (Giant Segmented Mirror Telescope), and the infrared Next Generation Space Telescope (NGST; now James Webb Space Telescope, JWST). To provide a more detailed scientific case for the synergies from concurrent operation of a Giant Segmented Mirror Telescope (GSMT) and the James Webb Space Telescope (JWST), the AAAC requests the GSMT Science Working Group (SWG) to develop a document in collaboration with the JWST SWG that would enunciate the science gains to be made with overlapping operation."

In response to the request from AAAC, the GSMT SWG developed a draft report detailing representative research areas where the synergy between JWST and GSMT is significant, particularly if they were to operate contemporaneously, as well as those areas where each makes a unique contribution. The SWG then worked iteratively with its counterpart advisory group, the JWST SWG, to ensure that the final document accurately reflected the collective perspective of its members.

This report concludes that many of the most ambitious scientific goals of the next decades -- for example, understanding the formation of galaxies and the chemical elements and the formation of stars and planets -- can only be fully realized through construction of both GSMT and JWST and via their concurrent operation. We hope that this message evokes an enthusiastic response among federal officials. Providing the support for such frontier facilities promises a great legacy for science and for the United States.

Yours sincerely,

Rolf-Peter Kudritzki, Chair
GSMT Science Working Group

EXECUTIVE SUMMARY

The following report, “A Giant Segmented Mirror Telescope: Synergy with the James Webb Space Telescope” was prepared by the Giant Segmented Mirror Telescope Science Working Group (GSMT SWG) in response to a charge from the Astronomy and Astrophysics Advisory Committee (AAAC): To provide a more detailed scientific case for the synergies arising from concurrent operation of a Giant Segmented Mirror Telescope (GSMT) and the James Webb Space Telescope (JWST) and to enunciate the science gains to be made with overlapping operation." The GSMT SWG, with the concurrence of its counterpart, the JWST SWG, concludes that the most ambitious scientific goals of the next decade — understanding the formation and evolution of galaxies, stars and planetary system — can only be realized fully through construction of both GSMT and JWST and via their concurrent operation.

Our understanding of how the Universe came to be, of how galaxies within it like the Milky Way have formed and evolved, and of how planets like the earth are born has grown remarkably over the past 50 years. Nevertheless, many fundamental questions remain unanswered—questions that have engaged the imagination of humans for millennia.

How did the first galaxies coalesce and what did they look like? How did they evolve to assume the variety of shapes and sizes we see today? We are especially interested in understanding how systems similar to our own galaxy, the Milky Way, formed and evolved. How do stars and their associated planetary systems form? How common are solar systems with architectures similar to our own? Are life-sustaining planets similar to Earth common or rare? To address these questions, astronomers have proposed building two powerful facilities over the next decade. Each of these new telescopes has a unique but complementary set of characteristics that will enable them on their own to explore new, non-intersecting areas of discovery space that will almost certainly guarantee the finding of unanticipated phenomena over an exceptionally wide range of temporal and spatial scales. Operating together, in the same time frame, their combined power will give us truly profound new insights to the birth and evolution of the Universe and all of its components.

The first new telescope is the *James Webb Space Telescope* (JWST), the successor to the pioneering Hubble Space Telescope (HST) and the recently launched Spitzer Space Telescope. JWST is currently well into its design phase and is scheduled to be launched in 2011. It will have 5.5 times the photon-collecting area of HST, 50 times that of Spitzer, and will be cooled to a temperature of just 40 K above absolute zero. Together, JWST’s greater aperture and cooled optics and instruments will provide the incredible sensitivity required to detect and determine the distances to—and thus ages of—the first stars and galaxies in the Universe, and to detect planets similar to Jupiter around parent stars located up to about 30 light years away.

The second new facility is the *Giant Segmented Mirror Telescope* (GSMT), a next generation ground-based telescope that will build on the heritage of 8-m to 10-m diameter telescopes, such as Gemini and Keck. Current designs for GSMT envision a telescope with 10 times the collecting area of the 10-m diameter Keck telescopes and 28 times that of JWST. It will be sensitive to light throughout the blue and visible part of the electromagnetic spectrum, whereas JWST is designed to operate primarily in the near- to mid-infrared. GSMT will deliver images with 5 times the clarity of JWST's. This will be possible because GSMT will be equipped with sophisticated “adaptive optics” systems designed to precisely compensate for the effects of “image blurring” of the light from cosmic sources caused by its passage through the turbulent terrestrial atmosphere. With this combination of unmatched sensitivity and superb imaging quality, GSMT will be able to measure physical characteristics such as mass and chemical composition of spatially-resolved substructures in many of the very young galaxies that JWST and GSMT itself will discover. It will also be able to separate the light of newly-formed Jupiter-like planets from the bright glare of their parent stars out to distances as large as 500 light years. GSMT will also be able to reveal the structure and chemical composition of the atmospheres of these planets.

The potential of JWST and GSMT to address fundamental questions regarding the origin and fate of the Universe, and the origin and architecture of extra-solar planetary systems, led the National Academy of Sciences' National Research Council to rank these two facilities first and second respectively, among all projects recommended for federal funding in the 2000–2010 time frame in the most recent decadal survey of astronomy and astrophysics, *Astronomy and Astrophysics in the New Millennium.* The decadal survey noted as well that while JWST is designed to carry out frontier science independently, in combination, JWST and GSMT will be even more powerful working together.

Although smaller in size than the GSMT, the cooled JWST telescope operating outside the Earth's atmosphere will have unprecedented sensitivity for broad-band imaging of astronomical sources in the near- and mid-infrared and for making relatively low-resolution spectroscopic studies of these sources. GSMT's great sensitivity in the optical and near infrared and its spatial resolving power will enable it to “deconstruct” images at the limits of JWST's spatial resolution and to obtain high-resolution spectroscopy of objects brighter than JWST's limiting sensitivity. As one example of complementarity, JWST will be able to image the faint light from the first-forming galaxies, and then measure their redshifts and integrated properties of these “about-to-be” galaxies. With GSMT's spatial resolving power, astronomers will be able to search for compact components within these systems. In many cases, GSMT will be able to use its powerful spectrographs to probe physical characteristics in these components, such as velocities, mass and chemical composition.

The well-documented synergy between the Hubble Space Telescope and 8–10m ground-based telescopes provides a compelling historical precedent for the potential power of contemporaneous operation of JWST and GSMT. One of the most dramatic examples of this synergy is the discovery of “dark energy”, the mysterious force which appears responsible for countering the gravitational pull of the matter contained within the Universe—a discovery that many scientists believe is the most unexpected yet fundamental discovery of the past decade.

Evidence for “dark energy” is manifest in the acceleration of the Universe found from careful analysis of the relationship between the distance of a galaxy and its recession velocity. Ground-based telescopes are able to carry out large area surveys of galaxies and hunt for supernovae—ultra-luminous stellar explosions signaling the “self-immolation” of a star. A particular kind of supernovae known as Type Ia act as “standard candles”—all supernovae of this type have nearly the same intrinsic brightness when they explode.

Thus we can measure the relative distances to the supernovae and their parent galaxies with high accuracy if we know the relative brightnesses of the supernovae. HST's key role is to provide the spatial resolution needed to cleanly separate the light of the supernova from that of the host galaxy so that we can accurately measure the apparent brightness of the supernova. Ground-based telescopes then provide recessional velocities for the distant galaxies via measurement of their "redshifts," or that of the supernova. When observations such as these were obtained for a number of distant supernovae and galaxies, it was found that the more distant galaxies were receding more rapidly than would be expected from the simple, straight-line relationship between distance and recessional velocity originally found by Hubble nearly 75 years ago. The acceleration inferred from these observations, which are at the limit of current capabilities from the ground and space, is what compels the introduction of "dark energy" into the lexicon of physics and astronomy—and the search for its origin and larger implications.

The document that follows describes in richer detail both the power of JWST and GSMT each working independently, and the "power of two"—JWST and GSMT working together concurrently— to dramatically enhance our ability to address problems of profound scientific and philosophical import. A federal commitment to ensure the availability of GSMT during JWST's lifetime will leverage enormous scientific return by exploiting this synergy.

Context and Overview

The two highest-ranked programs in the Astronomy and Astrophysics Survey Committee Decadal Survey were a 30-m class ground-based telescope, GSMT (Giant Segmented Mirror Telescope), and the infrared Next Generation Space Telescope (NGST; now James Webb Space Telescope, JWST). The Decadal Survey noted the urgency of early investment in design and technology for the GSMT so that it could operate concurrently with JWST. In spring, 2004, the Astronomy and Astrophysics Advisory charged the Giant Segmented Mirror Science Working Group (GSMT SWG) to provide a more detailed scientific case for the synergies deriving from concurrent operation of a Giant Segmented Mirror Telescope (GSMT) and the James Webb Space Telescope (JWST)

In response to the request from AAAC, the GSMT SWG developed a draft report detailing representative research areas where the synergy between JWST and GSMT is significant, particularly if they were to operate contemporaneously, as well as those areas where each makes a unique contribution. The SWG then worked iteratively with its counterpart advisory group, the JWST SWG, to ensure that its final report accurately reflects the collective perspective of its members.

This report, "A Giant Segmented Mirror Telescope: Synergy with the James Webb Space Telescope" concludes that many of the most ambitious scientific goals of the next decades—for example, understanding the formation of galaxies and the chemical elements and the formation of stars and planets—can only be fully realized through construction of both GSMT and JWST and via their simultaneous operation. The SWG believes that federal investment in both frontier facilities promises both a great legacy for science and for the citizens of the United States.

A 30-meter class ground-based telescope capable of diffraction-limited imaging in the near- to mid-infrared and operating in conjunction with the James Webb Space Telescope opens up the possibility of attacking fundamental problems in astronomy and astrophysics that would not be possible with either telescope operating on its own. This possibility was a key factor that led the most recent NAS/NRC decadal survey (*Astronomy and Astrophysics in the New Millennium*) to give a Giant Segmented Mirror Telescope (GSMT) the highest priority among all new ground-based projects.

On their own both the JWST and the GSMT are fully expected to explore completely new, non-intersecting areas of discovery space that virtually assure the finding of unanticipated phenomena over an exceptionally wide range of scales, both temporal and spatial. This is because the unique capabilities of each of the telescopes are being designed to take maximum advantage of one being in space and the other on the ground. For JWST, this means concentrating on the advantages gained from operating above the Earth's atmosphere and in a very low background environment at L2. For GSMT, it means the ability to build an extremely large aperture (hence great light gathering power) telescope relative to what realistically could be put into space over the next decade, and using adaptive optics (AO) technology to allow spatial imaging at the diffraction limit of the telescope's full aperture. The most important of these unique capabilities of the two telescopes are:

James Webb Space Telescope:

- Full sky coverage with high observing efficiency (no "weather" or daylight)
- Continuous wavelength coverage from 0.6 to 27 μm
- Very high sensitivity for broadband imaging due to extremely low background emission
- Stable, diffraction-limited imaging for wavelengths > 2 μm across its entire field of view
- High dynamic range observations

Giant Segmented-Mirror Telescope:

- Thirty-meter aperture with 25 × the collecting area of JWST
- Blue/optical sensitivity with wide field of view (≥10') for imaging and spectroscopy
- With adaptive optics, the potential for spatial resolution 5 × greater than JWST
- High spectral resolution (~100,000) observations in the optical and IR are possible
- Very high sensitivity for non-background-limited infrared observations, e.g., spectral resolutions ≥3,000 in the near-IR.
- Flexible and upgradeable to take advantage of new technical developments.

