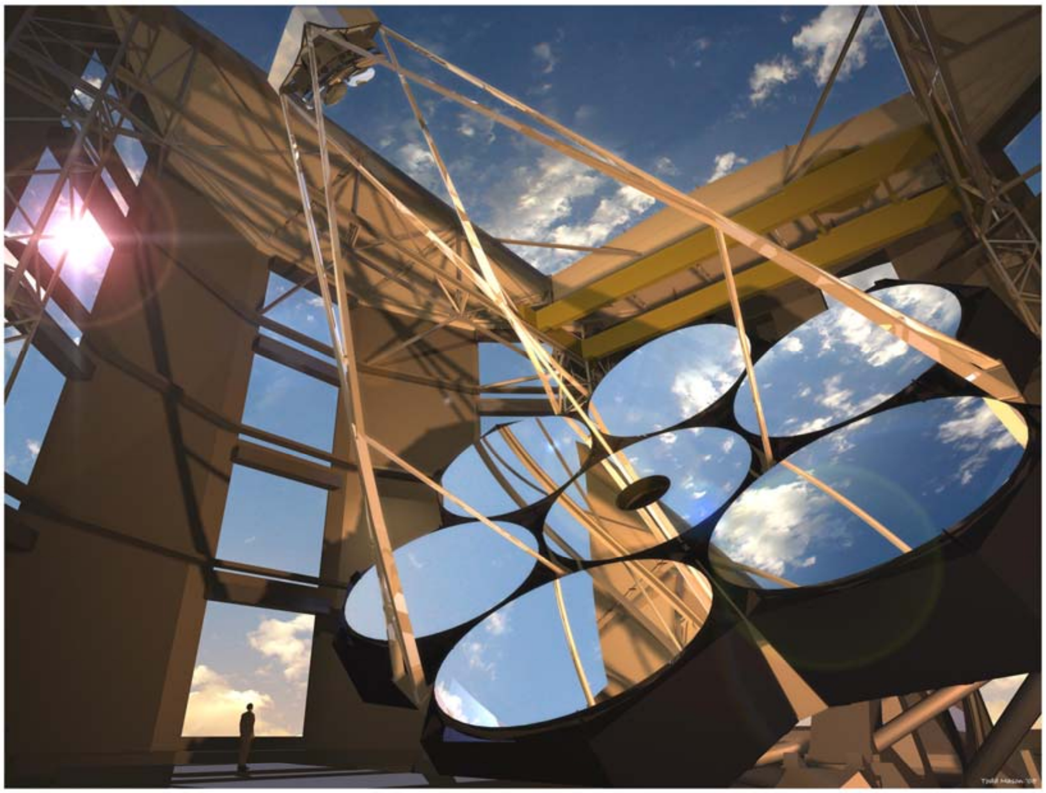
THE GIANT MAGELLAN TELESCOPE



GMT PROJECT STATUS

March 2007

THE GIANT MAGELLAN TELESCOPE:

A CONSORTIUM FOR 21ST CENTURY DISCOVERY

The nine partners[1] comprising the Giant Magellan Telescope (GMT) consortium have undertaken to design, construct and operate a telescope that, when completed, will be the world's largest ground-based optical/infrared facility. The telescope is composed of seven primary mirror segments, each 8.4m in diameter and an adaptive secondary mirror allowing diffraction-limited imaging performance from the ground. The GMT will be located in the dry desert mountains in Chile at one of the world's premier astronomical sites. The telescope will produce unprecedented gains in angular resolution and sensitivity and will provide a critical tool for investigating extremely important problems in contemporary astronomy and astrophysics. Among these are:

- Understanding Planets outside the Solar System
- Determining the Nature of Dark Matter and Dark Energy
- Understanding Stellar Populations and the Origin of the Chemical Elements
- Probing the Growth of Black Holes in the Universe
- Understanding the Formation of Galaxies
- Detecting First Light and the Reionization of the Universe

As has been the case with all new telescopes, the GMT's unanticipated discoveries will open frontiers previously unexpected and unimagined, providing new windows onto the cosmos.

The GMT partnership is the successor to the highly successful Magellan Project, a collaboration that designed and built two 6.5-meter telescopes, under budget and on time. These two telescopes went into operation in Chile in 2000 and 2002. With their twin, the 6.5-meter MMT Telescope in Arizona, the Magellan telescopes' extraordinary image quality has played a key role in observations that have significantly deepened our understanding of the Universe and guided us into another century of scientific discovery.

