Astronomers over the next decade will focus their research on the processes that transform the universe from a not-quite-smooth distribution of very simple elementary particles to the richly complex world that we see around us.

The 1991 survey by the National Research Council of priorities in astronomy was entitled, "The Decade of Discovery." The number of discoveries has indeed been remarkable: circumstellar disks of solar-system mass and size are ubiquitous among forming stars; there are now more planets known outside our own solar system than within it; there is compelling evidence for massive black holes at the centers of many galaxies, including our own; galaxies evolve over redshifts that are accessible to direct observation; there are measurable fluctuations in the microwave background; galaxies and quasars had already formed when the universe was little more than a billion years old; the cosmological constant may not be zero after all; measurable changes in the energy output of the Sun have direct consequences for the climate of the Earth; the interior structure of the Sun changes during the solar cycle; and neutrinos have mass.

In the next decade, the emphasis will be on developing an understanding of how all of these objects and their distribution in space are transformed over the lifetime of the universe and on discovering the physical processes that shape those transformations. Laboratory sciences study physical processes by repeated experiments that probe different environmental conditions relating to temperature, density, magnetic field strength, degree of ionization, etc. In astronomy, the universe itself must serve as the laboratory. Just as repeated laboratory experiments are required to sample the full range in the parameters that may affect the outcome, so too we will require in the next decade measurements that sample the full range of conditions that may influence the processes that transform the cosmos.

Discovery of the processes that drive the evolution of the major constituents of the universe will require campaigns that combine groundbased optical and infrared observations with data obtained at other wavelengths, both on the ground and in space. These campaigns will involve large scale surveys to define well-chosen samples; snapshots to identify objects discovered at other wavelengths; synoptic observations; and interrupt-driven observations of transient phenomena. The potential of such coordinated campaigns has been demonstrated by the dramatic successes of the Hubble Deep Field survey combined with follow-up spectroscopic observations on the ground and deep infrared observations with NICMOS on HST; ground and space-based programs to discover and characterize supernovae near the edge of the observable universe; and campaigns to locate and characterize gamma-ray burst sources.

Cosmic Transformations

- *How and when were small fluctuations in density in the early universe amplified and transformed into galaxies and clusters of galaxies?*
- *How are clouds of dust and gas transformed into stars?*
- *How are disks surrounding newly formed stars transformed into planets? And what are the characteristics of these planetary systems?*
- *How are changes in magnetic structure in the Sun and stars transformed into changes in irradiance, varying levels of coronal emission, and other manifestations of activity, and what are the implications for the Earth's environment?*

Over the next two decades, NASA plans to launch a number of flagship missions—SIRTF, AXAF, SIM, NGST, TPF—aimed at understanding the origin and evolution of galaxies, stars, and planetary systems, and determining whether habitable planets exist. Achieving the full scientific potential of these missions will require extensive planning and coordination of ground- and space-based campaigns.

This extensive suite of facilities constitutes an observing system, and a comprehensive strategy is required in order to take full advantage of the potential synergies. NOAO plans to play a leadership role in establishing the framework needed for groundbased facilities to contribute to this comprehensive strategy. All of the following are critical elements in creating a system matched to the challenges and opportunities of the next decade:

***New telescopes* –** including 6.5-m telescopes with a 3° field of view for obtaining deep imaging and spectrosopic surveys critical to defining unbiased samples for detailed study with large telescopes, and an extremely large (25m), spectroscopic telescope to follow up on NGST imaging.