The 2003 report of the GSMT Science Working Group, "Frontier Science Enabled by a Giant Segmented Mirror Telescope," lays out the compelling science case for the construction of a 30-meter class ground-based telescope. It also presents examples of "complementarity" with JWST and other telescopes. Similarly, the JWST Science Requirements Document lays out the scientific objectives of that telescope.

Naturally, there is overlap in the broad areas to which JWST and GSMT are expected to make fundamental breakthroughs in our understanding of the Universe, but the specific scientific questions addressed by the two are different as each telescope utilizes to the fullest its unique advantages. This document first gives current examples of synergy between existing optical and near-infrared ground and space based facilities *operating concurrently* in several cutting-edge areas of research. This is followed by a discussion of the complementarity that exists between the key science goals of GSMT and JWST. Given current and expected advances in application of the technique of adaptive optics on large ground-based facilities, the power of complementarity in advancing our knowledge of the Universe can only increase. Finally, in the appendices, we give a brief summary of the compelling science cases for a GSMT in three distinct areas, and short descriptions of the four key science themes of JWST.

A portion of the Hubble Deep Field image obtained with HST is shown on the left. On the upper right is an enlargement of the image of one of the thousands of galaxies detected in the field. On the lower right is a simulation of how the same galaxy would appear if imaged with a 30 meter ground based telescope with an adaptive optics system operating at the diffraction limit of a 30 meter GSMT. This image is an order of magnitude sharper than that obtained with the HST and would be about 5 times sharper than that obtainable with JWST.

EXAMPLES OF SYNERGY IN CONTEMPORANEOUS OPERATION OF CURRENT GROUND- AND SPACE-BASED TELESCOPES

Introduction

Observations from telescopes in space increasingly rely on ground-based observations, not just as a "supplement," but also as a critical component of a research program. As the capability of ground-based facilities has increased, so has the degree of inter-dependence between space and ground.

One measure of the growing importance of the synergy between observations from the Hubble Space Telescope (HST) and from ground-based optical/infrared facilities is the percentage of refereed research papers based on HST data that rely on observations from the ground. In 1995, only 4 percent of all HST papers had a significant component of ground-based support. Since then, the percentage has grown steadily and is now close to 20 percent of all HST papers. Nearly all of this increase comes from complementary observations on the largest ground-based facilities, especially Keck and the Very Large Telescope (VLT). But what simple statistics alone do not show is that these ground-based observations do not just support the HST research programs, but that they are often absolutely necessary and critical to the success of a number of the most well-known and scientifically significant of the HST programs. Two examples which we will describe in a moment are the Hubble Deep Field (HDF) survey and the discovery that the Universe is not expanding at a constant rate, but instead, that expansion is accelerating.

GSMT and JWST will have 10 and 50 times the collecting area of their largest immediate predecessors, Keck and Spitzer. While the details of its final instrument complement are not yet known, JWST as a facility will be optimized for observations in the near- to mid-infrared, GSMT will be capable of observing throughout the optical region of the spectrum as well as being able to exploit its large diameter to provide diffraction-limited imaging longward of about one micron. As we mentioned in the Introduction, these and the other unique capabilities of the two telescopes, while quite distinct from one another, are highly complementary. Operating together the two telescopes will greatly enhance our ability to answer fundamental questions about origins—the origin of the Universe, of stars and galaxies, of planetary systems, and of life itself—beyond what either telescope on its own would be capable of doing.

Examples of Synergy: Surveys

For a number of key research areas, near-contemporaneous observations with different facilities are required. Particularly important examples are programs for which the initial observations are multi-wavelength surveys either from the ground or space. Such surveys are then followed up by increasingly detailed observations where the specifics of each new set of observations are driven by findings from the previous sets, and each exploits the unique capabilities of facilities on the ground and in space. Equally important are programs for which near simultaneity of the observations is critical; for example, in the study of highly transient phenomenon, such as supernovae and gamma ray bursts. In most cases, for both of these broad classes of examples, spectroscopy with the largest ground-based telescopes has been and will continue to be an essential ingredient, as is the rapid response time possible and access to a choice of ground-based facilities. It is also worth noting that the past decade has demonstrated that the great gain to be had from contemporaneous observations by the largest Optical/Infrared (O/IR) telescopes on the ground with space telescopes is by no means limited to HST, but extends across the electromagnetic spectrum from the shortest wavelengths observed by the Compton Gamma Ray Observatory and the Chandra X-ray Observatory, through the ultraviolet by the International Ultraviolet Explorer (IUE) and Far Ultraviolet Spectroscopic Explorer (FUSE) to the infrared being explored by the last of NASA's Great Observatories, the Spitzer Space Observatory.

The Hubble Deep Field survey produced spectacular images that revealed an incredible rich variety of galaxy morphologies. Additional deep imaging by Chandra and Spitzer has helped reveal the underlying activity in these galaxies. However, without spectroscopy from the ground, the science that could be derived from the HDF survey would have been much more limited. The same is true for subsequent deep extra-galactic surveys with Hubble. The spectroscopic observations from the largest ground-based telescopes are needed to determine accurate Doppler shift distances to these distant galaxies – essential to determining the emitted energy and ages of these objects. In addition to velocity information, the physical properties of many of the galaxies can be determined from the ground-based spectroscopy; examples are rates of star formation and age distribution of the stellar population.

Figure 1 is an example of results from one such survey, the Team Keck Survey (TKS), (details in Wirth et al., 2004, AJ, 127, 3121). The TKS field is that chosen for study by the GOODS (Great Observatories Origins Deep Survey) Legacy Program. Over 2000 objects in the field were then observed spectroscopically with large ground-based telescopes in order to determine accurate redshifts. High spatial resolution multi-color images of these objects were then extracted from the deep images obtained with the Advanced Camera for Surveys on HST as part of the GOODS program. Figure 1 is a very small portion of the large field imaged by Keck. Objects circled are those observed spectroscopically by the TKS. The ACS images and Keck spectra for six of these objects have been extracted from their Web site at http://alamoana.keck.hawaii.edu/science/tksurvey/.

Examples of Synergy: Supernovae and Gamma Ray Bursts

For 80 years we have known that the Universe is expanding. But in what may be the most fundamental, exciting, and puzzling discovery of the past decade, it now appears that the expansion is accelerating—it is faster today than it was billions of years ago. Scientists think that a heretofore unforeseen component of the Universe—"dark energy"—is driving the accelerating expansion.

Evidence for this acceleration comes from careful comparison of the recession velocities of nearby and distant galaxies for which accurate relative distances can be determined. If there were no acceleration, then the relationship between recession velocity and distance would be linear, as Hubble originally thought. With acceleration, the most distant galaxies appear to be receding from us slower than predicted by the linear model. In order to measure this acceleration, we need to derive accurate relative distances to faint, distant galaxies and to

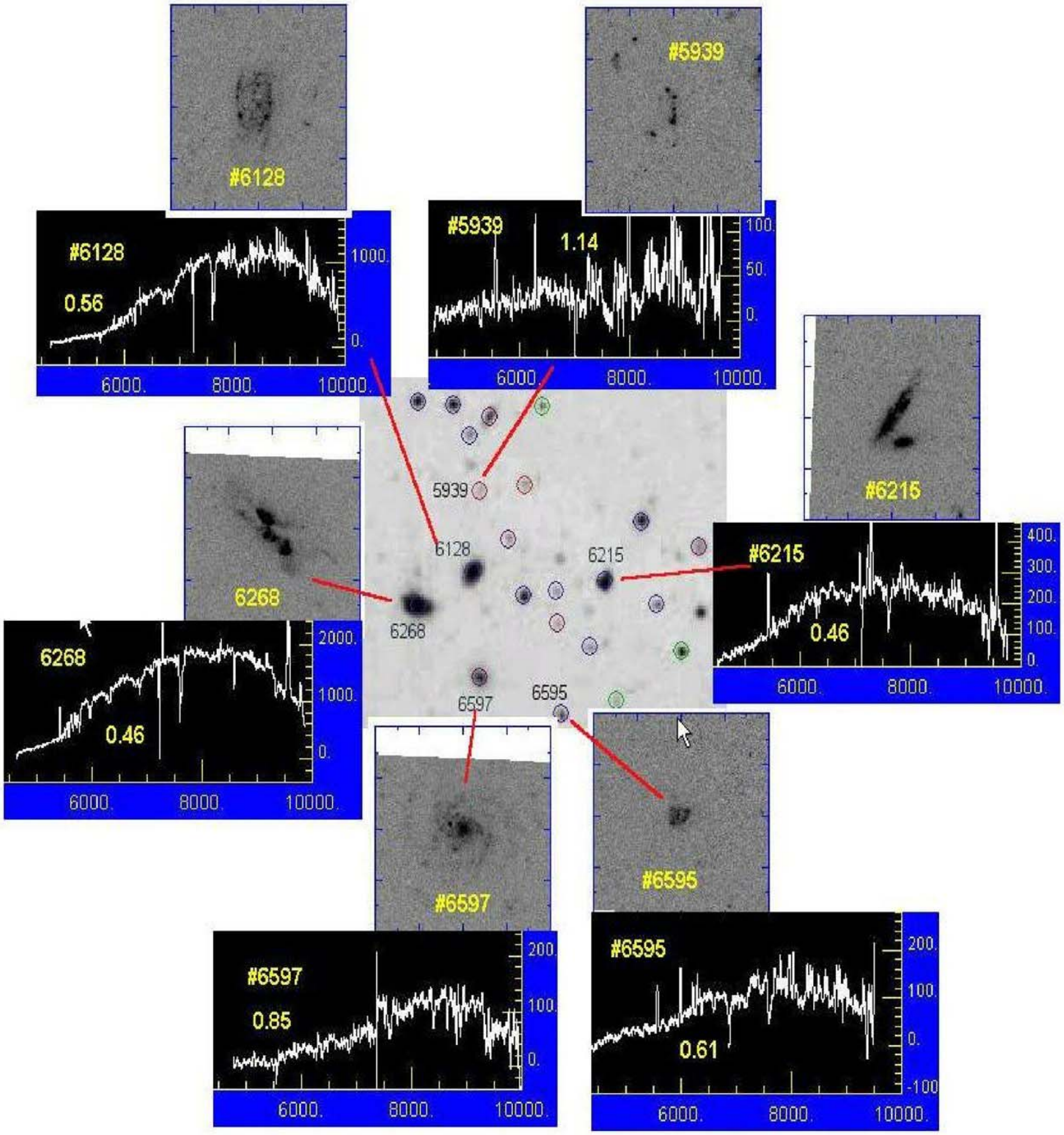

FIGURE 1. In the center of this figure is a very small portion of a deep wide field Keck image of the field chosen for study by the GOODS (Great Observatories Origins Deep Survey) Legacy Program. The Keck image was obtained by the Team Keck Survey, TKS (details in Wirth, et al., 2004, AJ., 127, .3121). Magnitudes and positions were measured for the objects on the Keck images. Those circled are those observed spectroscopically by the TKS with DEIMOS on Keck. For the entire field over 2000 objects were observed spectroscopically in order to determine accurate redshifts. High spatial resolution multi-color images of these objects were extracted from the deep images obtained with the Advanced Camera for Surveys (ACS) on HST as part of the GOODS program. The ACS images and Keck spectra for six galaxies have been obtained from the TKS website at http://alamoana.keck.hawaii.edu/science/tksurvey/ and are illustrated in the figure.

measure their recessional velocities. Both of these tasks present enormous challenges. To accomplish them requires the combined strengths and unique capabilities of ground- and space- based facilities. Relative distances to galaxies can be obtained by measuring the brightness of a "standard candle"—an object of known intrinsic brightness. The standard candles must be of sufficient intrinsic brightness that they can be seen over vast distances. Supernovae of type Ia appear to be excellent standard candles. Their intrinsic luminosity is so great that they often outshine the galaxies in which they are found. Furthermore, the variation in luminosity from one supernova to another is small and can be calculated based on other observed properties. The second key task—the determination of the recessional velocity of a faint, distant galaxy—is done by measuring the Doppler shift of emission or absorption lines in the spectrum.