A telescope of at least 20-meter aperture was the top priority for new ground-based facilities that emerged in the most recent decadal study of astronomy and astrophysics conducted by the National Academy of Sciences (NAS)[2]. Building such a large telescope is now possible because of recent advances in two key telescope technologies: (1) casting and processing huge but relatively lightweight spun-cast mirrors and (2) using adaptive optics[3] to remove image distortion caused by turbulence in the Earth's atmosphere. The first of the GMT's seven giant (8.4-meter diameter) mirrors was cast in July 2005. Grinding and polishing of this 20-ton spun-cast mirror is now underway at the Steward Observatory Mirror Lab at the University of Arizona.

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[1] *The Australian National University, Carnegie Observatories (Carnegie Institute of Washington), Harvard University, Massachusetts Institute of Technology, Smithsonian Astrophysical Observatory, Texas A & M University, the University of Arizona, the University of Michigan, and the University of Texas at Austin.*

[2] *Study was entitled "Astronomy and Astrophysics in the New Millennium," National Academy Press, 2001.*

[3] *Adaptive optics is a technology whereby thousands of mechanical actuators adjust the shape of the deformable mirrors to correct for the image blurring caused by turbulence in the Earth's atmosphere.*

20^{th} CENTURY COSMIC DISCOVERIES

This image of the Triangulum galaxy (M33) was taken with the MMT Observatory's Megacam instrument, a 340-megapixel monster that some have described as a "turbocharged" household digital camera. Similar megacameras will image extremely distant objects with the GMT.

Scientific discovery depends on having the right tools. From Galileo's time to today, the completion of each new generation of telescopes has opened new views on the Universe. The size and power of our telescopes have steadily evolved, gated only by the growth of technology and our engineering sophistication. During the 20^{th} century, four generations of telescope building took us from telescopes with apertures of 1.5 meters (~60 inches) to those with apertures of 10 meters (~400 inches). The result was a century of unprecedented and riveting scientific discovery. We now know that our Solar System contains thousands of comets and minor planets beyond the orbit of Neptune, in addition to the eight major planets. We have mapped the extent of our Milky Way Galaxy with its 100 billion stars and have found that it contains the bizarre remnants of dead stars that emit copious quantities of X-rays, i.e., neutron stars and black holes. We have come to understand that the Universe is populated with billions of galaxies like our Milky Way that are distributed in vast string-like structures of bubbles and voids spanning hundreds of millions of light years. Supermassive black holes at the centers of these galaxies power quasars when the galaxies are young. We have discovered that the Universe began with a Big Bang and that it has been expanding for some 13.7 billion years. Very recently, we have found strong evidence that this expansion has not been constant: it has been accelerated by a mysterious and invisible "dark energy." Looking ahead to another century of scientific discoveries, we propose to lead the development of the next generation of ground-based optical and infrared telescopes with the Giant Magellan Telescope.

21^{st} CENTURY TECHNOLOGYY: SHARPER IMAGES OF FAINTER OBJECTS

One might ask why we should embark on a new telescope project now that 10-meter class optical/infrared telescopes[4] are in operation. For one, addressing the pressing science questions demands significant gains in sensitivity and resolution. Second, the science and technology that have driven many of the groundbreaking discoveries in astronomy motivates our desire to create the most powerful scientific instruments possible.

Some 80 to 100 years ago, George Ellery Hale set the standard for technology development when he quickly progressed from the Mt. Wilson 60-inch and 100-inch reflecting telescopes to the 200-inch aperture Hale telescope at Palomar Mountain. These telescopes came into operation in 1910, 1919, and 1948, respectively. The Hale telescope defined the limit of telescope making for half a century.

