



Harvard - Smithsonian Center for Astrophysics

Science Strategic Plan

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Harvard-Smithsonian Center for Astrophysics

Science Strategic Plan

Executive Summary

Mission Statement

"The mission of the Harvard-Smithsonian Center for Astrophysics is to advance our knowledge and understanding of the Universe through research and education in astronomy and astrophysics."

Introduction

At the Center for Astrophysics we engage in forefront research in many different ways, from small individual projects to research centers to the utilization and operation of unique major ground- and space-based facilities. We excel as observers, theoreticians, instrumentalists and laboratory experimentalists. Our research spans the breadth of the electromagnetic spectrum, helping to create the distinctively fertile research environment that is the underpinning of our success. Our vision is to remain the leading center in multi-wavelength observing while strengthening our theoretical, computational and laboratory astrophysics efforts. How best to sustain and strengthen our Center is a challenging matter. The opportunities for breakthroughs in our field are numerous – this is the new “golden age” of astronomy – and they beckon our full participation.

The Science Strategic Planning Committee (SSPC) was charged by the Director with determining which new facilities and programs will best suit our distinctive competencies. For the past year this committee, comprised of members from the scientific divisions, crafted this strategic plan to accomplish two objectives:

- 1. identify those new facilities and programs that tackle the most important science goals of our generation, make maximum use of our expertise in these areas, and promise the most significant benefit to our research, and*
- 2. establish an appropriate balance between these few strategic projects and the important research carried out by our colleagues as individuals and in small groups.*

These twin objectives will guide the participation in new opportunities and the allocation of resources over the coming decade. We will optimize the capabilities of our current facilities and centers even as we seek lead roles in several “next-generation” facilities and missions. The plan addresses our need for better and larger physical facilities, high-speed, high-performance computing capability and better ways to attract the best and the brightest scientists and students. The committee also notes that improved communications – internal and external – are critical to our future success.

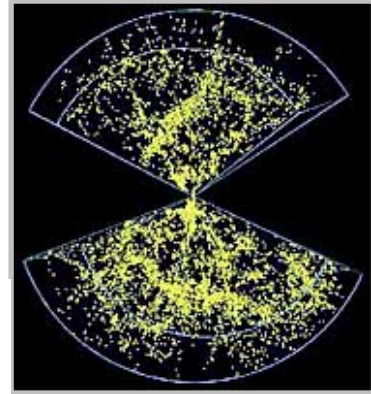
Science Drivers

The committee has organized the plan around four themes that exploit our current strengths and that we expect will be extremely fruitful in the next ten years. These clear science goals draw on our distinctive capabilities and require significant Center resources. These themes are:

Inflation, Dark Matter and Dark Energy

Working from the standard model of the “Big Bang” some 14 million years ago, we’re investigating the early epoch of inflation and the nature and role of dark matter in the evolution of structure in the Universe. We also seek to understand the nature and properties of the “dark energy” that is speeding up the expansion of the Universe.

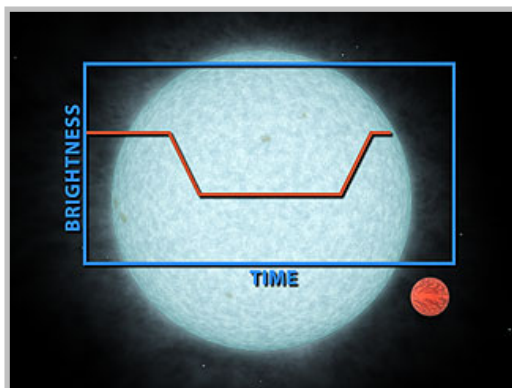
Right: A map of the distribution of galaxies in the Universe. The CfA pioneered the mapping of galaxies and made the first surprising discoveries about the large-scale structure of the Universe: that the galaxies are not uniformly scattered throughout space, but are instead clumped into huge bubbles and filaments.



Galaxies and Black Holes

Soon after the Big Bang, the Universe became a space filled with “stuff:” neutral gas, dark matter, and radiation. After several hundred million years, primitive structures began to form from the first chemical elements, creating the first massive stars and eventually the first galaxies. We want to know how they formed, how they interact, and the processes that create supermassive black holes.

Right: Spiral galaxy M81, image taken by the Infrared Array Camera on the Spitzer Space Telescope. The unprecedented sensitivity of the infrared camera shows regions of intense star formation, and the glow of the interstellar gas that is excited by the birth of the new stars.



Stars and Planets

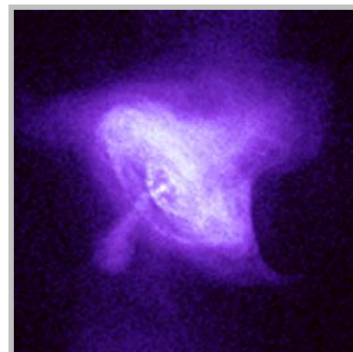
We think we know how stars live and die, but our picture of how stars form to begin with is incomplete. Although astronomers have discovered well over 200 planets in other solar systems, we do not really know what conditions actually produce life. We seek to resolve major uncertainties about the complex processes that lead from clouds of gas and dust to stars, planets, and the emergence of life.

Left: In 2005, a CfA scientist led the team that made the first direct detection of the light from a planet in a distant solar system. Using the Spitzer Space Telescope, the astronomers combined the light before and after the planet passed behind its parent star during its orbit to characterize the light reflected by the planet only.

Extreme Astrophysics

The most violent and energetic phenomena in the Universe are gamma-ray bursts, the birth of neutron stars or stellar black holes in supernovae, whose huge explosions release the basic elements from which life formed, including us. Because the physical conditions in these phenomena can't be replicated in our Earth-bound labs, we must develop and use new tools to unlock the extreme physics of our Universe.

Right: This 1999 image of the Crab Nebula was taken by the Chandra X-ray Observatory. It shows the detailed structures of waves radiating out from a rapidly spinning pulsar at the collapsed star's center. CfA played lead roles in designing the x-ray telescope and its high resolution camera. SAO also operates the spacecraft from a control center in Cambridge, MA.



Priorities and Balance

The highest priority new initiative for the Center for Astrophysics is to play a leading role in the development and operation of the exciting new Giant Magellan Telescope (GMT). Our goal is to obtain 20-25% share of the observing time with this facility. The large collecting area and high angular resolution of this next generation optical/IR telescope will enable critical investigations central to all four of the science themes identified above.

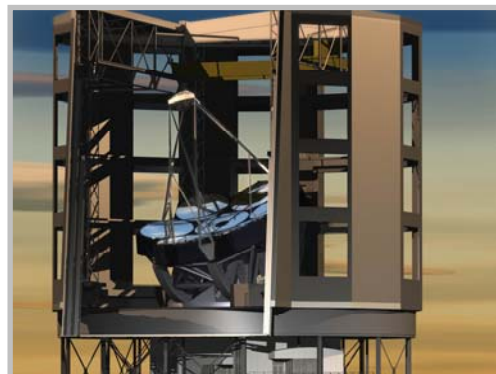
CfA participation in new NASA activities is of critical importance to the Center's future, in particular, high energy astrophysics missions.. Constellation-X (Con-X) is one of just two Beyond Einstein (BE) flagship missions, and it is the CfA's highest priority space astrophysics program. The CfA is partnered with NASA's Goddard Space Flight Center (GSFC) to provide the science leadership for this major facility, an important function for the science breadth and balance of the Center. Con-X and other post-Chandra missions require new technology, and the CfA should lead these developments. Accordingly, ***the Center for X-ray Technology (CXT) will provide critical strategic leadership in new optics and detectors for the nation's space astrophysics program.***

These two major initiatives are extremely demanding intellectually and financially. We will aggressively seek support for them, and contribute intellectual and technical leadership to their development. Our research program requires that we balance these initiatives with a portfolio of programs that span the range of scales from the very large to modest, including ground-breaking projects where higher levels of risk can be tolerated (even encouraged). The major elements of this balanced program are:

New Facilities:

The Giant Magellan Telescope (GMT)

The GMT is a planned ground-based optical/infrared telescope with the resolving power of a 24.5-meter mirror, comprised of seven 8.4-meter diameter segments. The GMT is scheduled for commissioning in 2016. Our goal is to support a 20-25% share of telescope observing time and to develop first light instruments, particularly the near-IR multiobject spectrograph. The GMT addresses all four science themes. We will use the GMT for direct detection of light from terrestrial and gas giant planets; measurements of the large scale structure and evolution of galaxies (and AGN) at redshifts of 3-5; studies of the transformation of dusty gaseous disks into planetary systems; investigations of the evolution of stellar populations in galaxies at redshifts 1-2; and the evolution of metals at redshifts 2-10.



An artist's conception of the GMT, which is likely to be built in Chile.

The Mileura Wide-field Array will be sited at one of the last remaining radio-quiet area on Earth in a remote region of Australia. One of its most important scientific goals is to study hydrogen emission to characterize the so-called Epoch of Reionization, the period approximately 150 million years after the Big Bang. The observations will tell us much about how the early Universe formed.

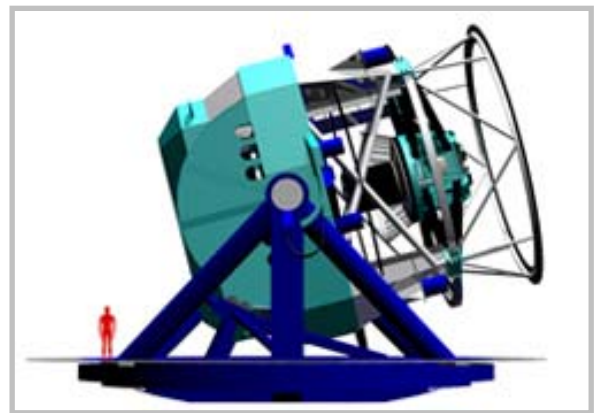


The Mileura Wide-Field Array (MWA) and the Square Kilometer Array (SKA)

The MWA/Low Frequency Demonstrator (LFD) is a low frequency radio telescope funded (in the US) by NSF and sited in Australia. The MWA/LFD is a precursor to the low frequency component of the SKA, also likely to be sited in Australia. Our goals are to start work on the LFD in mid-2006; start deployment of hardware to site in 2007; start science operations in 2009.

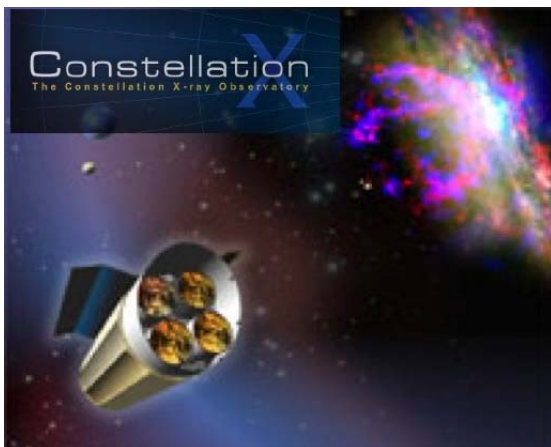
PanSTARRS and the Large Synoptic Survey Telescope (LSST)

PanSTARRS will consist of four 1.8-meter optical telescopes. The first telescope is sited at Maui, Hawaii. Funding is from the Air Force (for construction only) and partners. LSST is an 8.5-meter class optical telescope. It is funded by NSF, DOE and various private sources. It will be sited in Chile. Our goals are to participate in PanSTARRS data reduction pipeline and analysis and to continue our membership in the LSST Corporation with involvement in focal plane cameras and the data pipeline.