Ground-based telescopes have played a key role in the systematic search for distant supernova because they are capable of carrying out surveys over wide fields of view of large numbers of distant galaxies which harbor these rare, short-lived exploding stars. For the most distant objects, the galaxy itself may be too faint to be detected in the relatively short exposures taken during the survey; only the supernova will appear as a star-like object where, on an image made only a few days or weeks earlier, there was blank sky. An example from a ground-based survey is shown in Figure 2. This supernova is located in a galaxy at a distance of 5.2 billion light years. Recently, a number of distant supernovae have also been found on

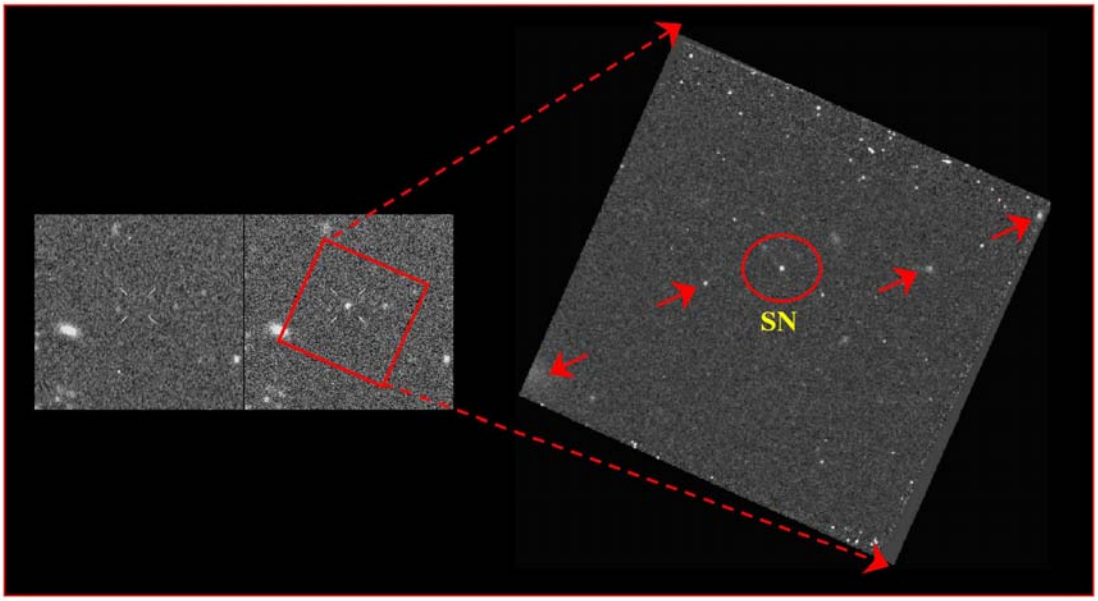

FIGURE 2: The left side of this figure shows two views of the same small region of a large survey field imaged with the Blanco 4-meter reflector at Cerro Tololo Interamerican Observatory in the course of a supernova search. The left-most image is the "template" against which subsequent images are compared. The one to the right taken several weeks later reveals the discovery of a new supernova, SN 2003 le. The large image on the right was taken with HST. The supernova is within the circle. Some of the other objects in common to both images are indicated with arrows. The underlying galaxy appears to be invisible even on the deeper HST image. (Images courtesy of K. Krisciunas of the ESSENCE project))

HST images taken for the GOODS Program. An example of one is in Figure 3. Ground-based telescopes will be critical for measuring the Doppler shift of the host galaxy and supernova, hence their recessional velocity, and for verifying spectroscopically that the SN in question is precisely similar to nearby ones that have been determined to be standard candles. Only the largest ground-based telescopes will have the requisite sensitivity to obtain spectra of the most distant galaxies and supernovae with sufficient resolution and clarity. The spectrum of SN 2003le (discovery image in Figure 2) as obtained at the Keck Observatory is illustrated in Figure 4 along with that of SN 1992a, a template spectrum.

Once a supernova is located and its type determined, accurate measurements of changes in its brightness over a period of several weeks to a couple of months are essential in order to determine its true intrinsic brightness. Because of the distorting effects of "seeing" introduced by the earth's atmosphere, supernova and galaxy light are blurred together, rendering accurate brightness measurements impossible. Only with the undistorted and stable images provided by a telescope in space is it possible to carefully separate supernova and galaxy light and derive accurate supernova brightness. This is done by subtracting the template image which has just the galaxy on it from the image of the galaxy plus supernova, leaving just the supernova (see Figure 3). (See also: http://www.cfht.hawaii.edu/Science/CFHLS/)

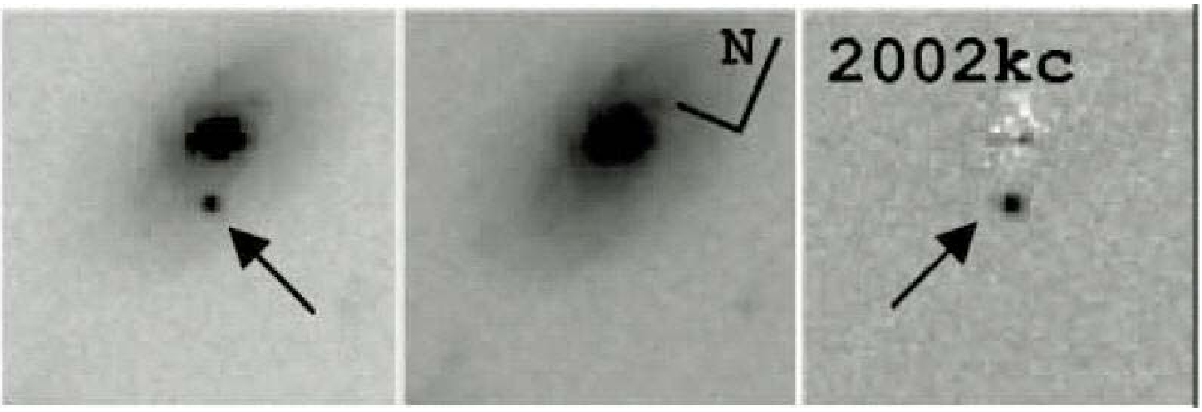

FIGURE 3. These images, taken with the Advanced Camera for Surveys on the Hubble Space Telescope, show a newly discovered supernova for which subtraction of the background light from the parent galaxy will be critical for an accurate measurement of the brightness of the supernova. The left image shows the discovery of SN 2002kc in the course of the GOODS survey. The center one is the template image taken before discovery. The image on the right shows the result of subtracting the template image from the discovery one (Riess, et al. 2004, ApJ, 607, 665)

Next, consider sources of intense gamma ray emission. They are among the most powerful objects in the known Universe—at least for the brief moment in time when they undergo their burst. Because of their great distance and faintness, it has been difficult to obtain detailed observations of them. On the other hand, because of their great intrinsic brightness, they can serve as excellent probes of the very early Universe. Simultaneous observations over multiple wavelength bands are critical to understanding the afterglow emission from the bursts. Only with such monitoring can one form a clear picture of the processes that produce the emission as well as the underlying physical nature of the interstellar medium in which these processes occur. In addition to the origin of the afterglow emission, one can use the emission itself as a probe of the material surrounding the Gamma Ray Bursters (GRBs). At high redshift, the most direct picture is through mid-IR observations. There also appear to be some bursts that are dark (i.e., with little optical emission). These may occur at high redshift or they may be obscured by dust. In either case, multi-wavelength observations both photometric and spectroscopic from space and the ground will be required to reveal their true nature. Obviously, because of the highly transient nature of these bursts, near simultaneous operation of GSMT and JWST is essential.

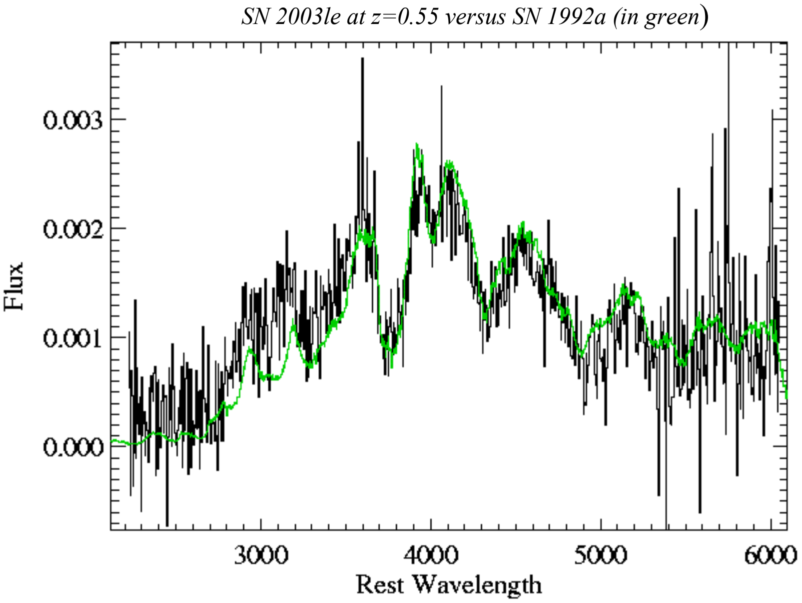

FIGURE 4. A spectrum of SN 2003le taken with the Keck telescope shifted to rest wave lengths. In green is a spectrum of SN 1992a for comparison.

Finally, we mention the case of galaxies with active galactic nuclei (AGNs). It is possible that all large galaxies go through such a phase, particularly early in their lives, when their energy output is dominated not by starlight but by violent events happening in their nuclei. Deep surveys with JWST will reveal many such objects at high redshifts. Multi-wavelength data, though, will be needed to further our understanding of these mysterious and powerful objects that probably play a key role in galaxy evolution. The next step then would be to obtain ground-based optical spectroscopy of a sample of the AGNs found in the JWST surveys. We expect that some fraction of these objects will be undetectable optically even with GSMT. According to the standard model of AGNs, a non-detection from the ground in the optical would mean that the nucleus of the galaxy itself, i.e., the AGN, is obscured from view by a surrounding dust torus. Such objects would be ideal examples for follow up with mid-IR spectroscopy with JWST. The extent of obscuration by the dust torus will depend in part on geometry—does the torus lie exactly in the line of sight to the AGN or is it tilted somewhat? How does the size and thickness of the torus change as it evolves? A large sample of AGNs over a range in look-back time will need to be identified and studied to answer these questions. For some AGNs, only emission from their narrow line regions are visible, the broad line region is completely obscured by the dust. With its high spectral resolution, GSMT will be able to resolve these narrow emission lines and study in considerable detail physical conditions in the outer regions of the AGN where these lines originate without the confusing presence of the broad lines. Similarly, diffraction-limited imaging with GSMT will be an important component in understanding the structure of these objects. Clearly, there will be considerable interplay between JWST and GSMT as what is learned with one instrument directs the next round of observations with the other.

SYNERGY BETWEEN THE KEY SCIENCE PROGRAMS OF GSMT AND JWST

Optical/near-infrared astronomy in the next decade will more than likely be dominated by the two largest telescopes in space and on the ground—the JWST and the GSMT. As defined in the Introduction, each of these telescopes has a set of unique capabilities that allows them to take maximum advantage of where they are located. Each telescope will be able to tackle some of the most fundamental questions in science: Why does the Universe appear to be the way it is? How did our galaxy form? How do stars like the Sun with planetary systems form? How common is the occurrence of life in the Universe and where else might it be found? Although both telescopes will attempt to answer questions in the same broad areas of enquiry, the specific questions that each will address will be different. Each telescope will address those specific questions that can best be approached with its own set of unique capabilities. Operating together, the two telescopes—one in space, the other on the ground—will be a powerful complement to one another. Together, they will give us the most complete picture yet obtained of our Universe as it is today, as it was in the distant past, and as it might be in the distant future.