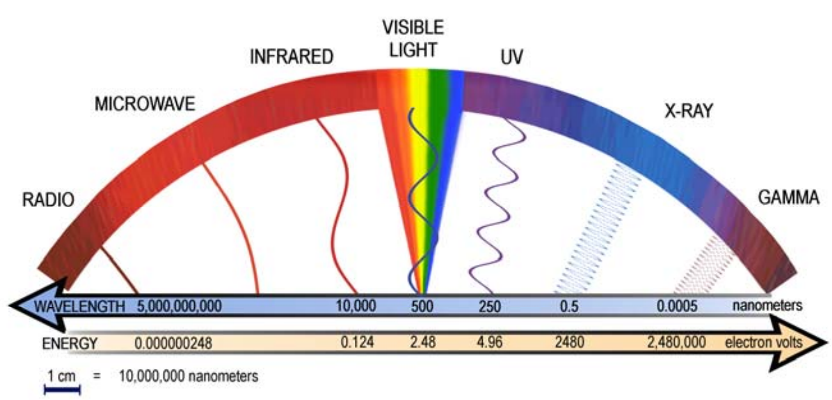
[4] *The twin telescopes of the W.M. Keck Observatory on Mauna Kea, Hawaii, are operated by the California Association for Research in Astronomy (CARA).*

Today, astronomers worldwide are again probing the new limits to telescope aperture and the GMT is an innovative approach to surmounting the size limit for casting and polishing individual glass elements. GMT, with its eight 8.4 meter primary mirror segments, will have a factor of 11 greater light collecting area than the Magellan telescopes. Another technological challenge in the performance of ground-based telescopes is the image blurring introduced by turbulence in the Earth's atmosphere. The GMT will use the latest in *adaptive optics* technology to correct for image degradation due to atmospheric turbulence. Thousands of mechanical actuators will adjust the shape of a deformable mirror (composed of a set of thin glass shells) 1,000 times each second to cancel the image distortions induced by the atmosphere. This sharpening of the images allows the telescope to work to its full potential – diffraction limited – providing gains both in terms of sensitivity and angular resolution. In the adaptive optics mode, GMT will be 130 *times faster than the Magellan and MMT telescopes in detecting faint astronomical sources.*

The GMT design strikes a balance between innovation and proven technology. As such it represents a bold initiative by the GMT partners to maintain their competitive place at the forefront of cosmic discovery and exploration.

THE PROMISE OF HIGH RESOLUTION MULTIWAVELENGTH ASTRONOMY

The National Academy's decadal review stated that a new generation of astronomical facilities would be required before significant advances could be made in many of the most important scientific questions. The facilities that are needed span a range of wavelengths and require a combination of space- and ground-based instruments. The committee identified the Next Generation Space Telescope and a Giant Segmented Mirror Telescope as the top space and ground-based priorities, respectively. The James Web Space Telescope, the successor to the Hubble Space Telescope, is expected to fulfill the need for a next-generation space telescope and should provide an enormous gain in infrared sensitivity. The Atacama Large Millimeter Array (ALMA) will provide large gains in sensitivity and resolution at millimeter and sub-millimeter wavelength. These telescopes, currently under development, will provide a rich array of astrophysical data on a wide variety of celestial objects. They will remain largely dependent on large ground-based telescopes for fundamental discovery and supporting observations.

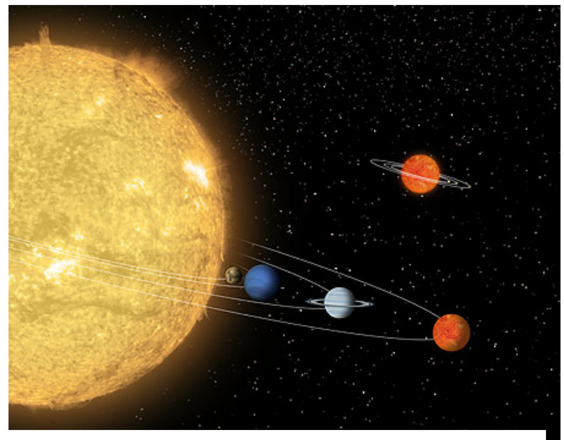


The Electromagnetic Spectrum

GMT'S SCIENCE OBJECTIVES

The GMT will investigate many cutting-edge projects that will arise during the next decade. It is important to keep in mind that surprises will also arise, e.g., observations will demonstrate that some of our present theoretical models and interpretations are incorrect or incomplete. These surprises and the associated serendipitous discoveries will undoubtedly affect the choices of projects to be undertaken with the GMT. Even so, some important directions of our science are clear; below we discuss a few of the important challenges we will address with the new telescope. We also note that, like the development of digital imaging cameras (charge-coupled devices, i.e., CCDs) and their profound impact on astronomical instrumentation, other new technologies will be developed in the next decade that will further enhance the power of the GMT.

Planets and Their Formation



An artist's conception of planets in orbit around a star in another distant solar system.