Above: The Large Synoptic Survey Telescope (LSST) is an international collaboration that includes the CfA. The LSST will cover the entire sky every three nights, providing massive data on such objects as exploding supernovae, near-Earth asteroids and far-distant galaxies. Observations of the latter will help characterize Dark Matter and Dark Energy.

New Missions:



Constellation-X (Con-X)

We expect to play a lead role in Con-X, one of two flagship missions of NASA's Beyond Einstein program. It may consist of several X-ray telescopes working in unison to generate the observing power of one giant telescope. SAO will operate the Science Operations Center for Con-X and will work with GSFC on pre-Phase-A systems engineering for optics, technical development for detectors and lead of Facility Science Team (2007). We plan for a major hardware role in the mission

Left: Con-X is a planned NASA space mission that will function as one large, extremely high spectral resolution telescope. Among many science questions, Con-X will study black holes, galaxy assembly and the nature of Dark Energy. It will have 100 times the sensitivity of existing x-ray telescopes.

New Centers:

Center for X-ray Technology (CXT)

CXT is located within the High Energy Astrophysics Division of the CfA, with laboratories at Cambridge Discovery Park. It will be funded by NASA grants, SAO, and private donations. Our goals are to support the staff through SI and private donations in 2006, with successful grant support via NASA, NSF, DOE, etc. in 2007 and beyond.

Right: The Chandra High Resolution Camera laboratory at SAO which designed and built the camera for the Chandra X-ray Observatory. The CXT will develop advanced technologies in optics and detectors for future NASA x-ray missions.



Ongoing Facilities:



The MMT and Magellan Telescopes

The 6.5-meter diameter telescopes are our major optical/infrared facilities. The MMT, in Arizona, is a joint project of the Smithsonian and the University of Arizona. The twin Magellan Telescopes in Chile are jointly operated by Harvard, the Carnegie Institution, MIT, the University of Michigan, and the University of Arizona. Our goals are to optimize the capabilities of these facilities, and to complete the Magellan f/5 secondary in 2007, the MMIRS instrument in 2007 and Binospec in 2009.

Above: The MMT Telescope is located on Mount Hopkins in southern Arizona; its twins are located at Las Campanas in Chile. These facilities have been crucial in many CfA discoveries, including the discovery of the first "hyper-velocity stars" being flung out of the Milky Way galaxy by their encounter with a black hole at the galaxy's center.

The Submillimeter Array (SMA)

The SMA comprises eight moveable 6-meter diameter antennas on Mauna Kea in Hawaii. The SMA is a joint project of the Smithsonian, the Academia Sinica Institute for Astronomy and Astrophysics, and the University of Hawaii's Institute for Astronomy. Our goals are to continue operations and to complete high frequency receivers for polarization measurements; expand the SMA to include the Caltech Submillimeter Observatory and the James Clerk Maxwell Telescope.



The Submillimeter Array was completed and dedicated in November 2003. Now in full operation, it can study planetary systems, asteroids, comets, planets in our own Solar System, dying as well as newborn stars, redshifted radiation from the most distant (and therefore oldest) objects in our Universe and even radiation from the Big Bang.

The Very Energetic Radiation Imaging Telescope Array System (VERITAS)

VERITAS consists of four 12-meter aperture telescopes presently sited at Mt. Hopkins, AZ. It is funded by NSF, DOE, and SAO, and operated by SAO with a collaboration of several colleges and universities worldwide. Our goals were to construct four telescopes at Mt Hopkins in 2006 and to operate them there for two years while a permanent site is determined. VERITAS will relocate to its permanent site in 2008 and potentially expand to seven telescopes thereafter.

Right: The prototype 10-meter diameter reflector that gave birth to the Very Energetic Radiation Imaging Telescope Array System (VERITAS) project. This facility studies a phenomenon called "Cherenkov radiation," a shower of charged particles in the Earth's atmosphere caused by gamma ray bursts in space.

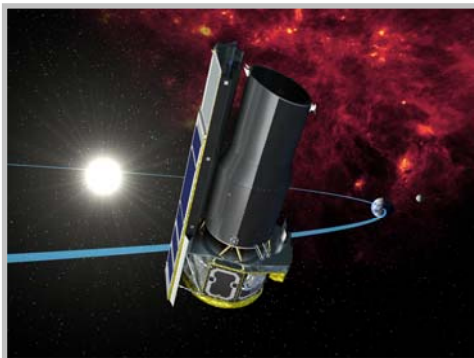


Ongoing Missions:

Chandra X-ray Observatory

The Chandra X-ray Observatory is part of NASA's Great Observatory Program. It is funded by NASA, and is operated by SAO on behalf of NASA. The Observatory is an international facility that carries out observations for several hundred GOs each year. Our goal is to continue Chandra operations beyond 2014.

Right: The Chandra X-ray Observatory is in its second six-year cycle, operated at the CfA by SAO. Chandra observations span the gamut of astrophysics from planets to clusters of galaxies – covering virtually every type of cosmic object known.



The Spitzer Space Telescope

The Spitzer Space Telescope is the infrared telescope of NASA's Great Observatories Program. SAO provided the Infra-Red Array Camera (IRAC) and the IRAC Team has guaranteed observing time on Spitzer. The project is NASA-funded. Our goal is to continue IRAC operations after 2009 (when the coolant will have been exhausted.)

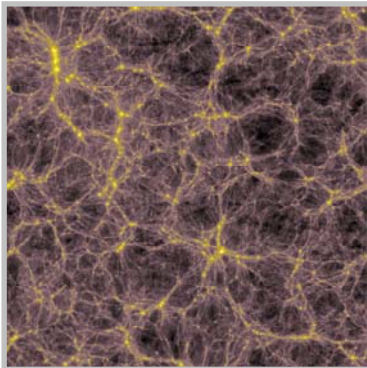
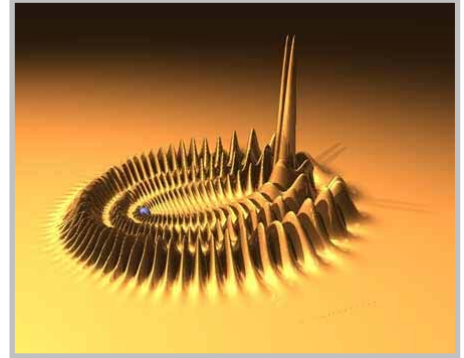
Left: Launched in August 2003, the Spitzer Space Telescope flies in an Earth-trailing heliocentric orbit that keeps it cool enough not to require large amounts of coolant on board to meet a five year mission lifetime. Spitzer's main Infrared Array Camera was designed and developed by a CfA scientist. Spitzer's infrared "eyes" penetrate dense clouds to view the birth of stars and planets, and to study the very distant Universe whose light has been redshifted into the infrared.

Ongoing Centers:

Institute for Theoretical, Atomic, Molecular and Optical Physics (ITAMP)

ITAMP is an NSF funded center of excellence jointly located and operated by CfA and the Harvard Physics Department. Our goal is to continue providing the intellectual leadership in the theoretical AMO Physics community with continued NSF funding from 2007-2011 and other grant support, possibly through DOE.

Right: The existence of a ubiquitous class of ultra-long range molecular Rydberg states was predicted by a JILA/ITAMP collaboration in 2000. These giant molecules have an electron cloud resembling a trilobite, the ancient, hard-shelled creature of the Paleozoic era. These molecules are estimated to live about 1-10 milliseconds, far shorter than the life span of a trilobite!



Institute for Theory and Computation (ITC)

ITC is a center of excellence in theoretical astrophysics. Its funding is through the Harvard Astronomy Department. Our goal is to continue our leadership in computational astrophysics through ongoing support from Harvard.

Left: A computational model of the initial perturbations that grow via gravitational instability to form a "cosmic web" of structure on many scales. Numerical approaches, including the use of a custom built set of computer clusters, are being developed at the CfA to calculate properties of this evolving structure.

Science Strategic Planning Committee (SSPC) Members:

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Andrea Dupree
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Date:

January 23, 2007

1. Introduction

The diversity, scale and quality of scientific activity at the Center for Astrophysics contribute in a major way to the success of our organization. CfA scientists engage in forefront research in diverse ways, from individual research projects to the exploitation and operation of unique major facilities. This breadth of activity, across the electromagnetic spectrum, is critical to our continued success. A long-term plan must maintain this fertile intellectual environment, and we must continue to attract outstanding scientists to the CfA. In addition, we recognize that new major facilities are essential to our scientific future. The scale, cost, and timetable for the construction of new facilities require that we choose carefully from among the many opportunities that arise in this golden age of astrophysics. This selection should be guided by our scientific priorities and by our ability to both contribute to and benefit from a project.

This Science Strategic Plan builds upon the work done over the past several years in formulating the draft Long Range Plan (LRP) for the Center. It is not our intent to reproduce that effort. Rather, we have used the LRP to inform the discussions of the Science Strategic Planning Committee (SSPC), made up of representatives from the various science divisions of the Center. Members were asked to take a broad view of the future, a view that is based on the Center's areas of scientific excellence, and how they relate to the large questions facing astronomy and astrophysics in the five, ten and even 20-year timeframes, and in which we can make significant progress.

A strategic plan for science at the CfA is an important resource that forms the basis for long range planning in the Director's Office and helps to guide the allocation of Center resources. This strategic plan is science driven and puts forth only a few of the many activities that can and will take place at the Center. The criteria for inclusion in this high level plan were two: that there be clear science goals to which CfA can contribute significantly; and that these be major activities which will involve significant resources of the Center. These are the areas where a coherent plan can help to achieve success, and where guidance is needed to assure that scarce resources will be wisely allocated, in accord with a shared vision for the future. However, it is recognized as essential that agile research activities involving individuals or small groups continue as a major part of the overall makeup of the CfA. Such activities contribute significantly to the Center's vitality and excitement. Setting an appropriate balance between a few large strategic programs and the many smaller investigations at the CfA must be an important concern for the Center's leadership.

2. Strategic Themes and Science Drivers:

Theme 1: What are the ingredients (composition and initial conditions) of the Universe, and what processes generate the observed structure?

According to the standard cosmological model, the Universe started with a Big Bang about 14 billion years ago. During an early epoch of accelerated superluminal expansion, called inflation, a region of microscopic size stretched to a scale much larger than the visible Universe and our local geometry became flat. At the same time, quantum mechanical fluctuations of the vacuum generated primordial density fluctuations in the matter distribution. Gravity enhanced these inhomogeneities, seeding the formation of present-day structure. The mass density of ordinary (baryonic) matter makes up only a fifth of the matter that led to the emergence of structure. The rest is in the form of an unknown dark matter component. Recently, the Universe entered a new phase of accelerated expansion due to the dominance of some dark vacuum energy density over the ever-lower matter density. This "dark energy" accounts for more than 70% of the mass-energy density of the Universe.

In detail, we want to know:

(a) Did inflation occur and, if so, when? What drove it and how did it stop?

(b) What is the nature of the dark matter, and how did it regulate the evolution of structure in the Universe?

(c) What is the nature of the dark energy and how does it change over time and space?