We wish to emphasize the great 'value-added' of having both GSMT and JWST operating contemporaneously in order to achieve synergy analogous to that which resulted from the contemporaneous operation of the HST and the largest ground-based telescopes as discussed earlier.

The remainder of this section gives three examples of the complementary nature of the key science programs for the two telescopes. These key science programs themselves are summarized in the appendices to this document.

Large-Scale Structure and Star Formation in the Early Universe

The Problem and GSMT's Approach

How does the primordial mix of hydrogen and helium gas collapse to form the first generation of stars and galaxies? How are the heavier elements returned to the intergalactic gas after they are produced by nuclear fusion in stars? How does this cycling of material between gas and stars affect the evolution of subsequent generations of stars and galaxies? And how does the large-scale structure of the Universe— the cosmic web—affect galaxy formation? When in the course of establishing the large scale structure did the early stars and galaxies in the Universe form? What were the properties of these stars? When did the intergalactic medium shift from neutral to ionized hydrogen and what objects were responsible for this shift?

These questions can be most directly tackled by observations at early epochs (using a sample of high redshift galaxies located at large distances and correspondingly large look-back times) when the bulk of stars in galaxies were being formed. A high-resolution three-dimensional map of the distribution of the galaxies and gas at large distances, together with information on the enrichment of the gas with heavy elements, is an essential requirement for understanding the complex interactions between star-forming galaxies and the intergalactic medium. The overall approach for the large-scale structure problem is to map the galaxies by means of a redshift survey and to map the gas by locating it in absorption as a shadow against background sources (quasars and galaxies), as shown in Figure 6. With sufficient background sources, the full three-dimensional distribution of the intergalactic gas (and its enrichment) can be reconstructed from the many lines of sight. These maps of both the stellar and gaseous components will reveal the mechanisms by which gas is converted into stars and galaxies, and then recycled by supernovae, galactic outflows, and other feedback processes. The maps will also reveal how larger-scale structures affect the processes of galaxy formation and produce the variety in morphological type, stellar content, age, and metallicity that is observed in different environments.

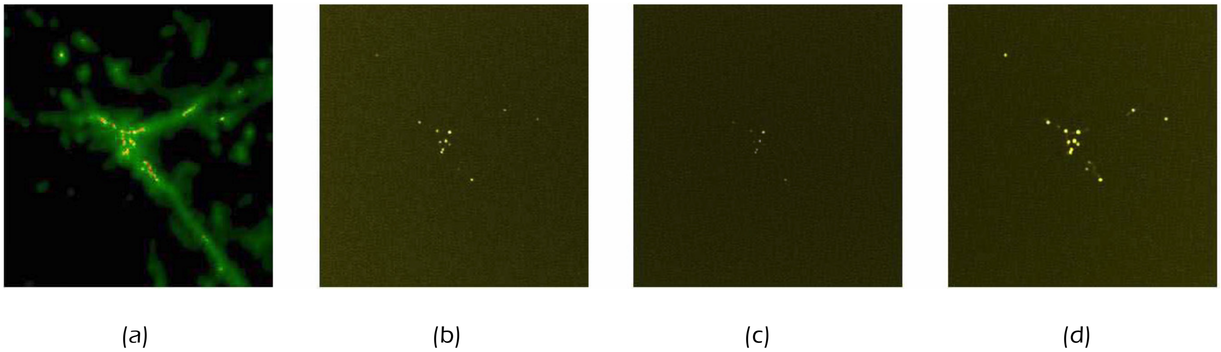
(a) (b) (c) (d)

FIGURE 5. Early star formation from a hydrodynamical simulation by Dave, Katz, & Weinberg. Panel (a) shows a simulation of a collapsing galaxy in the newly forming Universe at z=10, as seen in Ly-α radiation from cooling clouds of gas (green) and from newly forming stars (yellow, red). The remaining panels show simulated 8-hour observations of a forming galaxy with a 30-m telescope; the region is 1 x 1 comoving megaparsec/h across and 1000 km/s deep. The observations are assumed to be between the OH lines at high resolution (R=3000) using ground-layer adaptive optics. The image represents 10 stacked exposures taken with a tunable filter centered at several selected wavelengths or, equivalently, a "collapsed" image of 10 resolution elements near Lyman αwith an IFU. The panels show (b) observations of the Lyman-alpha line at z=10 assuming a Salpeter IMF with 1/5 solar metallicity and a total escape fraction of 20%, (c) observations of the HeII (1640) line at z=10 for a "top-heavy" IMF with a Salpeter slope and stars from 1-500 solar masses with zero metallicity, and (d) observations of the HeII (1640) line at z=10 for a top-heavy IMF with zero metallicity. A GSMT will detect extremely high redshift galaxies in formation and diagnose the properties of initial mass function of these early stars. Courtesy: E. Barton-Gillespie.

Because most distant objects with extremely high redshifts are observed with little or no light at visual wavelengths, observations in the range of the I-band filter ($z < 6$) and the near-infrared ($z > 6$) are the best wavelengths to detect and study them. The Ly α line is a promising feature for detecting high-z star formation (see Figure 5); at least one object at $z > 6$ has already been discovered. Other spectral features that may be used for confirmation are the Lyman break (caused by the continuous absorption of hydrogen in its ground-state) and the HeII line (1640 Å). Thus, an ideal approach to studying these objects would be discovery through either the Lyman break technique or through narrow-band imaging searches for Ly α emission followed by spectroscopy for confirmation and more detailed study.

Complementarity with JWST

The imaging and spectroscopic survey envisaged here for GSMT will be an important complement to the centerpiece of the JWST science program—an ultra-deep galaxy survey. This ultra-deep survey is a search over a small area of the sky in the near- and mid-IR for “first-light objects” such as super star clusters, supernova, or dwarf galaxies potentially out to a redshift of z ~ 30. JWST will attempt to determine the epoch and source of reionization of the Universe after the Big Bang via studies of these first-light objects.

Although it will not be able to observe the most distant objects that JWST will discover, GSMT, with its enormous light gathering power in the optical and in the near-IR, an order of magnitude greater spectral resolving power, up to five times greater spatial resolving power, will complement JWST’s work via analysis of emission line profiles at high z and more detailed analysis of objects at somewhat lower redshift to determine the latter’s dynamical masses, ages, and chemical compositions. For luminous high redshift objects, JWST will detect their ultraviolet continua with broadband filters in the near-infrared, revealing any systems in which Ly α is absent. Indeed, if the JWST broad or medium-band surveys are efficient, they may replace the need for discovery with GSMT, directly enabling pointed follow-up spectroscopy with a multi-object spectrograph on GSMT. In any case, spectroscopic observation with GSMT will enable a physical understanding of the stars that formed in the very early Universe. Figure 5 gives an indication of what we might expect to see.

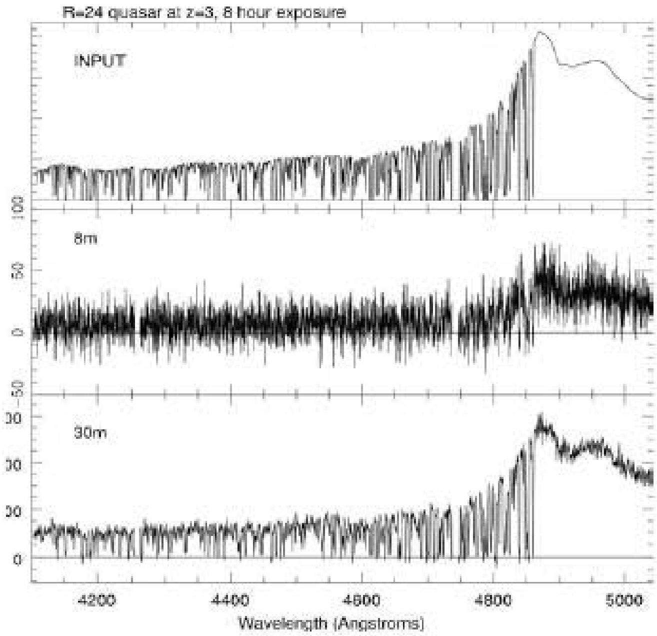

FIGURE 6. A simulation of the “forest” of hydrogen and metal absorption lines as they might appear observed against the spectrum of a faint quasar (top). The middle spectrum reveals the best result we could expect for today’s 8 to 10-m diameter telescopes even with an all-night exposure. The bottom spectrum illustrates the potential of GSMT to deliver spectra capable of analyzing chemical composition and motions of intergalactic gas. To gather the million galaxy sample capable of providing a tomographic map of the intergalactic medium will require two full years of observation with a 30-m GSMT. Courtesy: J. Bechtold

GSMT’s mapping of large-scale structure will also be highly complementary to the JWST studies and help to give a complete picture of the appearance of the early Universe. Just as 8 to 10-m telescopes were needed to obtain spectra of galaxies in the HST Deep Field, spectroscopy and diffraction-limited imaging with a 30-m class telescope will be necessary to expand and extend the scientific potential of the deep imaging surveys of JWST. What will result will be a complete picture of the lifecycles of gas and galaxies at high redshift.

The Formation and Evolution of Galaxies

The Problem and GSMT's Approach

This broad theme explores in more detail the formation and evolution of galaxies mentioned in the previous section. Motivated by models of the collapse of matter in the Universe, the hierarchical assembly theory for galaxies provides an indispensable framework for studying their formation and evolution. In this picture, galaxies are built through the smooth accretion of gas and the merging of smaller units. We want to know what are the *intrinsic* properties of these galaxies we see at high redshifts and how did they evolve into the galaxies we see today? A schematic representation of the problem is shown in Figure 7. The most direct method of answering these questions is through a census of the detailed properties of galaxies at large distances (and correspondingly large redshifts and look-back times), and the most efficient and comprehensive way to achieve this goal is through an integrated program of spectroscopic surveys. First, a broad optical spectroscopic survey over as wide a range of galaxy luminosities as possible will measure the star formation rates of galaxies as a function of redshift. Then a subset of these galaxies will be the targets for deeper, higher-quality optical spectra with the objective of determining elemental abundances and properties of their stellar population. A subset of these will then be chosen for the study in the near-infrared of their spatially resolved properties, revealing the dynamical masses and dynamical status of these galaxies as well as internal variations in their star formation and chemical enrichment histories. These observations will take full advantage of the near-infrared diffraction-limited imaging and spectroscopic sensitivity of a GSMT. This full set of observations, together with those briefly described in the previous subsection, will reveal not only the early star formation history of the Universe, but also the physical properties of the systems in which these stars formed. They will thus yield important pieces of the evolutionary puzzle of how these systems evolved into galaxies like the Milky Way and its neighbors.

Complementarity with JWST

Understanding how galaxies formed is the second of JWST's four key science themes. By taking advantage of its extraordinary broad and medium-band sensitivity in the near- and mid-IR, JWST will conduct a survey for galaxies with redshifts, z, between 1 and 7 including the most heavily obscured objects. Spectroscopy of the integrated light emerging from these objects with JWST provides the best measure of overall (spatially unresolved) abundances and star formation rates (SFR) for the brighter galaxies in its sample. Its mid-IR spectroscopic capabilities will allow JWST to measure velocity dispersions for the most distant galaxies, hence some idea of their internal dynamics.