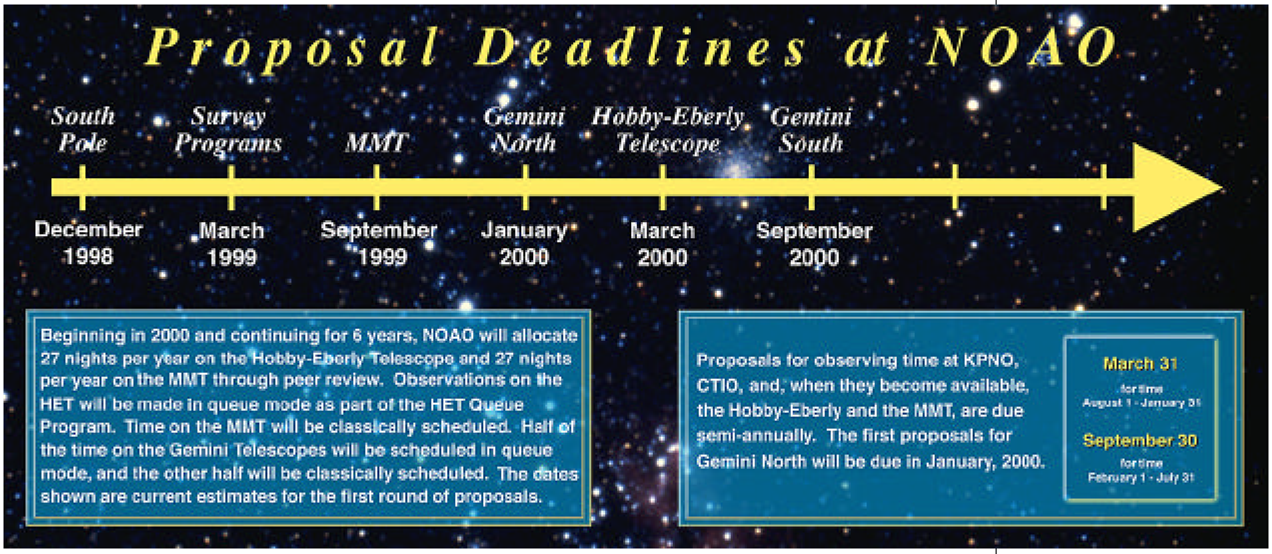
New instrumentation – with emphasis on wide-field imagers and spectrographs for the optical and infrared on 4-m class telescopes and on instrumentation for the Gemini telescopes.

New scheduling modes – to enable large scale surveys, snapshot imaging, targets-of-opportunity (e.g. gamma-ray bursters, supernovae, near-Earth asteroids), and synoptic studies of variable objects.

New software capabilities – to enable efficient pipelining, archiving, archive querying, and archive mining.

An impressive array of new astronomical facilities will be available during the next decade:

- *The Gemini telescopes and at least 13 other groundbased optical/infrared (OIR) facilities with apertures greater than 6.5-m*
- *HST, NGST, SIRTF, AXAF, Planck, FIRST, GLAST, Constellation-X, and a variety of other missions in space*
- *SOHO, TRACE, and Solar B to support studies of the Sun*



Beginning in 2000 and continuing for 6 years, NOAO will allocate 27 nights per year on the Hobby-Eberly Telescope and 27 nights per year on the MMT through peer review. Observations on the HET will be made in queue mode as part of the HET Queue Program. Time on the MMT will be classically scheduled. Half of the time on the Gemini Telescopes will be scheduled in queue mode, and the other half will be classically scheduled. The dates shown are current estimates for the first round of proposals.

Proposals for observing time at KPNO, CTIO, and, when they become available, the Hobby-Eberly and the MMT, are due semi-annually. The first proposals for Gemini North will be due in January, 2000.

March 31
for time
August 1 - January 31

September 30
for time
February 1 - July 31

The scientific programs enabled by NOAO are as broad as the interests of the more than 1,000 researchers who use our facilities and databases annually.

NOAO's responsibility is to anticipate where opportunities for significant advances are greatest in order to develop the telescopes and instruments that will be required. Here we summarize likely directions for research in three areas: the *Evolution of the Universe*, *Star Formation*, and the *Origins of Solar Variability*.