Before recombination, the Universe was opaque to electromagnetic radiation. The only way to probe inflation is through the fossil record left behind in the form of density perturbations and gravitational waves. Following inflation, the Universe went through several other phases that left a detectable record. These include: baryogenesis (which produced the observed asymmetry between matter and anti-matter), the electroweak phase transition (which broke the symmetry between electromagnetic and weak interactions), the Quantum Chromodynamics (QCD) phase transition (when protons and neutrons formed out of quarks and gluons), the dark matter freeze-out epoch (when the dark matter decoupled from the cosmic plasma), neutrino decoupling, electron-positron annihilation, and light-element nucleosynthesis (when helium, deuterium and lithium were synthesized). The signatures that these processes left behind constrain the basic parameters of the Universe and enable us to address the above questions.

About 380,000 years after the Big Bang, neutral hydrogen began to form through the recombination of protons and electrons. The Universe became transparent. The next billion years was a critical epoch of reionization during which the first stars, galaxies, and quasars formed, but little data exist to constrain our understanding of the processes involved. The ultimate goal of observational cosmology is to understand the entire history of the Universe after recombination. Currently, we have a snapshot of the Universe at recombination from the cosmic microwave background (CMB), and from detailed observations of its evolution starting from the end of reionization until the present time. The evolution between a million and a billion years has not yet been directly observed. Future observations with the proposed Mileura Wide-field Array/Low Frequency Demonstrator-MWA/LFD (2009), will map cosmic hydrogen during reionization. The NASA Beyond Einstein Cosmic Inflation Probe (CIP) can survey the imprint of reionization on the distributions of galaxies at redshift 3-4.

Luminous tracers (including non-visible electromagnetic radiation) indirectly probe the dark ingredients of the Universe. Gravitational lensing provides one of the best probes of the evolution of dark matter in time and space. Strongly lensed active galactic nuclei (AGN) and arcs in galaxy clusters probe the haloes of individual galaxies; arcs constrain the dark matter distribution within cluster cores and sometimes within galaxy dark matter haloes. Weak lensing constrains dark matter on larger scales, including the infall regions of clusters, and the great walls and voids that define the Cosmic Web. Current observations with the Hubble Space Telescope (HST) and 4-m to 10-m class optical telescopes [MMT, Magellan, Keck, VLT and eventually the Large Binocular Telescope (LBT)] probe dark matter in clusters and individual galaxies to $z \sim 1$. Future observations with the Giant Magellan Telescope GMT, (2016) and James Webb Space Telescope (JWST) will enable study of dark matter up to $z \sim 2$. The total mass, and gas mass fraction of groups and clusters of galaxies, as probed by their X-ray surface brightness profiles (Chandra and XMM) provide important and precise constraints on the amount of dark matter in the Universe and its interaction cross section with normal baryonic matter.

The evolution of dark energy over this same range will be fostered over the next decade, by surveys of Type Ia supernovae and gravitational lensing of field galaxies and galaxies in X-ray clusters (HST, Magellan, MMT). Over time, new ground-based [GMT, the Square Kilometer Array-SKA (2020), and Large Synoptic Survey Telescope-LSST (2015)] and space-based facilities (JWST and Dark Energy Probe-DEP) will extend the depth and areal coverage of these investigations. Complementing the supernovae and gravitational lensing observations are X-ray

cluster surveys, which examine the growth of structure in the Universe as another means of characterizing dark energy. Current observations using Chandra and XMM-Newton, when combined with CMB and supernovae data, constrain the properties of dark energy and its evolution. An all-sky X-ray cluster survey mission (Dark Energy Cluster Survey–DECS) is being studied as a candidate Einstein Probe to extend these constraints.

On large scales (> 10 Mpc), the power-spectrum of primordial density fluctuations is already known from measured CMB anisotropies, galaxy surveys, and the Lyman-alpha forest. Future programs (GMT, JWST, SKA) will refine current knowledge and will seek additional trademarks of the inflation era, such as gravitational waves (through CMB polarization), small-scale structure (through optical/infrared and HI redshift surveys at large z), and the Gaussian statistics of the initial perturbations. One of NASA's Beyond Einstein Probes will also study cosmic inflation (Cosmic Inflation Probe CIP).

Theme 2: How do galaxies form and evolve?

Soon after the Big Bang, the Universe evolved from a hot primordial plasma, which we now observe as the cosmic microwave background (CMB), to a space filled with dark matter, radiation, and neutral gas. During recombination, the Universe entered a starless Dark Age. Over the next several hundred million years, gravity produced a web of cores and interconnecting filamentary structure. As the cores grew, portions collapsed to form the first stars and clusters of stars. Eventually, groups of star clusters surrounded by gas became the first galaxies. At roughly this time, the first supermassive black holes emerged to power quasars, probably as a result of stellar evolution and subsequent accretion. At the end of the Dark Ages, ultraviolet and X-ray radiation from forming stars and quasars ionized bubbles in the surrounding HI (neutral hydrogen). Growth and merging of bubbles marked the transition to a nearly fully reionized IGM. As the Universe evolved to $z \sim 1$, galaxies developed the basic Hubble types observed nearby and large-scale structure developed into a tapestry of dense clusters, voids, and extended sheets.

In detail, we want to know:

(a) How did the Universe and its contents evolve between recombination and re-ionization?

(b) How and when did galaxy clusters, galaxies, and supermassive black holes form, evolve and interact?

(c) What was the nature of the first stars and when did they form?

(d) How and when were the chemical elements first manufactured and dispersed throughout the Universe?

The “reionization era” marks the earliest time when stars, galaxies, and quasars can be observed. From CMB data obtained with the Wilkinson Microwave Anisotropy Probe (WMAP) and observations of extended Lyman alpha troughs in the spectra of high redshift quasars ($z \sim 6.2 - 6.4$), the reionization era is believed to have occurred roughly 200 million years to 1 billion years after the Big Bang ($z \sim 20 - 6$).

We know very little about the formation and evolution of structure during and after reionization. In the early Universe, galaxy mergers played an important role in their formation and evolution. However, the details of how clusters, voids, and sheets evolved, including the roles of dark matter and magnetic fields, remain uncertain.

During early epochs, the star formation rate and the space density of active galaxies (AGN) increased dramatically. Apparent correlation of the mass of the central supermassive black hole (SMBH) and the velocity dispersion of galaxy bulges suggests a relation between the formation

of SMBHs and galaxies. Observations of fully developed quasars and AGN at $z \sim 6$ testify to relatively early SMBH formation and support suggestions that fledgling objects developed well before, motivating study of the Universe at redshifts of at least $z \sim 10$.

The evolving chemical composition of the Universe affected the formation of stars and galaxies during reionization. After recombination, there were no heavy elements and few molecular species (comprising only hydrogen, helium, and lithium isotopes). Gas cooled more slowly than today; stars formed with larger masses (hundreds of solar masses) and lived relatively short lives. Nucleosynthesis within stars produced carbon, nitrogen, oxygen, and heavier elements. Supernovae dispersed these elements into the interstellar medium (ISM) inside galaxies and the intergalactic medium (IGM) between them. Heightened cooling efficiency drove the formation of large numbers of lower mass stars. Although we observe similar cycling of material from the ISM/IGM into stars and from stars back into the ISM/IGM in nearby galaxies, how and when this process began in the early Universe is still not understood. Observations of spectral lines from heavy elements (e.g., sulfur) and molecules (e.g., CO) toward galaxies and quasars at $z \sim 6$ suggests contamination of the ISM/IGM was widespread early, again motivating observation of the Universe at redshifts at $z \sim 10$ and beyond.

Theory of the formation of compact objects during reionization is relatively unconstrained by available data and progress will require interplay between observation and theory. Several ongoing and planned efforts begin to address these issues. Radio observations of HI up to $z \sim 15$ with the Low Frequency Array-LOFAR (2009), the proposed Mileura Wide-field Array/Low Frequency Demonstrator-MWA (2009), and the existing Primeval Structure Telescope (PaST) are anticipated to deliver the first power spectra and maps of inhomogeneities and reionizing sources in the early Universe. Second generation extensions of these instruments and ultimately the SKA are intended to map increasingly well the cosmic web in *three dimensions* back into the Dark Ages.

The SKA, along with millimeter and submillimeter (mm/submm) instruments, such as the Submillimeter Array-SMA, Atacama Large Millimeter Array-ALMA (2010), Single Aperture Far Infrared Observatory-SAFIR, and South Pole Telescope-SPT (2012), will probe the early evolution of heavy molecules and elements, with implications for formation and collapse of structures during reionization. Optical and near-IR observations (GMT-2016, JWST) will detect light from early stars ($z < 10$), as well as the evolution of SMBHs ($z \sim 2-10$), heavy element abundances ($z \sim 2-10$), and supernovae ($z \sim 1-10$).

SAFIR, SPT, the proposed Chilean 25m submm/far-IR telescope, and similar submm/fIR facilities will probe regions too dusty for JWST and too warm for ALMA. The Black Hole Finder Probe - Energetic X-ray Imaging Survey Telescope (EXIST) - will conduct an all sky survey for black holes, particularly the obscured ones, and provide information on the evolution of SMBHs over cosmic time. Constellation-X (Con-X) and Generation-X (Gen-X) will measure the physical and chemical conditions in AGN, galaxies, and clusters of galaxies at $z \sim 2-10$. Coupled with submm/IR and optical/near-IR data, Con-X and Gen-X will probe the accretion history of SMBH in AGN with $z \sim 5-10$.

Deep radio and optical redshift surveys will probe the evolution of galaxies and large-scale structure to $z \sim 1.5$ in the next few years (MMT, Magellan), and to $z \sim 5$ in the next decade (GMT, SKA). Optical, submm (SMA, ALMA, SPT), and infrared data (Spitzer Space Telescope-Spitzer, the Stratospheric Observatory for Infrared Astronomy-SOFIA, CIP and SAFIR) will enable detection of IMF evolution and star formation histories galaxies and clusters. X-ray data [the Chandra X-ray Observatory (Chandra), Con-X, Gen-X] will yield detailed information on the accretion history of galaxies and the formation and evolution of clusters.

Theme 3: What is the sequence of stars to planets to life?

Stellar evolution is one of the most successful theories of twentieth century astrophysics. Despite this success, we do not have good pictures for the structure and evolution of the lowest mass stars and brown dwarfs, how the surfaces of the Sun and stars influence their local environments, and how stars evolve from red giants to planetary nebulae and white dwarfs. These processes have broad implications throughout the Universe, from the evolution of life on Earth and the cycle of stellar birth and death, to the structure and evolution of galaxies.

Star formation is central to the evolution of galaxies. Interstellar material collapses to make new stars. Stars cycle new elements, molecular gas, and dust back into the galaxy. In the last 20 years, scientists have constructed a picture of star formation in our galaxy. Now, we seek to resolve major uncertainties in this picture and to understand the complex processes that lead from clouds of gas and dust to stars, planets, and the emergence of life.

In detail, we want to know:

(a) How do stars and planetary systems form and evolve?

(b) How does the stellar environment influence planet formation and habitability?

(c) What are the biomarkers that trace life? What atmospheric composition and what spectroscopic signatures indicate a planet where life might occur?

(d) How can study of the nearest star, our Sun, further our understanding of the significant areas of astrophysics whose foundation lies in solar physics?

Star formation begins with molecular clouds, where discrete clumps undergo gravitational collapse to form stars. Radio and submillimeter observations penetrate dark clouds, revealing the early stages of the collapse and clear evidence for complex molecules within the collapsing material. Our major goals are to identify and to understand the processes involved with gravitational collapse, the formation and early evolution of protostars, and the growth of complex organic molecules that form the basis of life.