These surveys with JWST will reveal broadband morphologies of targets for following narrowband and spectroscopic studies with GSMT. For the somewhat less distant galaxies in the JWST sample, the optical capabilities, extreme light-gathering power, and diffraction-limited imaging in the near-IR provided by GSMT will complement JWST's remarkable broadband sensitivity in the near- and mid-infrared. JWST will not carry an instrument with sufficient spectroscopic resolution to measure detailed *internal* kinematics of high redshift galaxies. By combining its diffraction-limited imaging capability with its order of magnitude greater spectral resolving power in the near-IR, GSMT will be able to fully resolve distant star-forming galaxies, determine the kinematics of individual super star clusters and giant H II regions, determine the chemical compositions within these star-forming regions from analysis of emission lines, and quantify star formation rates from a combination of line analysis and spectral energy distributions. A 30-meter GSMT will be able to detect regions of high star formation rate to redshifts as high as z~5 (see Figure 8). Spectroscopically, GSMT will obtain optical and near-IR high resolution spectra of galaxies in redshift range $1 \leq z \leq 3$ for detailed two dimensional analyses of structure, kinematics, and star formation rates as a function of redshift (note that spectroscopy with resolution above a few thousand in the near-

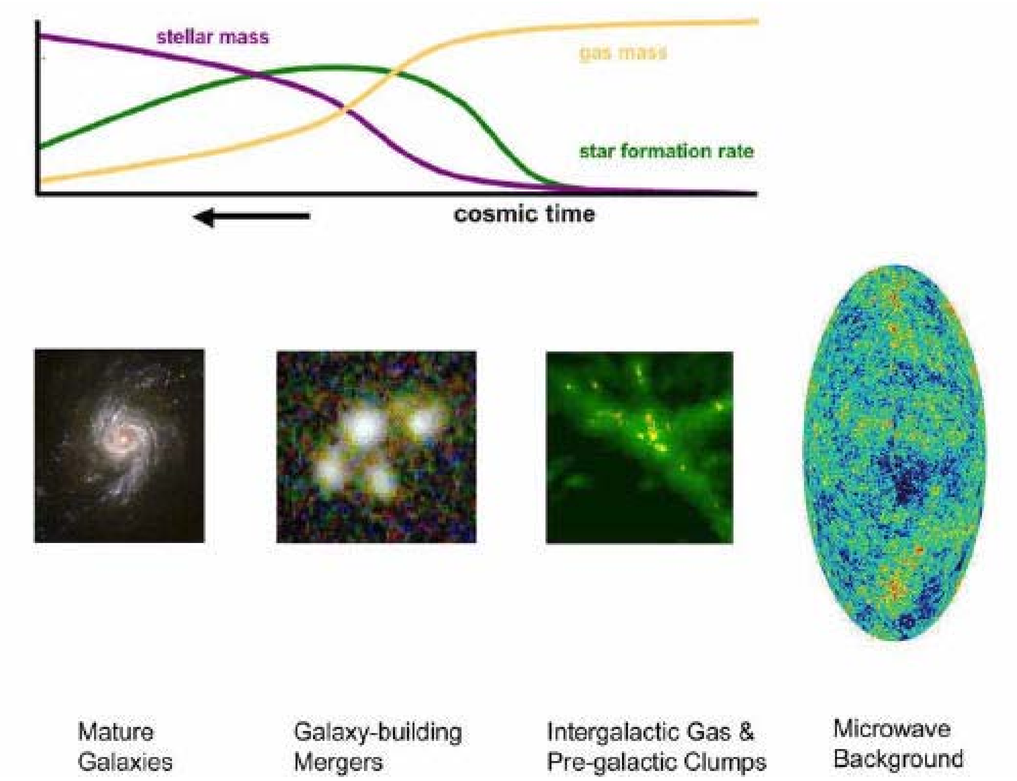

FIGURE 7. A schematic picture of the evolution of the Universe from the fluctuations seen in the microwave background, to the web-like structure of intergalactic gas and pre-galactic clumps, the merging pre-galactic structures, and finally to a mature galaxy. At the earliest epochs, the Universe is dominated by gas largely composed of hydrogen and helium. As time progresses, the first generation of stars and clusters form in the precursors of galaxies; the most massive of these stars become supernovae whose ejecta enrich the gas with elements heavier than helium. Gravity draws together galactic precursors which merge, and over time develop the galaxy morphologies we see in the nearby Universe. GSMT will have the power to map the 3-dimensional structure of the gas and link it to the fluctuations in the microwave background, to follow the evolution of the chemical evolution of the early Universe through spectroscopic observations of intergalactic gas, and to determine the masses, star-forming rates, and chemical composition of pre-galactic clumps.

IR are not limited by the OH emission line background). Stellar population studies will yield further understanding of galaxy formation and the early stages of their evolution. With GSMT, we will acquire a physical understanding of the stars that formed in the early Universe. Together, JWST and GSMT will pull back the curtain on the last great mystery of galaxy genesis.

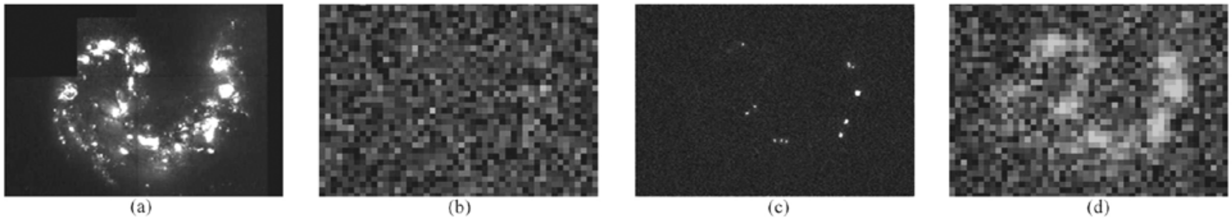

FIGURE 8: Observing star formation at high redshift: Panel (a) shows a narrow band image of the "Antennae", a nearby pair of interacting, star-forming galaxies taken in the strong H-alpha emission line of hydrogen. This emission line is an excellent tracer of regions of star formation. It arises from clouds of gas that have been ionized by the young stars. Now let's redshift this galaxy back in time and space to a z=4.74. This corresponds to a time when the Universe was only about 10% of its present age. Panels (b)-(d) show simulated 8-hour observations of what the Antennae would look like at this redshift in the 0.37 µm emission line of ionized oxygen. This line, also an excellent tracer of regions of star formation, would be redshifted to a wavelength of 2.14 µm in the near-IR and observed at high spectral resolution (R=3000), between the OH lines. The panels show simulated observations with (b) an 8-m telescope and multi conjugate adaptive optics (MCAO) with 0.05" pixels, (c) a 30-m telescope and MCAO (0.01" pixels), and (d) a 30-m telescope with only ground-layer adaptive optics (0.05" pixels). A GSMT equipped with adaptive optics will enable studies of the internal kinematics, star-formation rates, and metallicities of extremely high-redshift, star-forming galaxies.

Planetary Formation and Evolution

The Problem and GSMT's Approach

The study of planet formation environments is a central part of the quest to understand the origin of the Earth and solar system. The past decade has revolutionized our picture of both planetary formation and the characteristics of extra-solar planets. While the most revealing observations of proto-planets and planetary formation have come from both space and the ground, the remarkable discoveries and observations of extra-solar planets themselves have almost exclusively come from ground-based telescopes. These latter observations have revealed an unexpected diversity in the properties of the extra-solar planet population that has challenged traditional theories of planet formation and underscored the importance of answering fundamental questions such as: What are the necessary conditions that will permit the questions such as: systems around stars? How common is the formation of solar systems similar to our own? What values can be attached to the fundamental properties such as size, mass, chemical composition, and dynamics that characterize proto-planetary systems and the extra-solar planets themselves? The likely complexity of the planet formation process emphasizes the need for direct observational study of young planet-forming systems (at ages

1 Myr or less) in order to identify the basic physical processes that are responsible for the diversity of planetary architectures. High resolution spectroscopy is needed to study the structure of proto-planetary disks. Determining the motions of orbiting gas can provide a map of disk temperature, density, and composition as a function of radius, and locate the signatures of forming giant planets. We need to measure the environmental conditions at planet formation distances in order to provide observational constraints on the efficiency of various physical processes (e.g., grain growth, orbital migration of forming planets) during the planet formation epoch. With velocity-resolved profiles, we can determine the region of the disk responsible for the emission. Traditional emission line spectroscopic techniques can then be employed to measure the physical properties of disks. For example, from the measurement of multiple resolved line profiles, physical properties such as temperatures, densities, and column densities can be determined as a function of disk radius.

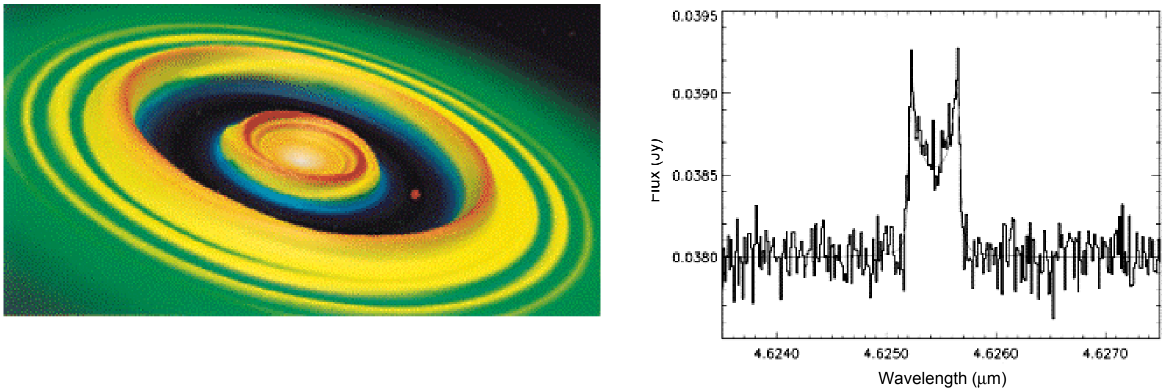

FIGURE 9. Simulation (left) depicting the dynamical effects of a newly formed gas giant planet (the red dot embedded within a dark elliptical ring) on a disk of circumstellar gas and dust surrounding a young star (Courtesy: Geoff Bryden). The gravitational effect of the planet on surrounding disk material opens up a gap or ring within which the amount of residual gas and dust is miniscule compared to the regions inward and outward of the ring. The residual gas produces a spectral signature (right panel, a simulated profile produced by a Jupiter mass planet orbiting a solar mass star at a distance of 1 AU), in this case a double horned profile manifest in emission from carbon monoxide. The wavelength separation of the horns diagnoses the distance of the planet from its parent sun, while the width of each horn measures the width of the gap, which in turn diagnoses the mass of the planet. The simulated spectrum is representative of the expected performance of a mid-IR spectrograph operating at a resolution of 100,000 on a 30 meter GSMT with an 8 hour exposure.