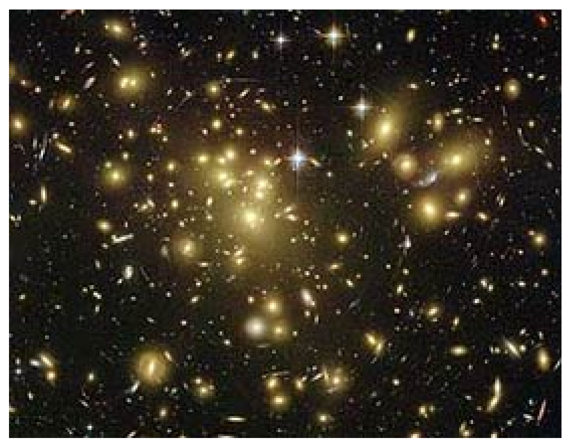
The 20th century was witness to enormous progress in our understanding of how stars evolve, starting with hydrogen and helium, and how the heavier elements necessary for life are produced. In the last thirty years, we have begun to understand how stars and their planetary systems form. Some ~200 planets have been detected in orbits around other stars. We are driven to know whether some of these planetary systems like our solar system are common among the billions of stellar systems that comprise our Milky Way Galaxy or if we are truly alone in the cosmos. How, where, and when are planets born in the flattened rotating disks that orbit young stars? How common are gas giants like Jupiter and Saturn? Are giant planets helpful or harmful to the emergence of life-bearing worlds? Are Earth-like terrestrial planets rare or common and how do they obtain the seed materials necessary for the emergence of life? Based on only about ten years of exploration the evidence is beginning to suggest that there are planetary systems similar to our own. Of course, while the discoveries may confirm that we are not alone, it is clearly a long way from one pale blue planet (Earth) to another. Currently, we are only able to detect planets by indirect - spectroscopic - means. The GMT will allow us to directly image planets around nearby stars and to discern their chemical compositions. Designed with high contrast imaging in mind, the GMT will have the ability to detect faint terrestrial-like planets in the presence of the enormous bright glare of their parent stars. There is a very positive link here, for these bright nearby stars will also serve as the natural guide stars to correct for the turbulence and thus enable observers to image the faint planets that orbit them and probe their planetary environs further.

Black Holes in the Universe

One of the most intriguing predictions of Einstein's General Relativity is the existence of black holes, which are detected by the rapid motion of gas and stars in orbit about a massive dark object. Jets, moving near the speed of light, are common among black holes with masses ranging from that of the Sun to billions of solar masses. Astronomy has provided spectacular confirmation of the existence of black holes, from solar-mass scales to the supermassive black holes – singularities containing the mass of billions of stars. Recent evidence has shown that massive black holes are commonplace in the Universe and that intermediate-mass black holes may be wandering throughout much of intergalactic space. Our own Milky Way contains a central black hole with a mass one million times that of the Sun. There appears to be a close connection between galaxy formation and black hole formation, but the mechanisms that link the two are not understood. The typical galaxy harbors a black hole containing 0.5% of the galaxy's central stellar mass. Why the mass of stars and that of the central singularity should be in a constant ratio is a great mystery. Did the earliest stars and black holes form at the same time, or did the black hole dictate the efficiency of star formation in young galaxies? Why are some black holes (like the one in the Milky Way) dark, while others host quasars, the most luminous objects in the Universe? The solutions to these puzzles lie, in part, in observations of black holes in distant, and hence young, galaxies. The GMT, operating with adaptive optics to achieve its maximum resolving power, can probe the centers of distant galaxies in unprecedented detail.