Disks play an essential role in the formation of stars and planets. Conservation of angular momentum during collapse results in a protostar surrounded by a disk. Interactions between the star and the disk drive a high speed jet and bipolar outflow. Related physical processes energize outflows from active galactic nuclei, from interacting binary stars, and from the Sun. A comprehensive multi-wavelength effort is needed to understand the physics that powers astrophysical jets, outflows, and winds.

Physical processes within the disk set the stage for planet formation. Large dust grains grow and rain out into a dense midplane, where the building blocks of planets form. Chemical reactions produce complex, possibly organic, molecules. Excellence in observations, laboratory measurements, and theory is necessary to understand how grains and complex molecules grow in the disk, and how these processes lead to planet formation.

As planets grow, collisions between smaller leftovers produce widespread dusty debris, as in the famous disks around β Pic and Vega. This debris is much easier to detect than planets and provides diagnostics of the underlying solar system. A broad effort to study how debris disks form and how their properties provide information on the underlying solar system will be important in understanding how planetary systems form and evolve.

Direct observations of planets yield the frequency of occurrence and physical conditions of

other worlds. In our solar system, the structure beyond 40 AU is poorly known. Despite the detection of over 180 extrasolar planets, we have no knowledge about the frequency of Earth-like planets or giant planets in wide orbits. Major goals are to derive a reliable census for the Solar System beyond 50 AU, to measure the population of planets around nearby stars, and to learn whether there are other Earth-like planets and solar systems like our own. The Kepler Mission (KEPLER) (2007), and the GMT (2016) will seek to find Earth-like planets in the habitable zone.

Once a planet forms, planetary dynamics and the physical properties of the central star establish the physical and chemical properties of the planetary atmosphere, possibly setting the stage for the development of biological systems. We want to learn which planetary systems are stable enough for life to develop and how planetary dynamics and initial composition affect the chemical development of the planet's atmosphere and surface composition. We also want to learn how changes in the radiation field and mass loss from the central star modify planetary chemistry.

Our Sun, the nearest star, is an excellent laboratory for studying phenomena that affect life on Earth. Many magneto-hydrodynamic (MHD) and plasma physics processes that produce magnetic fields, hot plasmas and high velocity flows, and that accelerate high energy particles are best (and in some cases can only be) studied on the Sun, where high spatial and spectral resolution observations probe scales undetectable in other astrophysical systems. The Solar Dynamics Observatory (SDO), Advanced Solar Coronagraph Explorer (ASCE), the Solar and Heliospheric Observatory (SOHO), Solar-B (now Hinode), and other NASA missions enable detailed study of these processes and their application to other areas of astrophysics (e.g., accretion disks, jets, and winds). New ground based facilities including MWA/LFD are also important in the study of fundamental astrophysical processes on the Sun.

Theme 4. What happens under extreme conditions of space, matter and time?

The Universe contains a remarkable variety of physical conditions. Astrophysical extremes of density, energy, gravity, magnetic field strength, and temperature surpass what we can produce in terrestrial laboratories and challenge our understanding of many physical processes.

In detail, we want to know:

(a) What is the physics through which compact objects form, evolve and interact with their environments?

(b) What is the origin of the highest energy particles and photons?

Compact objects are common throughout the Universe. The Milky Way contains millions of neutron stars and stellar mass black holes. Galactic nuclei harbor supermassive black holes, with masses of billions of Suns.

Supernovae produce neutron stars (NS) and stellar black holes (BH). Although we have a basic understanding, there is no complete theory of the collapse and subsequent explosion of a massive star. In the extreme conditions of a supernova, our incomplete understanding of differential rotation, magnetic fields, neutrino transport, turbulence, and other physical processes complicates numerical simulations and restricts our ability to predict the outcomes of stellar collapse. For particularly massive stars, the collapsar model predicts a luminous but narrowly beamed gamma-ray burst (GRB).

In the past decade, detailed spectral and timing data for GRBs (e.g., SWIFT), and their afterglows

(e.g., Chandra, HST, the VLA,) have enabled rigorous tests of models, such as NS-NS or NS-BH coalescence. In the next decade or two, current facilities and new missions [e.g., the Gamma Ray Large Area Space Telescope (GLAST) and MWA/LFD] will continue to improve our understanding of stellar collapse, particularly in the early Universe, where high apparent GRB luminosities provide critical tests of our understanding of the first generations of massive stars.

Neutron stars can acquire at birth large rotation frequencies (> 100 Hz), space velocities 100 - 1000 km s⁻¹, and surface magnetic fields (10^{12} - 10^{16} G). The extraordinary magnetospheres of these stars produce intense g-ray flares and beams of nonthermal radio to g radiation. Current observations concentrate on trying to understand the origin of these high energy phenomena. Eventually, higher sensitivity missions with broader energy response (e.g., GLAST, Con-X, and the EXIST) may enable fundamental tests of quantum electrodynamics and general relativity. Capabilities for high precision pulsar timing (with polarimetry) and large pulsar surveys will grow with the construction of the SKA and prototypes such as the MWA/LFD.

Stellar mass black holes are completely defined by their mass and spin. Accurate measurements allow better models of accretion flows and relativistic jets, and provide tests of general relativity. Currently, there are 40 good BH candidates. Accurate masses are known for ~ 10 of the 20 candidates confirmed as BH from dynamical mass estimates derived from optical spectra. For these ~ 10 , measurements of BH spin are a top priority. Models for the relativistically broadened Fe K α emission line provide an independent spin estimate, something to which Con-X and Gen-X will be ideally suited. Analyzing high frequency Quasi-Periodic Oscillations (QPOs) of accretion flows (100 - 450 Hz) is another promising approach for measuring the spin. The Rossi X-ray Timing Explorer (RXTE) observations show that the highest frequency oscillations scale inversely with BH mass, as expected if QPOs are produced at or close to the innermost stable orbit. Future, more sensitive, timing missions are a priority because they will provide a uniform sample of spin rates, thus enabling detailed model testing.

At the upper end of the mass spectrum supermassive black holes (SMBH), which lie in galactic nuclei, probably formed and have evolved via distinct mechanisms, though much is uncertain. The first probably arose during the epoch of reionization, accreted rapidly until $z \sim 1$ - 3 , and then more and more slowly to the present day. Uncertainties in the epoch of SMBH formation and in the time variation of accretion affects our understanding of structure formation, the star formation history of the Universe, and the origin of the cosmic X-ray, infrared, and submillimeter backgrounds. Studying correlation between BH mass and galactic bulge mass back to the epoch of reionization will help us to understand the evolution of supermassive objects and connection to their surroundings.

Using the Very Large Array (VLA)/Very Long Baseline Array (VLBA), Keck/VLT, Chandra/XMM-Newton, and smaller facilities, investigations of SMBH have been driven by reverberation mapping, measurement of light and velocity cusps in bulges, spectroscopy of relativistically broadened lines, position and velocity-resolved mapping of masers in accretion disks, and tracking of relativistic jets. New space missions (e.g., Con-X and EXIST) and ground-based facilities (e.g., GMT, the VLT interferometer, and SKA) will enable the large, detailed surveys needed for continued progress.

At the center of the Milky Way, SgrA* is a special SMBH. It is nearby, and it accretes at a low rate. Intensive and detailed study of this one object adds to our understanding of SMBHs in general. Operating near the peak of the spectral energy distribution, the SMA is an ideal instrument to monitor the fluctuations on the accretion flow, and to track and identify events in the accretion disk that occur close to the last stable orbit. Detailed 3D relativistic MHD simulations will be required to facilitate this understanding. Near-infrared observations with the VLT interferometer and millimeter/sub-millimeter observations with a very long baseline instrument (e.g., SMA/JCMT/CSO in Hawaii, CARMA in California, ALMA in Chile, SPT in Antarctica, and Large Millimeter Telescope in Mexico-LMT) will be first steps in imaging the inner accretion disk. Eventually, X-ray interferometry may allow direct imaging of the event horizon.

The Earth's atmosphere is continually bombarded with relativistic nuclei and other particles. These “cosmic rays” have a complicated energy spectrum extending from below 10^{11} eV to beyond 10^{21} eV, with a “knee” at roughly 10^{15} eV. Almost a hundred years after the discovery of cosmic rays, we have not identified the processes that convert gravitational, magnetic, or rotational energy into ultra-relativistic particles.

Several different processes probably produce cosmic rays. On the Sun, shock waves and magnetic reconnection in solar flares both produce energetic particles, and the source regions of these particles are prime targets for existing (UVCS, TRACE, HINODE) and future (SDO, ASCE) NASA missions. Strong shocks in young supernova remnants (SNRs) should produce particles with energies up to $\sim 10^{15}$ eV. However, X-ray (ASCA, Chandra and XMM) and gamma-ray (CANGAROO and HESS) observations of SNRs imply maximum particle energies of only $\sim 10^{14}$ eV. What limits shock acceleration is not currently known. Because the gyroradius of even higher energy ($>10^{15}$ eV) cosmic rays exceeds the size of the Galaxy, extragalactic sources must produce these particles, although the mechanism through which they do so is still unknown. Particles with energies above 10^{20} eV experience the Greisen-Zatsepin-Kuz'min cutoff due to collisions with relativistically boosted CMB photons and must originate from sources within ~ 50 Mpc. Because these very energetic particles are probably unaffected by Lorentz forces in the magnetized IGM and ISM, their trajectories should point back toward a point of origin and provide information on an acceleration mechanism. The expectation is that the new generation of cosmic ray experiments (e.g., Hi-Res and Auger) will be able to make the first identifications of the originating sources. In the next decade or two, space missions [e.g., the Extreme Universe Space Observatory (EUSO)] and ground-based facilities (e.g., LOFAR, possibly MWA, and eventually SKA) will enable improved mapping of particle trajectories and compositions, broader fields of view, and perhaps mapping of radio bursts associated with cosmic ray air showers.

In a related phenomenon, AGN (including the Galactic center), pulsar nebulae, SNRs, and X-ray binaries are strong sources of TeV photons. There is also a mysterious new group of “dark accelerators,” TeV sources with no known counterparts at other wavelengths. These sources show varied morphologies, from unresolved to extended, and time variability, from steady to highly time-variable. Thermal or synchrotron processes cannot produce TeV photons. Although pion decay, inverse Compton emission, and relativistic bremsstrahlung can produce TeV photons, these and other mechanisms require highly relativistic populations of hadrons or leptons.

New ground-based facilities [e.g., High Energy Stereoscopic System (HESS) and VERITAS] on four continents enable observations of the morphology, time-dependence, and spectrum of TeV sources. Combined with observations at lower energies and studies of the local environment, these facilities promise to provide direct constraints on the acceleration mechanisms of TeV sources. The high angular resolution and improved sensitivity of HESS (in operation) and VERITAS (online in 2006-7) will expand the known sample of TeV sources and yield new details on existing sources. We expect many detections of new AGN to redshifts ~ 0.3 , more “dark accelerators,” and possibly other new classes of sources. Follow-up observations at radio (the Long Wavelength Array-LWA, VLA), infrared (Spitzer, SAFIR), and X-ray (Chandra, INTEGRAL, RXTE, and XMM) wavelengths are critical to distinguish among possible emission mechanisms and to characterize environmental effects. GLAST enables studies at energies where there is a transition from synchrotron processes to other mechanisms, with an order of magnitude better sensitivity than what was offered by CGRO.

Future studies of very high energy photons require a technically feasible ground-based detector with collecting area of roughly 10^6 m². This detector would provide the sensitivity to explore the TeV Universe at redshifts ~ 1 and beyond, allowing the first direct study of how very high energy sources evolve and enabling detections of new populations among distant sources.