Potential diagnostics for observations of the disks include the CO fundamental lines at 4.7 µm, mid-infrared rotational lines of water, and the pure rotational lines of molecular hydrogen, the most important of which (as far as ground-based observations are concerned) is located at 1.7 µm. In order to measure resolved line profiles for gas at distances ~5-10 AU around solar mass stars, we require a velocity resolution of ~3 km/s or R=100,000 (see Figure

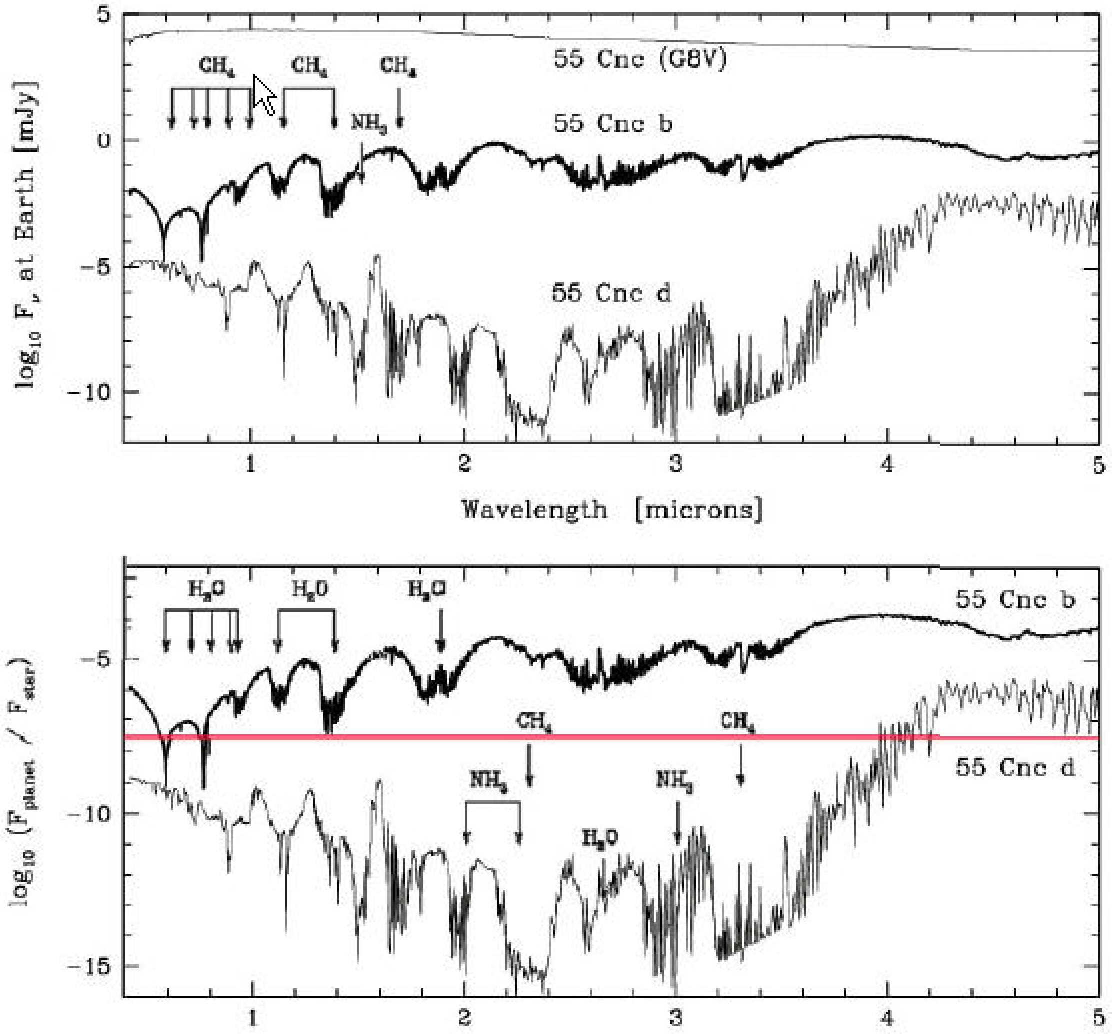

FIGURE 10. The upper panel shows a plot of the predicted spectra from (a) the nearby solar-like star 55 Cnc; (b) the warm, gas-giant planet (55Cnc b) located within 0.11 AU of its parent star, and (c) a Jupiter-like planet (55 Cnc d) located at nearly the same distance from 55 Cnc as Jupiter is from the Sun. (Courtesy: Sudarsky, Burrows, and Lunine, private communication.) Spectral features arising from methane, ammonia, and water are indicated in the upper and lower panels. Lower panel: The ratio of planetary flux to parent star flux for the two companions to 55Cnc. The red line indicates the level to which the light of 55 Cnc could be suppressed by the occulting disk of a well-designed coronagraph fed by an adaptively corrected GSMT image of the Cnc system. GSMT will have the power to detect both 55 Cnc b and d, and to determine the chemical composition of the atmosphere of 55 Cnc b from analysis of its spectrum.

9). With high contrast imaging and spectroscopy, it will be possible to directly image and disperse the light from extra-solar giant planets. Figure 10 depicts theoretical spectra computed for two giant planets located at distances of 0.5 and 5.5 astronomical units from their parent star, 51 Pegasi. By measuring such spectra with GMST, it will be possible to infer from strengths of selected molecular tracers the relative metallicity of the planet compared to its parent star and to learn thereby the mechanism by which these extrasolar giant plants likely formed. Further, by observing a statistically significant sample of planets, we should be able to determine the dominant planet formation pathway, and address the question of whether solar systems similar to our own are rare or commonplace.

Complementarity with JWST

Two of JWST's four key science themes are the study of proto-planetary and planetary systems and of their evolution, and the search for life. In the first area, the extremely high sensitivity and good resolution of the telescope in the 3 to 28 μm region will allow it to penetrate dense cores of molecular clouds to study the gas and dust as they collapse into newborn stars and protoplanetary disks. JWST uses imaging and spectroscopy across its operating spectral range to track the evolution of the protoplanetary disks toward planetary systems as these new stars emerge and age. In the second area, JWST will obtain detailed spectra of organic materials and of water in the regions surrounding very young stars. Such studies must be centered on the spectral regions where the interstellar gas and dust are relatively transparent, regions that are largely blocked from the ground by terrestrial atmospheric absorption.

GSMT's scientific objectives in these areas are strongly complementary to these themes. Its great sensitivity and small diffraction limit in the region shortward of 5 μm for high resolution imaging and spectroscopy combined with the possibility of sophisticated coronography and extreme adaptive optics will allow it to probe planets and study disk structure in this spectral range with significantly finer angular resolution, to smaller angular separations, and with higher spectral resolution than will be possible for JWST. For example, an important first step in delineating the properties of circumstellar and protoplanetary disks will be observations of the pure rotational lines of molecular hydrogen (in the 20 μm region) and other gas phase diagnostics at moderate spectral resolution with Spitzer and JWST. What will remain unclear even after these measurements are made is where in the disk the gas resides: is it in the region in which planets are believed to form (~5 AU) or at much larger distances from the central star? GSMT will measure the orbital radii from which the emission originates using high resolution spectra and enable analysis of how physical parameters such as temperature, velocity, density, and chemical abundances vary with radius in the disk.

CONCLUSION

The Hubble Space Telescope has been the flagship of NASA's Great Observatories in space. Its deployment coincided with the development of a new generation of large ground-based telescopes, such as Keck, Gemini, and the Very Large Telescope(s). These two types of observatory, with their unique and powerful capabilities, have made—and continues to make—fundamental contributions to many areas of astronomy. Operating together, on the same problems, the two made some truly astounding breakthroughs in our knowledge of the Universe. Studies of distant galaxies in the Hubble Deep Field and of distant supernovae are two examples. Obtaining the required observations for these two programs pushed both telescopes to their limits and entailed considerable interplay between the two.

JWST will continue NASA's Great Observatory tradition with breakthrough capabilities that can only be provided from space. The GSMT will lead the next generation of extremely large telescopes to revolutionize capabilities from the ground. As with the current large ground-based telescope and HST, GSMT and JWST will each have its own unique strengths in carrying out science programs with an order of magnitude or more sensitivity than existing ground- and spaced-based facilities. JWST's unique capabilities are based on very low background in the near- and mid-IR limited only by the Zodiacal light at wavelengths less than 10 μm, uninterrupted whole sky wavelength coverage from 0.6 to 28μm, (it can observe in regions of the spectrum that are completely blocked by the atmosphere for an Earth bound telescope), and a wide field of view with diffraction-limited imaging for wavelengths longer than 2μm. GSMT's unique capabilities are based on a collecting area 10 times greater than that of Keck and 25 times greater than JWST, sensitivity throughout the optical part of the spectrum, and diffraction-limited spatial resolution in the near- and mid-IR that will be up to 5 times greater than that of JWST. Because of the complete absence of background emission from atmospheric OH lines in the near-IR and extremely low thermal background in the mid-IR, JWST will be the instrument of choice for sensitive broadband imaging in the infrared. For spectral resolutions greater than a few thousand in the non-thermal near-IR, though, GSMT will be the instrument of choice for faint objects because of its enormous sensitivity and potential for diffraction-limited image performance. GSMT's high spectral resolution capabilities in the mid-IR will also be extremely valuable for studying bright objects when the thermal background is not an issue. These unique capabilities of the two telescopes are highly complementary and together can open up a new and exciting epoch for cosmic discovery. We conclude with a quote from the annual report of the Astronomy and Astrophysics Advisory Committee for 2003:

> "*The ambitious science goals [of the JWST and a 30-meter class GSMT], which include understanding the formation of galaxies and the chemical elements within just the first one billion years of the Big Bang, and the formation of stars and planets, will only be fully realized through operational overlap of the facilities, as HST and large-ground-based telescopes have demonstrated over the last decade. Progress on these scientific objectives is heavily dependent on GSMT being developed on the same timescale as JWST.*"

APPENDIX A

Examples of Key Science Programs With a Giant Segmented Mirror Telescope

GSMT's unprecedented light gathering power and spatial resolution capabilities represent significant performance gains over all existing ground-based optical and near- to mid-infrared telescopes. Three fundamental problems that the telescope will be able to attack because of these performance gains are to:

- Detect the emergence of large-scale structure in the Universe as mapped by galaxies and intergalactic gas during the first billion years following the Big Bang
- Observe the building blocks of galaxies and the process of galaxy assembly coupled with a determination of the early evolution of chemical elements heavier than helium
- Directly observe hundreds of extra-solar giant planets and the disks from which they form, thus adding immeasurably to our understanding of solar system formation and the emergence of life

While there are significant technical challenges to building a telescope of this size, the considerable amount of work already done on different design concepts has not revealed any insurmountable hurdles that would prevent the construction of a GSMT nor have they indicated any reason to think that the cost of a GSMT would lie outside of the envelope estimated by the most recent NAS/NRC decadal survey of approximately $700 million dollars. What follows is based closely on the report prepared for the NSF Astronomy Division by the GSMT Science Working Group.

The Emergence of Large-Scale Structure

More than 80% of the matter in the Universe is "dark"—it emits no radiation that we have been able to detect nor does it appear to be made of the protons, neutrons, and electrons, the building blocks of "ordinary" or visible matter. The existence of dark matter is known only by its gravitational effect on ordinary matter. Ordinary matter in the very early Universe consisted of a gas composed of hydrogen and helium. The gravitational attraction of dark matter concentrated this gas into clumps and filaments. The first galaxies to form did so within the first few hundred million to one billion years after the Big Bang in regions where the gas became most densely clumped.

The unique capabilities of a GSMT will allow it to detect hundreds of thousands of these very early galaxies and accurately locate them in 3-D space, i.e., direction *and* distance from us. GSMT will also be able to map out the clumps and filaments of intergalactic gas that lie between us and each galaxy. Astronomers refer to this process of mapping the 3-D distribution of gas and galaxies in the first few hundred million years after the Big Bang as "determining the Universe's large scale structure." (Figure 11) The unique power of the GSMT to attack the fundamental problem of determining the Universe's large-scale structure comes from its extremely large aperture, its ability to observe at optical as well as infrared wavelengths, and its ability to obtain high resolution spectra of a thousand galaxies with one observation.