The Evolution of the Universe

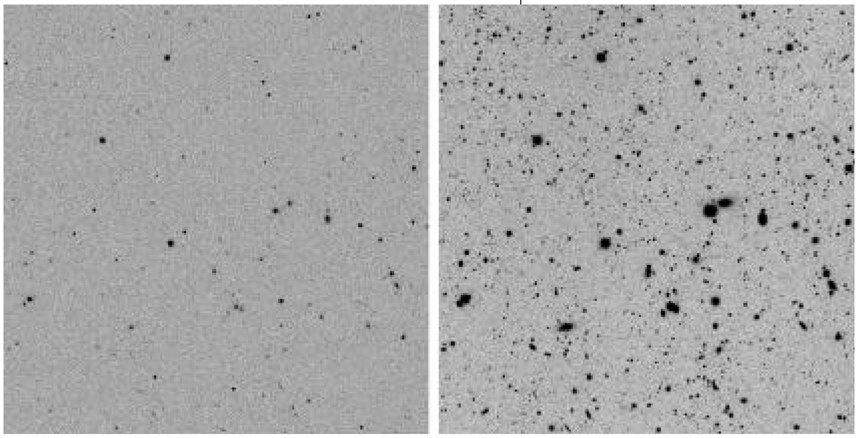
The standard model of the Universe depends upon at least three fundamental parameters: the rate of expansion (H_0), the density parameter (Ω_0), and the cosmological constant (Λ). One of the astronomical triumphs of this century has been the determination of the local expansion rate, a culmination of a concerted ground and spacebased effort. Astronomers have also made great strides in constraining the contribution of baryonic matter to the density of the Universe, and the recent evidence for a positive cosmological constant based on supernovae distances is well known.

The next decade will bring a philosophical change in our approach: we have graduated from characterizing the geometry of space-time in the local Universe to exploring how the Universe's geometry has evolved since the Big Bang. In the coming millennium, groundbased telescopes will play a critical role in quantifying the evolution of the Universe by determining the far-field Hubble constant; by estimating the total mass density of the Universe through measurements of clustering properties, bulk flows, and lensing; refining estimates of the cosmological constant; and studying the formation and evolution of the structures that constitute the Universe.

Deep imaging and spectroscopic surveys

The foundation of much of cosmology in the next decade will be deep imaging and spectroscopic surveys to identify galaxies and quasars at intermediate and high redshifts, followed by spectroscopic studies with Gemini-class telescopes.

The NOAO 4-m telescopes are already being used by several groups to identify objects for observations with Keck. The images below show what the sky looks like at the spectroscopic limit of a 4-m telescope (R=23) and at the Gemini spectroscopic limit (R=26). A whole new world will become observable.



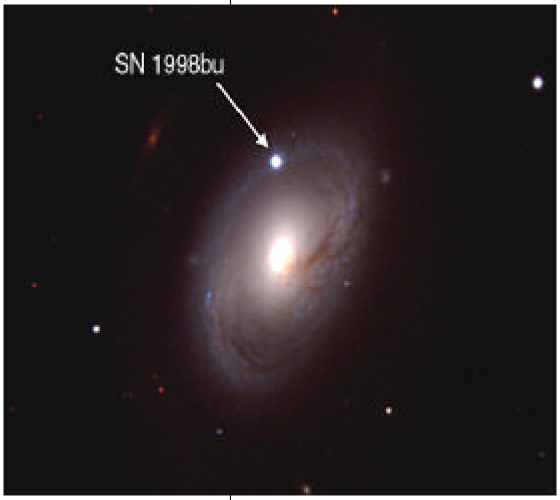
The form that the large scale structure of the universe assumes at the present epoch is still poorly known, and we know even less about its origin and its changes with redshift. The evolution of galaxy clustering on large scales is strongly dependent on Ω_0; clustering evolves rapidly in a flat universe, while it is frozen in at high redshifts in a low density universe. In order to study large scale clustering, it is necessary to explore the variation in clustering variation in clustering properties with galaxy type, luminosity, and environment inasmuch as the apparent distribution of galaxies may be biased by their evolutionary histories and star formation rates. Deep imaging surveys over wide areas to the spectroscopic limits of Gemini ($K_{AB} = 20$ and $R_{AB} = 26$) can be used to identify samples that cover a range of conditions and to derive the galaxy-galaxy correlation function, power spectrum amplitude, scale lengths, etc.