Cross-Cutting Science. Laboratory Astrophysics, Theory and Archives

Broad success in the proposed science themes requires strong efforts in laboratory, observational, and theoretical astrophysics. Although some research projects are completely self-contained, most require knowledge or resources that cut across the major science themes. Independent of theme, state-of-the-art instruments on first-rate telescopes enable sensitive observations of astronomical sources. In the next decade, 20-m class ground-based telescopes and 2-4 m class space missions spanning all wavelengths will enable order of magnitude improvement in light gathering power, and multiwavelength data needed to answer the questions posed in the science themes. Laboratory astrophysics, modeling, and theory turn these data into astrophysics, establishing the cycle where observations test theory and theory leads to new observations. Here, we outline these broader efforts that encompass all of the science themes.

Imaging, timing and spectroscopy are the observational tools of astrophysics. In addition to basic measurements of brightness, color, and position, imaging yields information on the spatial structure and physical conditions of astronomical sources. In the next decade, the CfA will need high spatial resolution images to provide measurements of MHD structures on the Sun, collapsing protostars and circumstellar disks, interacting pairs of nearby and distant galaxies, the nuclei of AGN and black hole binaries, and the environments of supernovae and the first stars and galaxies. Resolving structure in these systems will yield clear tests for theories of star/planet formation, MHD outflows, BH formation, and stellar explosions. Eventually, images will provide the first direct light from terrestrial-like planets, enabling the search for life beyond Earth.

Time variability of astronomical objects ranges from sub-millisecond bursts to multi-gigayear evolution. With high resolution timing we have discovered rapidly spinning neutron stars in pulsars and bursts of gamma rays from the most powerful explosions since the big bang. Orbital periods of compact binaries are only hours long and provide insights into the final stages of infall and coalescence of these objects. The orbital decay of the binary pulsar provides a precision laboratory for testing general relativity and the production of gravity waves. Accurate and precise timing measurements require high count rates and therefore high collection areas in order to maintain adequate signal to noise over short intervals. Precision photometry may provide a unique means to use occultation observations to detect small outer solar system bodies, on one extreme, and extrasolar planets at a larger limit.

Spectroscopy is a powerful tool of astrophysics. Spectroscopy enables accurate measurements of the age, chemical composition, density, and temperature of galaxies, nebulae, planets, and stars throughout the Universe. Because many astronomical sources vary slowly on a human lifetime, spectroscopic snapshots of large samples of objects provide information on the internal dynamics and evolution unavailable from observations of a single source. In our four science themes, we require sensitive spectroscopic measurements to probe the physical conditions of the early Universe, the growth of BHs in AGN, the chemistry of organic molecules in collapsing protostars, and the formation, evolution, and structure of galaxies, stars (including the Sun), and planets. Extracting the most information from astronomical spectroscopy requires a healthy synergy between observational and laboratory astrophysics. Distant astronomical sources produce radiation from collisions of atoms, electrons, ions, and molecules. Before we detect this ancient light, it interacts with intervening material in a variety of physical states. Thus, interpreting the spectroscopic observations from telescopes requires a complete understanding of the interactions of radiation with matter, including collision rates and cross-sections, that allow us to derive “diagnostics” of the astronomical environment from spectral line strengths and line ratios. In this way, laboratory measurements turn astronomy into astrophysics.

Laboratory astrophysics impacts our ability to understand astrophysical objects across the electromagnetic spectrum. From the early identification of “nebulium” as forbidden transitions in O^{++} to the modern understanding of molecule formation in interstellar clouds and X-rays from comets, theoretical calculations and laboratory measurements of atomic/molecular structure, spectroscopy and collision processes have been vital tools in observational astronomy. Detailed calculations of astrophysical plasmas are now a basic input to X-ray data reduction packages. The ionization state of material in accretion disks impacts observations of AGN, interacting binaries, and the youngest stars. In addition to providing a basic interpretative tool, laboratory astrophysics enables predictions of new phenomena accessible to observational tests. For example, because cometary X-rays are produced by collisions between highly ionized species in the solar wind and neutral molecules in the comet’s atmosphere, future high spectral resolution X-ray observations may yield diagnostics of solar wind composition that complement in situ measurements with solar satellites. Eventually, laboratory measurements of complex molecules will inform observations of the best ways to diagnose conditions in planetary atmospheres, enabling our search for extrasolar terrestrial planets and extraterrestrial life.

Theory is an important piece of a comprehensive research effort. Analytic theory often provides the first impetus for an observational program or the first insight into an unexpected observation. Following these vital first steps, more detailed numerical calculations of the structure and evolution of astronomical sources provide necessary information to interpret astronomical data in more detail and to make predictions for new observations. To make progress in our science themes, a strong synergy between theory and observation is essential. Theory provides the backdrop for understanding the early evolution of structure in the Universe and the formation of planets, stars, and galaxies within these structures. Theoretical predictions will help to formulate observational programs for the formation and evolution of BHs, bipolar jets and stellar winds, organic molecules, and stellar explosions. Finally, theory will help us to identify new strategies for optimizing observations of objects as diverse as the first stars and nearby extrasolar planets and to initiate and to execute plans for new instruments and observatories.

Data Archives are an essential component of data gathering, both for ensuring data preservation and for aiding scientific analysis by providing easy access to multi-wavelength data. The astronomical and astrophysical community is engaged in the development of the Virtual Observatory (VO), a set of protocols and software to allow easy user access to multi-wavelength data archives, theory data (e.g. spectral databases and simulation), and analysis software. Digitization of historical plates, modernization of existing digital archives, and establishment of Virtual Observatory compliant archives for future large volume data collections are all required aspects of modern data management. The CfA is committed to the preservation and diffusion of its scientific collections, the data archives, reflecting the CfA’s priorities for science.

3. Infrastructure Issues

The scientific productivity at CfA depends on more than the projects that the scientific and technical staff undertakes. There must also be an environment conducive to research and scholarly study. The physical plant of CfA, the computing environment, our core engineering capabilities, communications, and access to students are all important aspects of the infrastructure that deserve attention in strategic planning.

Space

Space at the CfA is a critical issue and impacts the Center’s ability to carry out the best scientific programs. In addition to sufficient quality office and laboratory space, ***we need common spaces, such as an auditorium and a cafeteria to ensure communication*** among

the scientists of the CfA. The Center's size and diversity, significant elements in our past and future success, have resulted in an ever decreasing opportunity for spontaneous interaction between scientists who are not in close proximity or already working on common projects. One way to improve this situation is to bring as many of the scientific staff together as possible for informal gatherings. In the event that a large contiguous space can be made available at the Garden Street complex, a Center lunchroom/cafeteria should be seriously considered. Similarly, an auditorium large enough to accommodate 250-300 people would be a valuable addition to the Center. The large physical separation of parts of the CfA is not optimal and adversely affects interaction between staff members, especially when communication is not face-to-face. While there are circumstances that have caused the CfA to become fragmented, ***it is desirable to examine long term strategies with the objective of reuniting the Cambridge components of the Center on a single site.***

Computing

Computing at the CfA has traditionally been a strong and essential component of our scientific accomplishments. The Computing Facility (CF) provides basic IT services including networking and security for the desktops and laptops for all scientists. For most scientists (those outside of the HEA division), the CF provides complete system administration services for their UNIX based computers (individual workstations and servers running either Sun Solaris or Redhat Linux). To a lesser degree, the CF provides some system support for desktops running MS Windows or Mac OS X. The CF generally meets the needs of these scientists by installing and updating the operating system and maintaining an array of applications (user software). For many users the CF provides regular disk backup (and restoration as needed) along with secure and reliable network services such as e-mail and web service.

The CF is currently stretched very thin just to maintain a basic level of support to scientists and to the administrative staff. After a comprehensive review in 2003, the CF Committee report suggested augmentation in the CF staff and their responsibilities. Despite some changes in the CF since that report, the chronic problem of understaffing remains. The needs for scientific computing at the CfA have grown faster than the resources of the CF to meet those needs. ***A strong, reliable commitment to scientific computing is required for the long-term success of our strategic priorities.*** The scientific goals we envision for the CfA impact several aspects of the CF operations and resources. Computing facilities for these new initiatives must be realistically assessed. The CF Science Advisory Committee is the appropriate body to provide this assessment and to help establish the necessary priorities for the CF in supporting the Center's scientific needs.

Among areas that should be considered are:

- *Development of a first-class high-performance computing capability accessible to a broad range of users.*
- *Support and management for the several "flavors" of computers and operating systems commonly in use by the scientific staff e.g.,. Solaris, Linux, MS-Windows, and Mac OS X*
- *Leading edge support for other forms of 'exotic' computing that may be needed by scientists.*

Central Engineering

The CfA has a long history of successfully managing, building and operating major astronomical facilities both in space and on the ground. Competence and expertise in mechanical, electrical, thermal, structural and systems engineering have been, and will continue to be, critical core capabilities needed to support the strategic priorities of the center. The continued allocation of resources such as laboratory and office space for Central Engineering, the operation of a modern machine shop (model shop), and close interaction of the scientific and technical staff are key to our future success.

Communications

Communications across an organization as large as the CfA requires targeted efforts. In addition to adequate “common” space and computer connectivity (discussed above), there should be centralized mechanisms for communicating scientific and technical activities. More creative use of existing technologies, e.g., web sites, databases, search engines, etc., could be applied to this area. On-line lists (and abstracts) of papers by the CfA staff (perhaps the complete papers), accepted proposals (at least their abstracts), and similar types of material would help to inform our staff of what is happening and invite broader participation in research areas. Large projects should be encouraged to set up web sites, and these should be linked to the CfA’s home page as well as the appropriate thematic and divisional web pages.

Better administrative communications, such as a bi-monthly newsletter from the CfA Director’s Office would be helpful. Similarly, more emphasis on cross Divisional meetings (perhaps using the suggested lunchroom/cafeteria) would provide a mechanism for a better-informed staff. Coffee/Tea hours hosted by the Director’s Office would provide a setting for informal discussions among the staff, especially when scheduled on a regular basis.

Education and Outreach

As the world’s leader in astrophysical research, the Center for Astrophysics shares the commitment to education embodied by its parent organizations. The goals of the CfA’s education efforts are to inspire, inform, and enable the next generation of astronomers and space scientists, engage the public in the excitement of astrophysics research, and further the public understanding of science. Education and outreach activities are guided by the desire to foster the participation of scientists and engineers, involve students and teachers in authentic research experiences, and engage women, minorities and underserved groups.

In pursuit of these goals, the CfA’s education programs include curriculum development; professional development for teachers; development of new technologies for teaching and learning; the creation of innovative scientific visualizations; and the presentation of publications, media, programs, and exhibits that engage the public in learning about astronomy and related fields; as well as research to ensure that its efforts are effective and that obstacles to learning are identified and addressed.

Students and Postdocs

Access to young scientists (undergraduates through postdocs) is one of the strengths of the CfA. Historically, there has been a great deal of interest among Harvard undergraduate students to carry out research projects with members of the scientific staff. High caliber graduate students have worked with many CfA scientists on a broad variety of projects. To recruit students from other disciplines, we must establish better links between the CfA and the Harvard FAS, particularly the Physics Department and the Division of Engineering and Applied Science (DEAS). However, the question of funding non-astronomy students needs to be explored.