Dark Matter, Dark Energy and the Accelerating Universe

The existence of Dark Matter, non-luminous material whose presence is felt only through its gravitational pull, was first deduced from dynamical studies of motions of individual galaxies in galaxy clusters. Detailed dynamical studies of spiral galaxies revealed that Dark Matter is the dominant form of mass in most, and perhaps all, galaxies. We now believe that 80% of the mass of the Universe is in this invisible form that astronomers call "non-baryonic matter." Very little is known about this mysterious matter, but we note that essentially all of our knowledge regarding its properties comes from astronomical observations. The GMT will have the ability to probe the signatures of Dark Matter, primarily through its gravitational lensing of light, on finer scales than ever before possible. Even more exotic than Dark Matter is the recently discovered Dark Energy. In a Universe containing only matter, the cosmic expansion is retarded by the mutual gravitational attraction of galaxies. Whether the Universe expands forever or eventually re-collapses depends on the large-scale density of gravitating matter. The remarkable discovery in recent years that the cosmic expansion is accelerating rather than slowing down has dramatically altered our understanding of the constituents of the Universe. The Dark Energy that drives this acceleration may be related to Einstein's Cosmological Constant, or it may be the manifestation of a form of exotic energy not predicted by current theories. At present our only direct measurements of the expansion history of the Universe come from observations of distant supernovae – exploding stars which leave behind neutron stars. Current ground-based telescopes cannot probe supernovae to sufficient distances to provide a definitive test of competing models of the Dark Energy. The GMT will allow us to observe supernovae to the highest redshifts and will aid in the full characterization of the expansion history of the Universe. The GMT will also enable purely geometric determinations of the distances to structures in the early Universe, further improving our knowledge of the history of cosmic expansion.



The bending of light by Dark Matter in galaxy clusters creates characteristic curved arcs of light. These are distorted images of very distant background galaxies. The shapes of the arcs provide very sensitive measures of the Dark Matter.

THE PROJECT PLAN

The current members in the GMT Project are: The Australian National University, The Carnegie Institution of Washington, Harvard University, Massachusetts Institute of Technology, Smithsonian Astrophysical Observatory, Texas A&M University, the University of Arizona, University of Michigan and The University of Texas at Austin. The astronomy programs of these institutions have signed a memorandum of understanding agreeing to collaborate on the preliminary phase of a project (GMT) whose ultimate goal is the design and construction of the first 20-meter class telescope. The MOU established a Board that is responsible for the overall governance of the GMT Project. The Board consists of two representatives from each member institution. During the initial phase of the project, until final shares have been determined, each institution has an equal vote. Dr. Wendy Freedman, director of the Carnegie Observatories, has been elected to chair the Board. The Board is responsible for the allocation of all resources that have been provided to the Project by the member institutions and for deciding on the appropriate schedule of contributions from the members. The Board also decides on the acceptability of proposed in-kind contributions from the Members that will be counted towards the final capital cost of the telescope. The MOU is an agreement between the astronomy programs of the signing institutions. Arrangements for subsequent phases of the GMT project that include Design Development, Construction, and Commissioning and provisions for the eventual operation of the facility will the established in a partnership agreement between the institutions to be executed before the end of the Preliminary Phase. A final draft of that agreement is now before the legal counsel of each of the partner institutions.

Project Management

The Board has appointed a Project Manager to direct engineering efforts during the Preliminary Phase. The Project Manager is responsible for assembling budgets and schedules, establishing the Project Office, and directing feasibility and cost studies. The GMT Board has appointed a Science Working Group (SWG) to develop the science case for the project. This committee reports directly to the Board and advises the Project Manager on the scientific requirements to be translated by the Project Office into actual designs. The Project Scientists Working Group (PSWG) advises the Project Manager on technical matters and is instrumental in developing observatory requirements and the concept design. While many of the functions of this group will be taken over by a single Project Scientist at the end of the Preliminary Phase, the PSWG will likely continue as an advisory committee throughout the project. The Implementation Plan for the Design Development and Construction Phases of the Project includes a Management Plan.

Timeline

The development of the Giant Magellan Telescope is organized into three phases shown in the table below. The actual durations will be adjusted if necessary once the funding situation is known.

GMT Project Phases			
Phase A	Preliminary Phase, Conceptual Design	2003-2006	
Phase B	Design Development	2007-2009	
Phase C	Construction and Commissioning	2010-2016	

In February 2006, a panel of external experts conducted a rigorous Conceptual Design Review (CoDR) to assess the basic design of the telescope and facilities that will be developed. They examined the technical issues facing the project, the organizational and project staffing plans, and cost and schedule estimates. The conceptual design review resulted in a very positive report in which the review team affirmed that the project's design and technical plans are more than feasible and likely to succeed within the cost parameters established in the project budget and cash flow projections.

The back surface of the first GMT mirror is now being prepared prior to polishing the front surface.