Lensing surveys can be used to constrain the total mass density in the universe and its distribution. The mass power spectrum can be measured directly, through the statistical variation of the lensing signal. Measurements of a few million galaxies with B ~ 24-26 (over 20-30 square degrees) will yield the angular peak of the orientation correlation function and, when coupled with redshift information, can be converted to the power spectrum amplitude. Lensing by superclusters can be used to measure the distribution of mass on 10-50 Mpc scales. This is best done with a very wide-field imager and telescope combination; even the NOAO Mosaic reaches only to a field of 5 Mpc at z = 0.2. With a very large field capability, one could conduct a 30° x 30° survey that would make it possible to reconstruct the mass distribution in a cone to z = 1. Such a study would also determine the mass distribution function of clusters as a function of redshift, which is one of the key constraints on cosmological models.

The measurement of bulk flows is another technique that can be used to quantify the geometry and mass of the largest structures in the universe. At present there is active debate and controversy on even the most basic questions of where the bulk flows die out and what generates the local motions with respect to the cosmic background. Key to resolving the debate will be mapping the distances and velocities of large samples of representative galaxies out to z = 0.10, probably through the use of SN Ia as standard candles.

Observations of supernovae in distant galaxies *provide evidence that the rate of expansion of the universe is accelerating, thereby suggesting that the cosmological constant may be positive. Nearly all the supernovae used in the two independent studies that arrived at this conclusion were discovered at Cerro Tololo. This result was selected by* Science *magazine as the most significant scientific achievement of 1998.*

Work on determining the cosmological constant can be extended by observing supernovae at higher redshift with Gemini-class telescopes, but the discoveries must be made through wide-field deep imaging, a capability currently offered only on 4-m class telescopes. A second effort will be to understand the physics of the supernovae explosions in order to characterize the factors that determine the intrinsic luminosity of SN Ia at maximum light. This latter problem will require the discovery of a large sample of supernovae, especially nearby and in differing environments, through wide-field imaging followed by spectroscopic and photometric observations with Gemini-class telescopes equipped with adaptive optics and with HST.



Studies of the life history of galaxies will be a centerpiece of astronomical research during the next decade. There are several ways to obtain independent constraints on the age of the universe, including the identification of red galaxies at redshifts z ~ 1.5 in which star formation has already stopped. The history of metal production in the Universe, according to the best current data, peaked somewhere between z = 1-2, but the samples on which this conclusion is based are small and limited by selection effects. It is unclear whether the enhanced metal production at this epoch is the result of a major increase in the star formation rate, the consequence of mergers, or evidence of the first collapse of the observed systems.

NGC 891
Detailed studies of nearby galaxies, including characterization of the chemical and dynamical evolution of the interstellar medium and of the roles of star birth, death, and mergers on the galaxian environment can assess the impact of stellar driven processes on the evolution of galaxies. Fossil records of the early history of galactic disks can be found in the halos of nearby galaxies, and dynamical and chemical studies can be used to quantify the role of accretion in assembling these galaxies.

Determination of merger rates, the ages of the oldest stars, clustering characteristics, chemical properties, etc., can all constrain models of galaxy formation, which in turn can place constraints on tests of cold dark matter and other currently fashionable theories.

Star Formation

The quest to understand the origin of stars and planetary systems similar to our own has advanced dramatically over the past 15 years. We can now probe the earliest stages of stellar and solar system birth, beginning with the dense molecular cores that are the precursors to the formation of stars and stellar aggregates. Kinematic measurements of gravitational collapse offer clear evidence that stars are beginning to take form. Circumstellar accretion disks appear to be ubiquitous among forming stars of all masses in all environments and strongly suggest that the material necessary to build solar systems surrounds all stars at birth. Energetic, highly-collimated streams of gas emanating from newly formed star-disk systems provide striking evidence for a subtle regulation system which apparently enables stars to grow to their final mass via addition of material channeled inward by the accretion disk and the stellar magnetosphere, but without the addition of angular momentum.