Over the past 5-10 years, the very successful CfA Postdoctoral program has grown smaller as the CfA scientific staff has grown larger. These postdoctoral fellowships are highly attractive: the appointees have complete freedom to pursue the research of their choice without programmatic responsibilities. Many outstanding CfA scientists started their careers as CfA postdoctoral fellows. In the past, this program was much larger, supported equally by HCO and SAO. The number of CfA postdoctoral fellowships has decreased, although two named postdoctoral fellowships have been established recently through generous donations. Given the large size of the CfA scientific staff, ***the number of CfA postdoctoral fellowships offered should increase to about 20 per year*** (this includes the named programs such as the Clay, Firestone, and Menzel fellowships). The Director may commit postdoctoral positions to support individual staff members as a management tool for awarding performance or retention.

However, these commitments should be limited in their number and duration.

Staffing

An important aspect of reaching our scientific goals concerns excellence in the CfA staff. To achieve this excellence, the CfA must recognize, attract, and retain the best scientists without regard to race or gender, and provide an outstanding working environment for all staff members. The recent CfA Gender Equity Study has raised a number of issues, which need to be addressed to ensure equity, not only across gender, but also racial boundaries. The CfA, a world leader in science, must be proactive and lead similarly in achieving racial and gender equity. The scientific, technical, engineering, and support staff needs to reflect the diversity present in the pools of strong candidates. The leadership of the CfA should address and correct any existing gender or racial biases, and improve the working and social environment for everyone.

There has been concern expressed about unbridled growth in the SAO scientific staff, which can occur when postdocs, visitors, and others find a way to obtain their own support through grants and contracts for which they become Principal Investigator (PI) at SAO. The rules regarding being a PI on the SAO side have been very liberal, and there appears to be no formal process established for deciding whether someone can become a self-supporting SAO trust-side scientist. ***The SSPC recommends that a committee be established, analogous to the Federal Scientist Appointments Committee (FSAC), which would advise the CfA Director on this issue.*** The committee would review the "hiring" of new people bringing in their own support through SAO, as well as requests from scientists already at SAO in a programmatic capacity who wish to become self-supporting for a major fraction of their time. The review process would be to ensure that we retain only the best-qualified scientists, particularly those who continue to address the challenges set by CfA science priorities.

4. Strategic Planning for CfA

There are many activities (current, planned and proposed) that are relevant to the science themes and questions presented above. Various members of the Center are involved with these activities, and participation in this broad base of projects is a necessary and fruitful state that should be encouraged. However, amongst all of these activities, it is equally necessary to establish priorities to provide guidance for how Center resources should be allocated by the Director.

The single most important strategic goal for the Center is to carry out high quality scientific research in astronomy and astrophysics. The set of themes and questions presented in Section 2 provides guidance as to what we believe to be the current science drivers for our future direction. The criteria for setting strategic priorities as to how CfA should proceed to address these rather broad areas are: that the impact should be large (involving a significant number of CfA staff); the Center's role should be significant (there are many ways to measure significance – scientific leadership, number of staff involved, overall cost to CfA, etc.); and that CfA involvement is likely to result in important scientific advancement in the field.

The transition from broadly stated scientific objectives to the specific set of strategic activities that can enable progress was accomplished by first reviewing the current “inventory” of large (or possibly large) activities and potential new involvements. Activities were classified as being facilities (things we would build and use mainly with CfA or private funds), missions (things for which we propose to get mostly outside public funding, e.g., from NASA or NSF), or centers (internal CfA organizational elements funded through various sources). Other classes of activity, such as technologies, software and databases, instruments, and archives were also considered. While important, the Committee decided at this time that these activities were surpassed by others in meeting the criteria above. This review consisted of understanding how an activity relates to the science drivers and what the leadership role for CfA is today and might be in the future. We also estimated the development cost, the operational cost, the potential users or involved staff, the space and computational needs, and the timeframe for each activity.

Based on this information and discussions within the committee, we list in Table 1a – 1e, the set of activities and strategic goals (that we currently know about) that are viewed as having the greatest value to the CfA. These activities are described in more detail in the Appendix.

We have divided the 13 strategic activities into two main classes:

- First are those activities that are ongoing and have long term strategic impact on the science themes. These need to be continued. They require sustained (and in some cases increased) investment of CfA resources to achieve their goals.
- Second are new initiatives that will carry CfA into the next several decades with capabilities beyond those currently in place. These activities require new allocations of CfA resources and should have high priority for both new funding and new staffing. For each category (facilities, missions and centers) we have rank ordered the new initiatives.

The highest priority new initiative for the Center for Astrophysics is to play a leading role in the development and operation of the exciting new Giant Magellan Telescope (GMT). Our goal is to obtain 20-25% share of the observing time with this facility. The large collecting area and high angular resolution of this next generation optical/IR telescope will enable critical investigations central to all four themes identified above. However, this project is large, expensive and spans several decades. It is important that not all of the CfA's resources are committed to this single new project. We recommend that balance be maintained across the categories of activities so that the broad scientific interests of the CfA are sustained.

CfA participation in new NASA activities is of critical importance to the Center's future, in particular, high energy astrophysics missions. As embodied in NASA's current space science planning, these activities center on the Beyond Einstein (BE) Program. **Constellation-X (Con-X) is one of just two BE flagship missions, and it is the CfA's highest priority space astrophysics program.** Con-X is a logical successor to the Chandra X-ray Observatory (in which the CfA played a major role). The CfA is partnered with NASA's Goddard Space Flight Center (GSFC) to provide the science leadership for this major facility, an important function for the science breadth and balance of the Center. Con-X and other post-Chandra missions require new technology, and the CfA should lead these developments. Accordingly, **the Center for X-ray Technology (CXT) will provide critical strategic leadership in new optics and detectors for the nation's space astrophysics program.**

There are numerous future mission concept studies that the CfA is involved with. These range from Explorer class small missions, to moderate sized Einstein Probes and Discovery class missions, and to large facility or flagship missions. It is not possible to know which of these missions will be selected for development and flight, but it is in the best interests of the Center to be actively involved in as many of these studies as possible. Processes such as the IR&D and REF proposal review, and Proposal Preparation support reviews are helpful in allocating Center resources to these future opportunities, and the committee recommends that these science strategic goals contained in this report be considered in the evaluation of requests for funding these activities.

In the new facilities area, the committee endorses CfA involvement in LSST as important for the future. In anticipation of LSST, the committee sees a Center involvement in PanSTARRS as desirable provided that non-Smithsonian funding can be obtained (note that some funding for PanSTARRS has been obtained through Harvard University). The committee also endorses CfA involvement in the MWA/LFD and SKA projects, pending successful funding from the NSF.

Table 1a: On-Going Facilities

Name	Description	Goal
MMT/Magellan	The MMT Observatory is a 6.5-m telescope located at Mt. Hopkins. It is jointly operated by SAO and the University of Arizona (UA). The Magellan Observatory consists of two 6.5-m telescopes located at Las Campanas in the Chilean Andes. It is jointly operated by Harvard and the Carnegie Institution of Washington (CIW), the Massachusetts Institute of Technology (MIT), the University of Michigan (UM), and UA.	Continued operation of these facilities; Magellan - completion of the f/5 secondary (mid-2007), transfer of MegaCam (2007-2008), transfer of MMIRS (2008-2009); MMT - completion of MMIRS (2007) and Binospec (2009).
Submillimeter Array (SMA)	The SMA consists of 8 movable 6-meter diameter antennas site on Mauna Kea, Hawaii. It is operated by SAO with Academia Sinica Institute for Astronomy and Astrophysics (ASIAA) and the Institute for Astronomy (IfA) as partner institutions.	Continued operation and the completion of high frequency receivers. Inclusion of the Caltech Submillimeter Observatory and the James Clerk Maxwell Telescope in the expanded SMA.
VERITAS	VERITAS consists of 4 12-meter aperture telescopes presently sited at Mt. Hopkins, AZ. It is funded by NSF, DOE, and SAO, and operated by SAO with a collaboration of several colleges and universities worldwide.	Four telescope operations at Mt Hopkins (2006) and operations there for two years while a permanent site is determined. Relocation to the permanent site (2008) and expansion to 7 telescopes.

Table 1b: On-Going Missions		
Name	Description	Goal
Chandra X-ray Observatory (CXO)	The Chandra X-ray Observatory is part of NASA's Great Observatory program. It is funded by NASA, and is operated by SAO on behalf of NASA. The Observatory is an international facility that carries out observations for several hundred GOs each year.	Continued operations beyond 2014.
Spitzer Space Telescope (SST)	The Spitzer Space Telescope in an infrared telescope. It is part of NASA's Great Observatories Program and SAO provided the Infra-Red Array Camera (IRAC). The IRAC Team has guaranteed observing time on Spitzer and is funded by NASA.	Continued operation of IRAC beyond 2009.

Table 1 c: New Facilities		
Name	Description	Goal
Giant Magellan Telescope (GMT)	The GMT will be a 20-meter class ground-based optical/IR telescope. It consists of 7 8.4-meter diameter mirrors. The CFA share will be 20-25% of the facility. Funding will be shared with SAO, Harvard, and private donations.	Support to ensure 20-25% share of telescope observing time, development of first light instruments for GMT, particularly near-IR multibject spectrograph, and CFA selection as site for GMT operations center. Direct detection of light from terrestrial and gas giant planets, measure the large-scale structure and evolution of galaxies (and AGN) at redshifts 3-5, study the transformation of dusty gaseous disks into planetary systems, investigate the evolution of stellar populations in galaxies at redshifts of 1-2 and the evolution of metals at redshifts of 2-10.
Mileura Widefield Array (MWA) and the Square Kilometer Array (SKA)	The MWA/LFD will be an array for 21-cm tomography of the early Universe and heliospheric science. Sited in Australia, it is a collaboration of Haystack, MIT, CFA and Australian institutions, with anticipated NSF funding. Located on a proposed SKA site, the MWA/LFD may become one of several SKA precursor instruments.	MWA/LFD – start (mid-2006); start deployment of hardware to site (2007); start science operations (2009).
The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) and the Large Synoptic Survey Telescope (LSST)	Pan-STARRS will consist of 4 1.8-meter optical telescopes. The first telescope is sited at Maui, Hawaii. Funding is from the Air Force (for construction only). LSST is an 8.5-meter class optical telescope. It is funded by NSF and various private sources. It is likely to be sited in either Chile or Mexico	Participation in Pan-STARRS data reduction pipeline and analysis and continued membership in LSST Corporation with involvement in focal plane cameras and the data pipeline.

Table 1d: New Missions

Name	Description	Goal
Constellation-X (Con-X)	Con-X is one of two flagship missions of NASA's Beyond Einstein program. Its primary science goals are to study black holes, dark energy and the chemical evolution of the Universe. It may consist of several X-ray satellites working in unison to generate the observing power of one giant telescope. SAO will operate the Science Operations Center for Con-X.	Continued leadership role in partnership with GSFC including pre-Phase-A systems engineering for optics, technical development for detectors and lead of Facility Science Team. Major hardware role in mission (2010).
Space Mission Concepts	NASA has frequently supported mission concept studies in order to plan for the future. SAO has been involved with numerous advanced missions either as the lead institution or a member of collaboration. These studies offer valuable opportunities for the Center to participate in future missions	Leverage NASA study funding to permit new mission ideas to be developed and discussed in the broad space science community with strong CfA identification as a lead organization in these potential future missions. Participate in future selected missions.