In order to usefully determine large scale structure, the 3-d distribution of galaxies and gas must be determined over a large volume of space; e.g., a cube of a few 100 million light years on a side located at a distance in space and time corresponding to the first 10% or one billion years of the Universe's lifetime. Several hundred thousand to one million galaxies would need to be identified and observed within this volume. The resulting empirically determined distribution of galaxies and gas will provide the basis for choosing between "model Universes" constructed by theorists on their computers in order to predict large-scale structure from the fluctuations encoded in the cosmic background radiation. A multi-object spectrograph that can obtain spectra of several thousand objects at once would easily, at low spectral resolution at optical wavelengths, determine the redshift distances of the requisite number of galaxies. Then observations at high resolution would study—via their sharp "shadows" against the light of the galaxies—the forest of absorption lines arising in intergalactic gas between us and the galaxy. These lines are diagnostic both of the gas's distribution (via its Doppler-shifted velocity) and chemical composition (via the strength of each element's absorption lines). The crucial need for faint galaxies as probes is to achieve a density of background sources high enough to map the clustering structure on a scale of tens of millions of light years. Only GSMT will have the sensitivity needed to carry out these high spectral resolution observations.

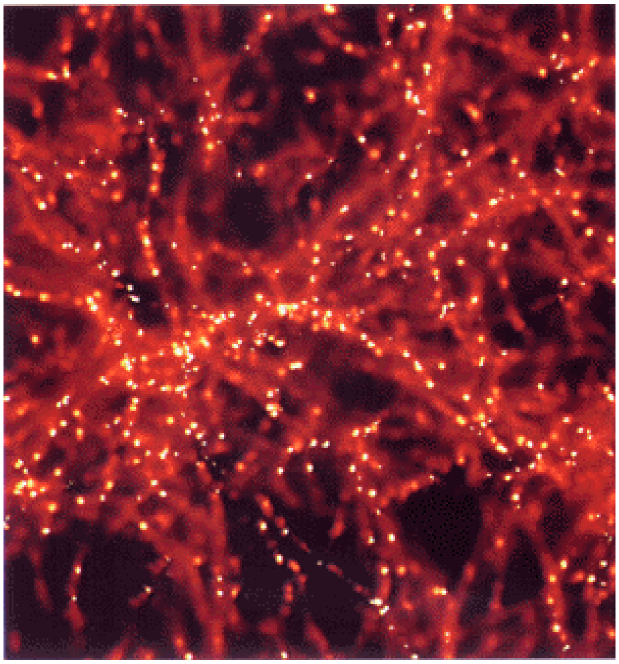

FIGURE 11. Results of a numerical simulation starting from a model Universe whose basic parameters derive from analysis of COBE and WMAP data. This simulation illustrates the web of intergalactic gas threading the early Universe. The brightest areas indicate regions where dark matter has concentrated gas into higher density clumps. GSMT has enough light-gathering power to use faint, distant galaxies as probes to detect intervening intergalactic gas, and to develop a tomographic map of the how it is distributed. The goal is to understand the link between the 3-dimensional distribution of this gas and the fluctuations observed in the microwave background, and to discover the interplay in dynamics and chemical composition between this gas and the first generations of stars in the nascent galaxies. (Courtesy L. Hernquist)

These same observations of ordinary matter will also be able to trace the distribution of dark matter via its gravitational effect on the motions of gas and galaxies. Hence we can learn how both types of matter were distributed during the earliest evolutionary phases of the Universe and how dark matter influences the formation and evolution of galaxies.

How Galaxies are Built

Observations with HST and the largest ground-based telescopes have shown that giant galaxies like the Milky Way are built up via multiple mergers and accretions of smaller systems. A successful theory of the growth of structure in the Universe, based on numerical modeling with powerful computers, paints much the same picture: Concentrations of stars and gas into aggregates about one-tenth the mass of the Milky Way emerged less than a billion years after the Big Bang. Pulled together by the gravitational attraction of dark matter, these first galactic nurseries were soon ablaze with the intense energy of newborn stars. Galaxies as majestic as our Milky Way came later, assembled from tens of these embryonic galaxies that were initially spread out over a volume 1000 times larger than the Milky Way is today. Over the next several billion years these growing infant galaxies were themselves united by mutual gravitation and reshaped, often by violent dynamical interactions, into today's familiar galactic forms. Each major merger was accompanied by spectacular bursts of newly-formed stars and star clusters. Figure 12 is an illustrative example of the process. These fireworks not only celebrated the galactic birth process but were also the source of almost all chemical elements (i.e., Big Bang Nucleosynthesis produces some Li, Be, and B, although not much) heavier than hydrogen and helium, the first step in the long chain of atomic and molecular processes that would lead to Earth-like planets and life itself. These first "heavy" elements were violently expelled from their parent stars into the surrounding galactic and intergalactic gas via enormous stellar explosions—supernovae. Left behind, though, was a complex, but eminently decipherable record of these events. With the next generation of telescopes on the ground and in space we can proceed with the decipherment.

FIGURE 12. Simulation (left) depicting a time sequence of a merger of two galaxies, drawn together by their mutual gravitational attraction to form a single system. On the right is a nearby pair of merging galaxies, the "Antennae." In the color composite HST image of the central part of the Antennae are spectacular blue clusters of new stars induced to form in the violent collision that will eventually produce a single, merged galaxy. Courtesy C. Mihos and L. Hernquist

Some of the fundamental questions that need answering are: What are the masses, structures, and dynamics of pre-galactic systems? What varieties of stars were first formed and what mix of the elements heavier than helium did they produce? How did these proto-galaxies grow and what was the detailed history of their chemical enrichment? How did they come together to form the Milky Way and the other galaxies we see today? Only by linking our observations back into deep time with studies of the resulting galaxies in the modern Universe can we endeavor to answer these fundamental questions.

An understanding of the galaxy building process will require GSMT's unique diffraction-limited imaging capability in the near IR, in addition to its other unique attributes mentioned earlier. While GSMT will not have the extremely low background and uninterrupted infrared wavelength coverage that JWST will possess, a 30-meter GSMT with adaptive optics will be able to obtain images in the near-IR with a spatial resolution that will be up to five times finer, although with lower sensitivity, than those obtainable with JWST. Also, GSMT will be equipped with near-IR spectrographs with spectral resolutions up to several tens of thousands or about 10 times greater than the near-IR spectrograph on JWST. This order of magnitude greater spectral resolution combined with a factor of 5 greater spatial resolution in the infrared will permit highly detailed dynamical studies of even very dusty regions in galaxies.

Observing the light of the first stars in the Universe and imaging the earliest phases of the galaxy building process will require the extraordinary sensitivity in the near- and mid-infrared of JWST. Although GSMT will be unable to observe these stars individually, its enormous light gathering power combined with its superb angular resolution in the near-IR will permit GSMT's spectrographs to resolve light emitted by compact and very populous *clusters* of these stars (see Figure 12), yielding a thorough analysis of their physical and chemical properties. For example, we will be able to determine the evolving chemical mix in the early Universe, measure the dynamical motions of individual clumps in the galaxies to determine the all-important total mass of the each system, and, from the spectral energy distribution of the individual clusters, infer the distribution in mass of the individual stars.

To get a complete picture of how galaxies in the nearby Universe got to be the way they are we need to observe the earliest stages of galaxy formation and also to conduct a thorough and extensive survey of all types of galaxies at all epochs. GSMT will have the power and the instrumentation to carry this out—from the earliest pre-galactic condensations to fully mature galaxies. From the rich information encoded in their spectra from the optical through the IR, astronomers will be able to chart the paths that different galaxies followed as their total masses grew through accretion and as their abundances of heavy elements increased through the actions of stellar evolution and supernovae. GSMT will be a critical tool for furthering our understanding of the detailed physical processes involved in galaxy formation and evolution.

Formation and Evolution of Planetary Systems

Only in the past decade has direct evidence for the existence of other planetary systems begun to accumulate and to reveal that they are quite common. Over 100 planetary mass bodies have now been discovered around stars near the Sun, indicating that at least 5% of solar-like stars possess at least one giant planet. In addition, space and ground-based observations have been able to directly image disks of orbiting gas and dust around stars. These disks have sizes similar to the solar system and mass comparable with that of the planets, asteroids, and comets now orbiting the sun. It is generally thought that planetary systems including our own form out of such circumstellar disks.

The unique power of the GSMT to attack the fundamental problem of determining the Universe's large-scale structure comes from its extremely large aperture, its ability to observe astronomers aware of the gaps in their knowledge about the process of planetary system formation and evolution. At the same time, though, these new discoveries have allowed us to formulate key questions that need to be addressed such as: What accounts for the diversity of planetary architectures that we observe? How and when do gas giant planets like Jupiter form? Did such gas giants form in a multi-step process of solids sticking together followed by accretion of gas—a process likely to lead as well to rocky planets like the Earth — or did they form like tiny stars, disrupting their nascent disks and hence mitigating against the existence around them of habitable worlds? How frequently can terrestrial planets similar to our own Earth and its neighbors Venus and Mars form? How many of these are located in favorable locations for life?

Over the next decade, continued ground-based observations will greatly increase our knowledge of other planetary systems, both by significantly enlarging the total sample of extra-solar systems and by exploring domains of planetary separations heretofore beyond the reach of the past decade's studies. Of particular importance will be GSMT's great collecting area – 25 × that of JWST for a 30-meter telescope—and a diffraction limit in the near- and mid-IR wavelengths accessible from the ground of up to 5 × greater than that of JWST. These properties will enable it to make fundamental contributions to answering questions about the formation and evolution of planetary systems. The unique capabilities of GSMT in the near- and mid-IR will be pushed to their limits in this effort. There are also a number of space-based missions in various stages of planning and development that hold out great promise for enhancing our knowledge and understanding of the formation and evolution of planetary systems. These include Kepler, the Space Interferometry Mission and the Terrestrial Planet

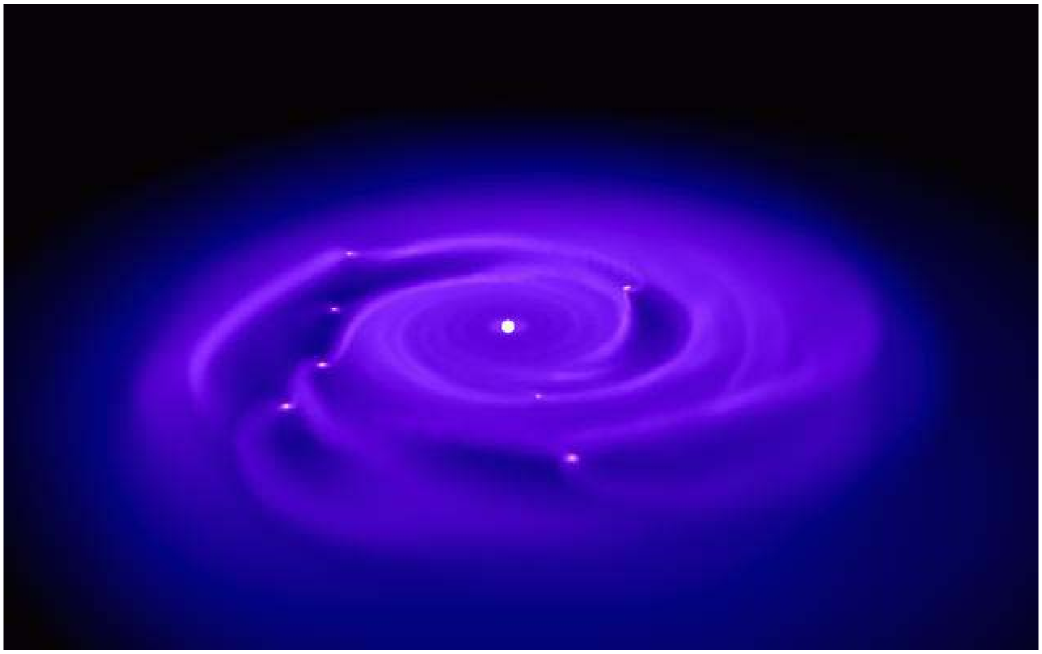

FIGURE 13. A numerical simulation of a planet-forming disk. Note the "gaps" produced by the gravitational effects of forming planets on the distribution of orbiting disk gas The location of these gaps can be inferred by exploiting the light gathering power of GSMT to feed a sensitive infrared spectrograph capable of "deconstructing" the structure of the disk from high resolution observations of emission arising from disk gas. Courtesy: University of Washington High Performance Computing Center.