Observations of more mature systems suggest that planets and possibly planetary systems represent a frequent if not ubiquitous outcome of the star-formation process. ***We now know of more planets outside the solar system than within it***; the recent detection of Jovian-mass planets orbiting nearby stars has captured the imagination of the astronomical community and the public alike.

Over the next decade, the major advances in understanding will come from discovering the patterns that characterize transformations during the main phases of stellar and planetary formation. Observational campaigns will define the range of morphologies, masses, and kinematic properties of the star-forming cores; determine the frequency with which stars form in isolation, in binaries, multiples, aggregates, and clusters; relate multiplicity to initial conditions; quantify the relationship between the distribution of emerging stellar masses and initial (molecular cloud) and environmental (number and density of protostars) conditions in a variety of star-forming regions; characterize the evolution of accretion disks in response to angular momentum transport; discover when, where, and how often planets form in circumstellar disks; and define the statistical properties of fully-formed, dynamically stable solar systems.

Groundbased telescopes will play a central role in these campaigns through their unique ability to provide:

- **Wide-angle imaging** to deep limiting magnitudes in both the optical and the infrared to survey molecular cloud complexes and catalog complete samples of objects with a range of ages from those emerging from their natal cores to those completing the disk accretion phase and with masses from the Eddington limit to as small as 10 Jupiter masses;
- **Wide-angle multi-object spectroscopy** to place these objects in the HR diagram and to derive accurate ages and masses;
- **High resolution spectroscopy** to quantify mass infall rates for stars of different masses; to relate core conditions to the final mass of the newly formed star; and to resolve molecular emission lines formed in circumstellar accretion disks to search for, and measure, the location and size of tidal gaps created by forming planets and low mass companions;
- **High angular resolution** via adaptive optics to resolve stellar companions and to analyze the gas and solid components of disks in the post-accretion phase; and
- **Time coverage** to extend spectroscopic surveys for planets to much larger samples of stars.

The facilities described later in this document are configured to provide these capabilities.

Observations of star-forming regions enable quantitative study of the distribution of stellar and substellar masses and the relationship between these distributions and the physical and chemical conditions in their parent molecular clouds. Surveys of nearby molecular clouds will make it possible to probe the initial mass function over the mass range 10 Jupiter masses to 100 solar masses. Understanding the physics underlying the shape of the initial mass function is in turn crucial to inferring the star-formation and chemical-evolution histories of galaxies. With the advent of the space infrared mission SIRTF, it will be possible to study directly the cosmological evolution of star burst galaxies and the evolution of the cosmic star formation rate over the redshift range 0.2-1.0. Groundbased data will play a crucial role in providing follow up redshift surveys, classifying identified targets as active galactic nuclei or starbursts, and quantifying the role of galaxy interactions in triggering starbursts.