Table 1e: Centers at CFA

Name	Description	Goal
The Center for X-ray Technology (CXT)	The CXT is located within the High Energy Astrophysics Division of the CFA, with laboratories at Cambridge Discovery Park. It will be funded by NASA grants, SAO, and private donations.	Staff support through SI and private donations (2006), successful grant support via NASA, NSF, DOE, etc. (2007).
The Institute for Theoretical Atomic, Molecular and Optical Physics (ITAMP)	ITAMP is an NSF-funded center of excellence jointly located and operated by CFA and the Harvard Physics Department.	Continued intellectual leadership in the theoretical AMO Physics community and Laboratory Astrophysics communities, with continued funding through NSF (2007-2011), and other grant support possibly through DOE.
The Institute for Theory and Computation (ITC)	ITC is a center of excellence in computational/theoretical astrophysics, funding is through the Harvard College Observatory (HCO). It is located at the CFA.	Continued leadership in computational astrophysics through support from Harvard.

5. Appendix

Major Projects - Facilities and Missions

On-Going Projects:

The MMT and Magellan Telescopes

The MMT Observatory is a 6.5-m telescope located at Mt. Hopkins. It is jointly operated by SAO and the University of Arizona (UA). Current instruments include the SAO Hectospec and Hectochelle spectrographs, and the MegaCam wide field imager. At SAO, Binospec and MMIRS are in development. Each year, approximately 50 CfA scientists, postdocs, and students use the MMT. The annual operating cost of MMT charged to SAO is about \$1.1M; the annual budget for instrument development is about \$2.5-3M.

The Magellan Observatory consists of two 6.5-m telescopes located at Las Campanas in the Chilean Andes. It is jointly operated by Harvard and the Carnegie Institution of Washington (CIW), the Massachusetts Institute of Technology (MIT), the University of Michigan (UM), and UA. Current instruments include Harvard-funded MagIC. MegaCam and MMIRS will be deployed at Magellan once the f/5 secondary is finished. CfA use of Magellan is comparable to that of the MMT. The annual cost of Magellan for operations (instruments) is roughly \$600 K (\$300 K).

Continued operation of Magellan and the MMT is critical to the scientific productivity of the CfA. Current programs on the MMT and Magellan provide important contributions to all of astrophysics, from the outer Solar System to the edge of the observable Universe. Recent highlights include discoveries of extrasolar planets, constraints on the rotation period of Sedna, detections of spiral shocks in the disks of cataclysmic variables, accurate masses for black hole binaries, the discovery of the first hyper-velocity star and characterization of its variability, detection of high velocity jets in Orion pre-main sequence stars, measurement of the AGN luminosity function for $z = 1-5$, and the first comparison of mass maps derived from weak lensing and a deep redshift survey. Within the next few years, we expect new results on planet searches and the IMF in nearby open clusters, deeper redshift surveys of galaxies to $z \sim 0.7$ and AGN to $z \sim 5$, measurements of star formation rates in galaxies at $z = 2-3$, and improved constraints on dark energy and dark matter from supernovae and strong/weak lensing measurements.

Completion of new instruments for the MMT and Magellan is also a high priority for the major science goals of the CfA. On the MMT, the multiobject near-IR spectrograph MMIRS (2006-2007) will enable the only wide field near-IR imager ($7' \times 7'$) at the MMT and the only near-IR spectrograph at either the MMT or Magellan. Wide-field multiobject near-IR spectroscopy has broad and growing interest among CfA scientists for comprehensive studies of the IMF, the structure of the halo of the Milky Way and nearby Local Group galaxies, emission and absorption line studies of AGN at a wide range of redshift, and deep redshift surveys. Binospec (2008-2009), a binocular multiobject optical slit spectrograph, will replace the outdated Blue and Red Channel spectrographs, and will reach 2 magnitudes deeper than Hectospec ($V = 23-24$). Coupled with the high efficiency in acquisition and guiding at the MMT, Binospec will compete favorably with DEIMOS, the world's premier multiobject spectrograph on the Keck, enabling, for example, probes of (i) galaxy evolution and large-scale structure at $z = 0.7-1$, (ii) gravitational lensing and the distribution of dark matter at $z = 0.4-1.4$, (iii) the evolution of stellar populations in nearby galaxies, (iv) the evolution of AGN and massive black holes at $z = 2-7$, (v) the IMF throughout the Milky Way, and (vi) icy planetesimals and planets in the outer Solar System.

Delivery of the Magellan f/5 secondary in mid-2007 will enable use of the MMT f/5 instruments, MegaCam and MMIRS, on the Clay Telescope. MegaCam will allow deep imaging surveys of (i) the galactic center, (ii) rich southern star-forming regions (Carina, r Oph, and in the LMC and SMC), and (iii) clusters of galaxies for supernovae and gravitational lensing programs. MMIRS will provide complementary probes of the galactic center and galactic and Local Group star forming regions. Deep IR spectroscopic programs will yield detailed studies of the dynamics of the galactic center, the Milky Way halo, and the star formation history of the Universe to $z = 1$.

Over the next 5-10 years, it is important to make the most of our investments in MMT, Magellan, and the f/5 instruments. At each observatory, support for operation and maintenance is a vital piece of a successful science program. Within the OIR division, the Telescope Data Center (TDC) has implemented a pipeline processing system for Hectospec, which has reduced more than 100,000 spectra. A pipeline system for Hectochelle is under development; plans for a MegaCam pipeline are underway. Continued support for the TDC is necessary to ensure timely reduction and archiving of these data and to enable reduction systems for GMT instruments.

The Sub-Millimeter Array (SMA)

The Submillimeter Array (SMA) was conceived at SAO as the world's first imaging interferometric telescope at submillimeter wavelengths, between the millimeter bands where several interferometers operate and far-infrared wavelengths accessible only from space. The SMA is sited near the 4000 meter summit of Mauna Kea, Hawaii, the best high, dry site in the United States for submillimeter atmospheric transmission. The SMA consists of eight movable 6-meter diameter antennas that combine to synthesize beams up to 1000 times smaller in area than any other submillimeter telescope, thereby obtaining uniquely detailed images. The SMA, dedicated in FY04, is currently the forefront telescope for high resolution studies of cool material in the Universe (temperatures of a few 10's of Kelvin), which generally remains unseen and unknown to telescopes at radio, optical, and X-ray wavelengths.

The SMA partner institutions share observing time in the ratios SAO:ASIAA:IfA /72:13:15. More than 150 SMA observing proposals were submitted this year by CfA scientists, and oversubscription for the available submillimeter weather is more than a factor of five. The SAO annual support for the SMA is \$2.2M for operations (including 6 postdocs and 9 graduate students), \$2.0M for instrument development, and \$3.4M for 34 Federal positions.

The submillimeter is rife with important physical diagnostics, including thermal emission from dust and solid bodies, rotational transitions of molecules, and fine structure transitions of atoms. Recent science highlights from the SMA include the first direct temperature measurements of Pluto and its moon Charon that show Pluto is colder due to the presence of surface ices, the first mass determinations of disks around young stars in the Orion Nebula that indicate enough material to form new Solar Systems like our own despite harsh stellar winds and an intense radiation environment, the first detection of organic molecules on Solar System scales around newly formed stars, showing how organic material is modified and incorporated into protostellar disks, the first imaging of magnetic field geometries in protostellar cores, the discovery of a new extragalactic water maser transition, and constraints on the accretion mechanism of the Galactic Center black hole through its submillimeter variability and polarization that probes to ~ 10 Schwarzschild radii free of obscuration and confusion. The SMA is blazing a trail that the \$1B world investment in the Atacama Large Millimeter Array (ALMA) will follow. (ALMA is currently scheduled to start full science operations in 2013).

In the next 5-10 years, the SMA is poised to enable CfA scientists to investigate a wide range of astrophysical phenomena in new ways. An ambitious agenda of PI-driven projects will address important questions in all four of the CfA strategic science themes. Examples of projects within the themes include (1) testing hierarchical structure formation models through the resolved velocity fields of dark matter dominated dwarf galaxies; (2) characterizing cosmologically distant starburst galaxies and dusty quasars whose spectral peaks are redshifted into the

submillimeter, imaging cool dust and gas in nearby galaxies to understand how physical conditions affect local star formation activity, and revealing the motions of molecular gas around obscured active galactic nuclei; (3) probing the fundamental processes of star formation, including gravitational collapse of dense molecular cores, mass accretion through circumstellar disks, and bipolar outflows, exploring high mass star formation and the origin of the initial mass function, performing detailed studies of protoplanetary disks, perhaps resolving the inner holes long predicted to be signatures of giant planets in formation, making astrochemical assays to identify pre-biotic species, refining dynamical and chemical models of Solar System objects through line observations of atmospheric constituents and continuum observations that probe the deep atmospheres of giant planets and the surface layers of rocky bodies; (4) monitoring variability of black hole sources to probe their near environments, and playing an essential role in global VLBI imaging of the Galactic Center black hole region to reveal strong field general relativistic effects.

The keys to utilizing the SMA to advance the CfA strategic science goals in the next 5-10 years will be to maintain operations support and to implement the full design capabilities of the array. Ongoing initiatives include completing construction of receivers for dual polarization operation and for complete submillimeter wavelength coverage, and developing phase correction techniques such as water vapor radiometry (the submillimeter equivalent of adaptive optics) to increase the observing time available for the highest angular resolution. In addition, efforts are underway to incorporate the two large submillimeter single dish telescopes on Mauna Kea, the James Clerk Maxwell Telescope (JCMT) and the Caltech Submillimeter Observatory (CSO) into an "expanded SMA" (eSMA) that will double the collecting area and provide 50% higher angular resolution.

In the long term, the science drivers of increased continuum sensitivity to study weaker sources and larger samples, as well as faint spectral lines from high redshift objects and rare species, will demand significant increases in SMA bandwidth and electronic processing power. The modest size of the SMA allows for the adoption of new technologies. That flexibility, together with unique access to the northern sky, ensures that the SMA will maintain forefront submillimeter observational capabilities into the foreseeable future.

The Very Energetic Radiation Imaging Telescope Array System (VERITAS)

VERITAS is an array of four 12-meter aperture telescopes at a dark site in southern Arizona, with sophisticated fast cameras with 499 pixels, that uses the atmospheric Cherenkov imaging technique to detect cosmic gamma-rays with energy from 50 GeV to 50 TeV. It is a state-of-the-art facility that will do for the northern hemisphere what the High Energy Stereoscopic System (HESS) has done for the southern hemisphere. It uses proven techniques and an experienced group (VERITAS collaboration). The two telescopes that are currently in operation at Whipple Observatory Base Camp meet all design specifications; software for data analysis is completed and priorities for the science program have been agreed upon with help of the External Science Advisory Committee. It is expected that the collaboration (which currently numbers 70 faculty, postdocs and students) will be expanded to include new members when the operation phase begins. Pending resolution of a stop-work order at the Kitt Peak Horseshoe Canyon site by the NSF (in response to protests by the Tohono-O'odham Nation), the project has been given permission to temporarily locate the four-telescope array at the Whipple Observatory Base Camp for 2-3 years, starting in fall of 2006, while working on a permanent site either at Horseshoe Canyon or elsewhere.