Finder (TPF). TPF, though, will observe only in the optical and thus not be able to detect self-luminous planets unless they are close enough to their parent stars to be detectable via reflected light.

GSMT is uniquely poised with its huge aperture, advanced adaptive optics systems, and coronography to pluck the faint light of large numbers of Jupiters out from under the glare of their parent stars. Young Jupiter-like planets that are self-emitting can be imaged around stars out to the nearest star-forming regions, more than 200 light years away. More mature planets, hence cooler and intrinsically less luminous, can be imaged around closer neighbors of the sun, out to distances of 30-60 light years. If there are planets similar to Venus or Earth orbiting stars located nearer than 20 light years from Earth, GSMT, with ultra-high performance adaptive optics systems, may eventually be able to image them as well. GSMT's light-gathering power will enable spectroscopic analysis of the constituents of giant planet atmospheres. The relative abundances of different gases (e.g., methane and ammonia) will provide direct insight into how gas giants typically form and implications for the formation of terrestrial planets.

GSMT will also have the light-gathering power and spatial resolution to peer into the disks surrounding just-born stars (see Figure 13) to learn whether planetary systems begin to take shape within the first few million years of a sun's life. While light from the planets themselves will be too weak to see against the bright emission arising from the disk, their presence can be revealed through observations "gaps" created by the effects of a forming planet's gravity on orbiting gas and dust (see Figure 9). From these observations, we can determine when and where giant planets form, and whether their location is benign or hostile to the development of life-bearing terrestrial planets.

APPENDIX B
Key Science Objectives of the James Webb Space Telescope

The scientific objectives of JWST are fully described in the Science Requirement Document assembled by the JWST Science Working Group. These science objectives take maximum advantage of the unique capabilities of the JWST as a cold, infrared-optimized telescope operating in the very low background environment to be found at the Lagrangian point L2 located about 1.5 million miles from the Earth on the side opposite that of the Sun. The most important of these unique capabilities are enumerated in the Introduction to this report. The science objectives of JWST fall into four broad themes which are summarized in M. Stiavelli, et al. 2004 "JWST Primer", Version 1.0 (Baltimore: STScI). Stiavelli et al.'s summary of these four themes is given below.

First Light

Theory and observation have given us a simple picture of the early Universe. The Big Bang produced (in decreasing order of present mass-energy density): dark energy (the cosmic acceleration force), dark matter, hydrogen, helium, cosmic microwave and neutrino background radiation, and trace quantities of lithium, beryllium, and boron. As the Universe expanded and cooled, some hydrogen molecules were formed, and these in turn enabled the formation of the first individual stars. The first stars formed in those regions that were densest. According to theory and the Wilkinson Microwave Anisotropy Probe (WMAP), the Universe has expanded by a factor of 20 since that time, the mean density was 8000 times greater than it is now, and the age was about 180 million years. Also according to theory, these first stars were 30 to 1000 times as massive as the Sun and millions of times as bright and burned for only a few million years before meeting a violent end. Each one would produce either a core collapse supernova (type II) or a black hole. The supernovae would enrich the surrounding gas with the chemical elements produced in their interiors, and future generations of stars would all contain these heavier elements ("metals"). The black holes would start to swallow gas and other stars to become mini-quasars, growing and merging to become the huge black holes now found at the centers of nearly all galaxies. The distinction is important because only the supernovae return heavy elements to the gas. The supernovae and the mini-quasars should be observable by the JWST. Both might also be sources of gamma ray bursts and gravity wave bursts that could be discovered by other observatories and then observed by JWST.

The JWST First Light key objective is to find and understand these predicted first light objects. To find them, the JWST must provide exceptional imaging capabilities in the near IR band. To verify that they are indeed first light objects, mid-infrared observations are required.

Assembly of Galaxies

Galaxies are the visible building blocks of the Universe. Theory and observation also give us a preferred picture of the assembly of galaxies. It seems that small objects formed first, and then were drawn together to form larger ones. This process is still occurring today, as the Milky Way merges with some of its dwarf companions, and as the Andromeda Nebula heads toward the Milky Way for a future collision. Galaxies have been observed back to times about one billion years after the Big Bang. While most of these early galaxies are smaller and more irregular than present-day galaxies, some early galaxies are very similar to those seen nearby today. This is a surprise.

Despite all the work done to date, many questions are still open. We do not really know how galaxies are formed, what controls their shapes, what makes them form stars, how the chemical elements are generated and redistributed through the galaxies, whether the central black holes exert great influence over the galaxies, or what are the global effects of violent events as small and large parts join together in collisions. The JWST Assembly of Galaxies key objective is to observe galaxies back to their earliest precursors ($z \sim 7$) so that we can understand their growth and their morphological and metallicity evolution. The JWST must provide imaging and spectroscopy over the 0.6 to 27 μm band to meet this objective.

Birth of Stars and Proto-planetary Systems

While stars are a classic topic of astronomy, only in recent times have we begun to understand them with detailed observations and computer simulations. A hundred years ago, we did not know that they are powered by nuclear fusion, and 50 years ago we did not know that stars are continually being formed. We still do not know the details of how they are formed from clouds of gas and dust, or why most stars form in groups, or how planets form with them. We also do not know the details of how they evolve and liberate the “metals” back into space for recycling into new generations of stars and planets. In many cases, these old stars have major effects on the formation of new ones.

Observations show that most stars are formed in multiple star systems and that many have planets. However, there is little agreement about how this occurs, and the discovery of large numbers of massive planets in very close orbits around their stars was very surprising. We also know that planets are common around late-type (cooler and less massive than the Sun) stars, and that debris disks might reveal their presence.

The JWST Birth of Stars and Protoplanetary Systems key objective is to unravel the birth and early evolution of stars, from infall on to dust-enshrouded proto-stars, to the genesis of planetary systems. The JWST must provide near- and mid-IR imaging and spectroscopy to observe these objects.

Planetary Systems and the Origins of Life

Understanding the origin of the Earth and its ability to support life is a key objective for all of astronomy and is central to the JWST science program. Key parts of the story include understanding the formation of small objects and how they combine to form large ones, learning how they reach their present orbits, learning how the large planets affect the others in systems like ours, and learning about the chemical and physical history of the small and large objects that formed the Earth and delivered the necessary chemical precursors for life. The cool objects and dust in the outer Solar System are evidence of conditions in the early

Solar System, and are directly comparable to cool objects and dust observed around other stars.

The JWST Planetary Systems and Origins of Life key objective is to determine the physical and chemical properties of planetary systems including our own, and investigate the potential for the origins of life in those systems. JWST must provide near- and mid-IR imaging and spectroscopy to observe these objects.

APPENDIX C

This document was prepared by the GSMT SWG in close consultation with the JWST SWG, whose feedback was essential to clearly defining the unique roles of GSMT and JWST as well as the potential synergies between them. Alan Dressler (OCIW) and Jay Frogel (AURA) merit special thanks for their efforts in preparing initial drafts of key portions of this report. George Rieke of the JWST SWG deserves special recognition as well for his efforts to ensure that the report accurately reflects the views of the JWST SWG community it serves.

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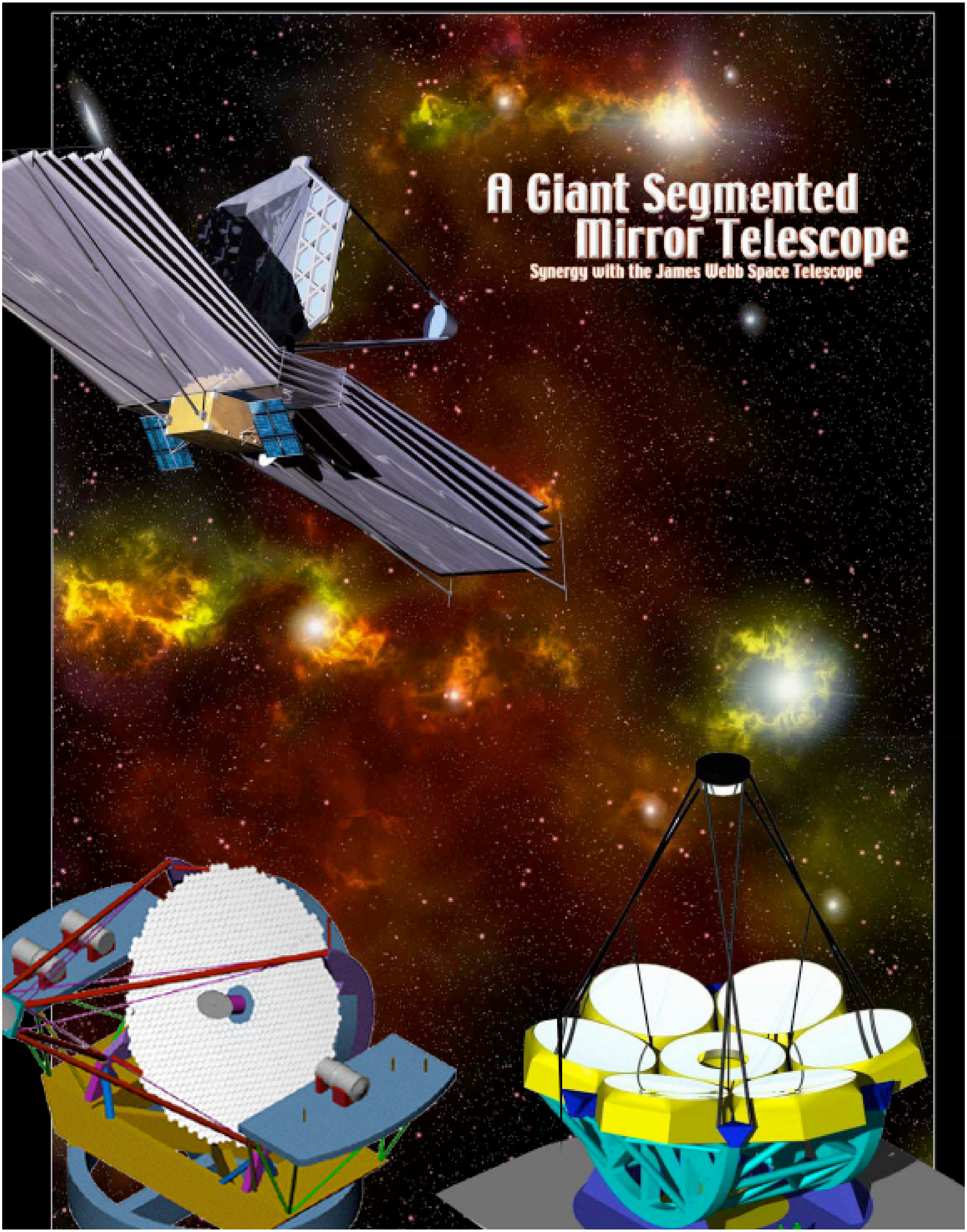

A Giant Segmented Mirror Telescope

Synergy with the James Webb Space Telescope