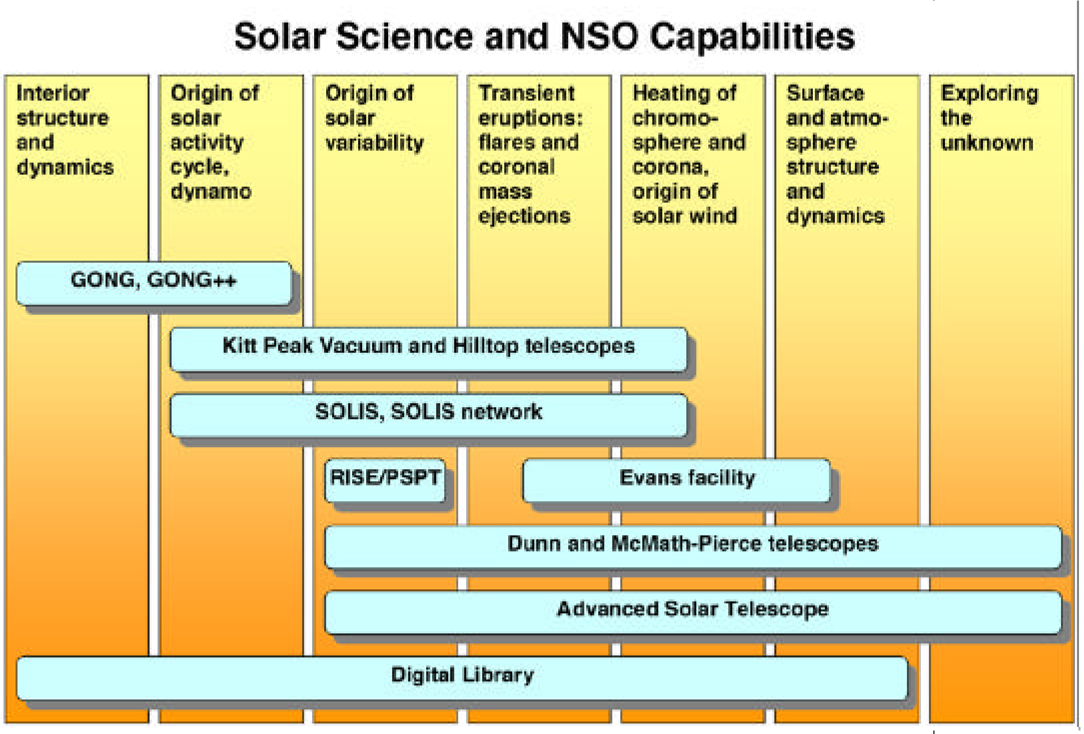
The Pelican Nebula
An ionization front at the edge of the Pelican Nebula (NGC 5067), a star-forming region in the constellation Cygnus. This image was taken with the T2KA CCD on the 0.9-meter telescope at Kitt Peak National Observatory.

Origins of Solar Variability

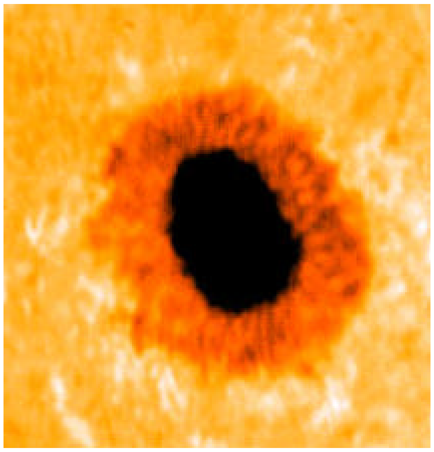
The Sun is a dynamic astrophysical body that displays spectacular variability on time scales that range from as short as a few milliseconds to as long as billions of years. The origin of solar variability, including the 11 year solar cycle, is intimately linked to magnetic fields—their generation inside the Sun and their subsequent emergence and evolution in the solar atmosphere.

The NSO has embarked on a comprehensive program of precise measurements of all the factors that contribute to an understanding of solar magnetism as the underlying cause of solar variability. Such a program serves the dual purpose of achieving an understanding of solar variability in the context of astrophysical processes and of its impact on the environment of the Earth.

Current and planned facilities of the NSO address the broad question of the nature and origin of solar variability in a complementary manner. The application of NSO facilities to specific topics concerning the variability of the Sun and its interior structure is encapsulated in the schematic below.