The casting and polishing of the seven 8.4-meter primary mirrors is the pacing item for the completion of the GMT telescope. Once the GMT "pipeline" is running on schedule, we expect to complete mirrors at a rate of approximately one every 10-12 months. The total time to cast and polish a mirror is 42 months once the production pipeline is well established. The production takes place in stages (casting, generating, polishing, etc.) that proceed in parallel to achieve the roughly one mirror per year production rate. The mirrors are being fabricated by the Mirror Laboratory of the Steward Observatory at the University of Arizona in Tucson. The first off-axis mirror was successfully cast in July 2005; grinding and polishing of the rear surface is underway prior to turning the mirror over and processing the front optical surface.

TECHNOLOGY DEVELOPMENT CHALLENGES

The major technology challenges for the GMT are to:

- Produce huge collecting area at affordable cost
- Design a telescope structure with sufficient stiffness to withstand wind loading
- Attain diffraction limited infrared performance with well integrated adaptive optics systems
- Attain excellent seeing-limited optical performance
- Build effective instrumentation to address the key scientific problems

Giant Magellan Telescope

Production of the seven 8.4-meter segments of the GMT primary mirror is one of the major challenges for the project. All of the segments have to be made to exquisite accuracy in order to perform together in the telescope as a single mirror. In addition, the surfaces of the six outer segments, unlike conventional mirrors, are not symmetrical about their center. This provides an added challenge in the polishing and testing of the surfaces and requires the development of new metrology and testing procedures. Four independent tests will insure with a very high level of confidence that the surface figures of the segments meet their specifications. Analysis of the proposed tests shows that will meet the accuracy requirements necessary for success.

The technical risks associated with the primary mirror are being mitigated by prototyping one of the full-size outer segments early in the GMT project (this is the mirror that was cast in July 2005). This mirror is valuable in several ways. It serves as a tangible proof of the GMT concept and greatly reduces the risk of encountering a fundamental difficulty in the GMT implementation. Once the production pipeline is up and running, a finished mirror will be produced every 10-12 months. The prototype forces the manufacturing group to develop and practice all of the detailed procedures – such as aligning meter-size optics to 10 micron accuracy (equivalent to the thickness of a thin piece of aluminum foil), that must come together to achieve the optimal image quality.

The GMT can perform to its maximum sensitivity (this is called "diffraction-limited performance") only by using the technique called adaptive optics (AO). Light coming from astronomical sources is distorted as it passes through the earth's atmosphere, blurring the images received by the telescope. AO compensates for the distortion by rapidly varying the surface figure of deformable mirrors in the telescope. These corrections take place hundreds of times a second and require an array of optics, sensors, and controls. In highly advanced AO systems, such as the one proposed for GMT, lasers are used to project artificial stars in the upper atmosphere to provide reference sources for measuring the atmospheric distortion. These techniques are being developed on the current generation of 6-10 meter telescopes. The scale-up of these techniques for GMT will require significant technological development for all of the AO components mentioned above. The 25-meter diameter GMT will produce diffraction-limited images in the infrared 2.5 times sharper than the current largest telescopes and 10 times sharper than those from the Hubble Space Telescope, enabling the GMT to resolve greater detail and work on much fainter sources.

The instruments for recording the images and spectra collected by GMT will be larger and more complex than those on today's telescopes. These instruments will be built by teams of scientists and engineers and will require the development of new technology in the fields of optics and optical materials, mechanical structures, detectors, controls, and data processing. Innovative approaches to scheduling the instruments will be required to make the best use of observing time. Conceptual designs have been produced during the preliminary phase of the project for a first-generation complement of instruments that address the GMT science goals. These concepts will be refined during subsequent phases to ensure that GMT will be ready to do excellent science at the start of operations. Technology development and prototyping will be funded in selected areas to enable these instruments to be built on schedule and within budget.

GMT and its instruments comprise a highly complex system. New software tools have been developed in recent years to simulate the performance of integrated telescope systems under various operating conditions. These will be applied to GMT during the design development phase with the objective of optimizing the design and at the same time reducing the risks associated with meeting the stringent performance specifications for the telescope.

GMT and enclosure at Las Campanas

CONCLUSION

The defining event in modern astronomy, and perhaps all of 20th century science, was the discovery of the Universe beyond the Milky Way. The determination of the vast extent and dynamic expansion of the Universe by Edwin Hubble and other astronomers set the stage for modern cosmology and our understanding of our place in the cosmos. At the dawn of the 21st century we look forward to a new century of profound discovery led by new generations of astronomers. The Giant Magellan Telescope can open a path to fundamental discoveries about the birth of stars and planetary systems, the mysteries of black holes and the genesis of galaxies.