Through GONG and its upgraded extensions, GONG$^+$ and GONG^{++}, images of the solar interior over extended periods of time using helioseismology are produced. GONG thereby enables the systematic study of the basic mechanisms deep inside the Sun that cause the solar cycle and related solar variability. SOLIS (Synoptic Optical Long-term Investigations of the Sun) will consist of a suite of three instruments that will perform well-calibrated, sustained



observations of the magnetic fields that are generated in the interior and subsequently appear in the solar atmosphere. SOLIS will ultimately yield a high-precision record of magnetic field-related activity over a long time period. The GONG upgrade and SOLIS projects are underway. Operating in parallel with these facilities are the RISE/PSPT (Precision Solar Photometric Telescopes) and the coronal measurements programs. The PSPT is dedicated to high precision observations of the subtle variability in the solar irradiance associated with various magnetic field features on the Sun. The coronal programs measure changes in coronal emissions associated with magnetic activity, and the interactions of magnetic loops in the corona; they will soon be making direct coronal magnetic field measurements with advanced infrared detectors. The AST is a future, large-aperture facility that will probe magnetic structures on the Sun with unprecedented resolution. With the AST, the magnetic microstructure that is responsible for coronal heating and contributes to solar irradiance variability will be resolved in the spatial, temporal, and spectral domains.

A fundamental problem in solar physics is to determine the cause of the solar cycle. Why does the number of sunspots vary with an 11-year cycle?

Despite the proximity of the Sun and its accessibility to detailed observation, the origins and causes of its activity cycle remain a mystery. ***It is not known with any certainty what produces variations in the total irradiance of the Sun, why it and other late-type stars emit X rays, or what causes flares and mass loss.*** Observations over the past two decades have established that the photospheric magnetic field consists of small fibrils or flux tubes. In order to understand the causes of solar activity it is necessary to characterize the structure and origin of the individual fibrils and their motions. For example, the topological interweaving of small scale magnetic fields both within fibrils and through interactions among fibrils, combined with the unique properties of the Maxwell stress tensor, lead to small reconnection events that may well be the source of coronal heating. The AST will permit definitive observations of these phenomena.

Recent satellite missions operating at short wavelengths can see the results of coronal heating in the form of nanoflares but groundbased observations at high angular resolution are required to see the origin of the energy supply in the photosphere via the interaction of turbulent gas motions and the fibril field bundles. The NSO coronographs have revealed the existence of many transient bright points in the solar corona. Subsequent high-resolution observations from space (NEXT, TRACE, YOHKOH) have demonstrated the existence of a myriad of these tiny explosive events (nanoflares) along with high-speed jets in the corona. The individual bursts of energy and the entire energy supply to the corona are evidently the result of the motions of the individual magnetic fibrils rooted through the photosphere into the convection zone. The motions likely involve both jitter and intermixing of the individual fibrils, producing Alfvén waves and a general wrapping of the lines of force in the fields in the corona. But there is currently no direct measure of any aspect of the fibril motions or any direct detection of waves or wrapping in the coronal magnetic fields. The AST will permit observations that directly address these problems.

Solar irradiance variations are produced primarily by sunspots and faculae. Faculae are the limb-manifestations of the very fine, bright network pattern evident in the photosphere and again are associated with the small scale magnetic field structure. ***The total irradiance variability and the strong wavelength dependence of solar spectral irradiance variations play an important role in the way in which the Sun influences the global climate system of the Earth.*** Recent measurements of spectral irradiance variations at three different wavelengths from space, in combination with modeling efforts, offer compelling evidence that the major part of solar irradiance variations is caused by magnetic fields at or close to the solar surface.

A full understanding of these data, however, has been significantly impeded by the lack of a reliable physical model of the facular contribution to the irradiance variability. The high spatial resolution observations to be provided by the AST are required to determine the real temperature stratification of network elements and the time-evolution of their structure. Only in this way can the roles of the facular contribution and the center-to-limb variations of the facular contrast be properly understood within the context of the total and spectral irradiance variability of the Sun. Accurate models, based on actual observations of the structure components, are the prerequisite for development of real predictive capability.

Through the application and development of the distinct yet complementary observational capabilities represented by GONG, SOLIS, AST and PSPT, the NSO will provide the observational data necessary for the unraveling of the mystery of solar magnetism and the crucial role it plays in the variability of the Sun.