Almost all major construction items have been completed; total cost (including R&D) about \$17.5M (\$7M from DOE, \$7M from NSF, \$2M from SAO/SI, \$0.5M from overseas); no further construction funding is required to complete the project. The operations cost is about 10% of the capital investment; a proposal has been submitted NSF/DOE/SAO detailing the operating costs. Staffing consists of two federal scientists, two postdocs, three graduate students plus

interactions with ten+ other CfA scientists (supernova, microquasar, GRBs, AGN, theorists, etc.) providing multiwavelength studies as project starts to produce science and unidentified sources. The science areas that VERITAS will study include; the early Universe, cosmology, the origin of cosmic rays, extreme conditions of space, matter and time, and the synergistic relationship with GLAST, which is set for launch in 2008.

The SAO gamma-ray group has played a lead role in the development of this technique and this project and currently is the managing organization. All U.S. VERITAS Project funds come via the local Whipple VERITAS Project Office, which supplies the spokesperson, project management, and local scientific direction. These roles would be expected to continue since SAO has pledged to support the operation of VERITAS (in partnership with DOE and NSF). As a founding member of VERITAS, the SAO group plays a dominant role in VERITAS science and operation. This is expected to continue. Observing time for the first two years at least will be assigned by the Time Allocation Committee, which will have representatives from all ten original member institutions. Members of all these groups will be entitled to authorship on all publications; in addition Associate membership (Guest Investigator status in other projects) will be available to those who wish to work on specific aspects of the observing program (it is expected that this is where many CfA scientists will choose to participate). There is no funding to support Guest Investigators and no obligation to assign time outside of the collaboration.

The Chandra X-ray Observatory (CXO)

The Chandra X-ray Observatory, which was launched on 23 July 1999, is the third of NASA's Great Observatories. The Chandra spacecraft carries a high-resolution mirror, two imaging detectors, and two sets of transmission gratings. Important Chandra features are: an order of magnitude improvement in spatial resolution over previous X-ray telescopes, good sensitivity from 0.1 to 10 keV, and the capability for high spectral resolution observations over most of this range. Chandra is in an elliptical high-earth orbit allowing uninterrupted observing intervals of more than 48 hours. Chandra represents a major step forward in X-ray observational capabilities and has made major new discoveries in many areas of astronomy, including finding X-ray jets in radio-loud quasars, finding pulsars – and the lack of them – in the middle of Supernova remnants, and detecting sharp and detailed structure in clusters of galaxies.

SAO is under contract from NASA's Marshall Space Flight Center to operate the Chandra X-ray Center (CXC), whose responsibilities include the scientific oversight of the Chandra instruments, interface with the astronomical community, and command, communications and maintenance of the Chandra spacecraft. CXC personnel are located at 60 Garden Street, at Cambridge Discovery Park, and at the Chandra Operations Control Center (OCC), close to Kendall Square, all in Cambridge. The CXC's scientific and Control Center staff perform all tasks associated with Chandra, including soliciting proposals and allocating observing time, planning observations, operating the observatory, calibrating the instruments, processing data and distributing it to observers, supporting Chandra users, designing, producing and distributing data analysis software, performing education and public outreach, archiving Chandra data and making it available to the scientific community, and doing scientific research. SAO also built and continues to support the High Resolution Camera (HRC), one of the two primary instruments on Chandra.

SAO subcontracts with several organizations to carry out the CXC's mission. CXC subcontractors include the Massachusetts Institute of Technology (CXC science support and Instrument Principal Investigator activities), Northrop Grumman Space Technologies (flight operations team), Northrop Grumman Mission Systems (systems engineering and software development), Computer Sciences Corporation (software and operations support), Pennsylvania State University (Instrument Principal Investigator activities), and Rutgers University and Tufts University (education and public outreach support).

A large number (>50) of CfA-based scientists are involved in Chandra science each year. An

average of about 25 out of ~200 total observing proposals with CfA Principal Investigators (PIs) are accepted during each annual observing cycle. Over the first seven Chandra observing cycles, 264 CfA-based scientists have been PIs or Co-Is funded by Chandra grants. In addition, CfA scientists are involved in Chandra science through unfunded use of data from the Chandra archive.

The Chandra X-ray Center is staffed by approximately 160 CfA employees, representing 157.3 full time equivalent (FTE) positions. A breakdown of SAO CXC staff is shown below. In addition, approximately 30 subcontractor staff work in SAO-supplied space at the OCC (flight operations team) and Cambridge Discovery Park (software developers).

	FY05 Full Time Equivalent (FTE) SAO Employees			
	Scientists	Programmers	Other Staff	Total
Operations Control Center	2.0		24.0	26.0
Chandra X-ray Center	42.5	23.0	65.8	131.3
Total CXC SAO Employees (FTE)	44.5	23.0	89.8	157.3

The total cost of developing, launching and operating Chandra is approximately \$2.6B, including approximately \$1.5B for development of the science instruments and spacecraft; \$0.2B for prelaunch science and operations development; \$0.3B for launch by the Space Shuttle; and \$0.6B for ten years of post-launch mission operations and data analysis. SAO is currently in the second five-year contract for operating the CXC. The first CXC contract had a contract value of \$289.2M, while the current contract has a value of \$373.2M. Both amounts include that value of subcontracts and of subgrants (monetary grants to scientists for Chandra-related scientific research).

Chandra science relates to all four strategic themes, providing fundamental, unique and complementary information to that at other wavelengths. Some examples are: searching for and tracing the evolution of active galaxies out to high redshift; resolving the Cosmic X-ray Background; studying the X-ray spectral properties of active galaxies, the profile of emission lines and source variability; investigating X-ray and multi-wavelength properties of jets; using clusters of galaxies to constrain cosmological constants and so seek to understand dark energy and dark matter; taking advantage of Chandra's exquisite spatial resolution to study the structure of clusters of galaxies and relate the x-ray structure to observations at other wavelengths in order to understand the structure and evolution of clusters; searching for the stellar remnants of supernovae, tracing the evolution of supernova outbursts, and so studying supernova structure and evolution; observing GRBs to identify and trace their light curves; studying the composition and structure of the X-ray emission from galaxies; and studying the detailed spectral properties of X-ray emitting stars of all types.

The Spitzer Space Telescope (Spitzer)

The Spitzer Space Telescope is the fourth and final element in NASA's Great Observatories program. Spitzer was launched on 25 August 2003 and is producing a significantly new view of the Universe at infrared wavelengths from its Earth-trailing solar orbit. It consists of an 85-cm telescope and three cryogenically cooled instruments capable of imaging from 3.6 to 160 microns wavelength and spectroscopy from 5 to 40 microns wavelength. Combining the intrinsic sensitivity achievable with a cryogenic telescope in space with the great imaging and spectroscopic power of modern detector arrays, Spitzer is proving the user community with huge gains in capability for exploration of the Universe at infrared wavelengths. The Observatory is performing as extremely well and the projected lifetime is in excess of 5 years. After the liquid helium is exhausted, the focal plane will still be cold enough such that two

cameras (3.6 and 4.5 microns) in Spitzer's Infrared Array Camera (IRAC) will continue to function with no expected change in sensitivity.

The Jet Propulsion Laboratory (JPL), Pasadena, CA, manages the Spitzer Space Telescope for NASA. The in-orbit operations of the telescope are located at JPL and Lockheed Martin Astronautics, Denver, CO. The Spitzer Science Center is located at the California Institute of Technology, Pasadena, CA. The Principal Investigator and the Project Office for IRAC are located at the Smithsonian Astrophysical Observatory, Cambridge, MA. The IRAC instrument was built by the NASA Goddard Space Flight Center, Greenbelt, MD. Before launch the IRAC Project Office, working with the IRAC Science Steering Committee, provided the management and science support, developmental infrared array detector procurement and testing, and mission operations planning and operations. The array detector development was carried out in collaboration with the University of Rochester and the NASA/Ames Research Center. The IRAC Project Office also provided the requirements and oversight for the NASA/GSFC IRAC Instrument Project Office, which had responsibility for instrument management, systems engineering, and instrument construction, integration, and testing. After launch the IRAC Project Office provides instrument and supporting mission operations to the JPL Project Office and the Spitzer Science Center.

The Spitzer Space Telescope cost \$670M through launch, and has a total lifetime cost of \$1.2B. The IRAC instrument cost \$47.7M through launch and receives approximately \$2M per year for operations after launch.

The IRAC group at CfA consists of two federal scientists, 16 trust scientists, and ten graduate students. More than 30 other CfA scientists (Optical and Infrared Astronomy, High-Energy Astrophysics, Radio and Geoastronomy, Solar and Stellar, and Theoretical Astrophysics Divisions) are actively involved in Spitzer observations. An extensive observational program using Spitzer Guaranteed Time Observations and General Observer time exists at CfA.

Spitzer science relates to all of the strategic themes. Examples are: understanding the earliest stages of galaxy formation and evolution; understanding how nearby galaxies formed and evolved; the origin of the infrared background radiation; the manufacturing and dispersal of the chemical elements throughout the Universe; understanding the later stages of stellar evolution: planetary nebulae, AGB stars, and supernovae; understanding stellar birth and evolution; the origin and evolution of brown dwarfs; the study of protoplanetary and debris disks around stars; the formation and evolution of planetary systems; and the direct study of transiting extra-solar planets; understanding the extreme conditions of space, matter and time; the nature of and evolution of compact objects: black holes, AGN, Ultraluminous Infrared Galaxies, quasars, etc.

New Projects:

The Giant Magellan Telescope (GMT)

The Giant Magellan Telescope (GMT) will be composed of seven 8.4-m mirrors, yielding a collecting area equivalent to a 21.4-m telescope, a large field (20' x 20'), and a diffraction limit equivalent of a filled aperture 24.5m telescope. The first off-axis mirror was cast successfully on 23 July 2005; processing began early 2006. The GMT Conceptual Design Review was held in February 2006, and was a major success. The proposed 20-25% CfA share of the GMT is currently estimated to cost roughly \$125-175M for construction and \$7-8M/yr for operations (including new instruments).

First light instruments for the GMT are included in the construction cost. These include optical and near-IR multiobject spectrographs, an optical high resolution spectrograph, a cryogenic near-IR echelle, a mid-IR AO imager and spectrograph, and a near-IR Extreme AO imager. The CfA is responsible for the design of the near-IR multiobject spectrograph. These instruments

will take advantage of the excellent image quality, stability, and field-of-view of the GMT. The AO systems are designed to take advantage of diffraction-limited performance at wavelengths of 1.6 mm and longer.

The GMT will enable stunning breakthroughs across all four major science themes. Deep imaging surveys will clarify the formation and evolution of the outer Solar System, the SMBH in nearby galaxies, and the evolution of supernovae with $z > 1$. Measurements of the IMF as a function of environment will provide the best tests of models for the formation of star clusters and provide an important baseline for the evolution of stellar populations in galaxies to $z = 1-3$. Multiobject spectroscopic surveys will delineate the structure and evolution of galaxies at $z = 3-5$ and detect AGN (and the first black holes) at $z = 10$. High resolution spectroscopic programs will discover thousands of extrasolar planets, measure the chemistry and growth of grains in circumstellar disks, identify the launching mechanisms of bipolar jets and outflows, and measure the evolution of metals at $z = 2-10$. Finally, the advanced adaptive optics system will enable the first direct detections of light from Earth-like planets, Jovian planets, and small structures in the terrestrial zones of disks around stars within 50-200 pc. We plan to leverage Harvard's investment in the Origins of Life in the Universe Initiative to play a leading role in GMT research.

Constellation-X (Con-X)

Con-X is one of the two flagship missions of NASA's Beyond Einstein program and is the next major X-ray mission planned worldwide. Con-X will consist of three or four co-aligned X-ray telescopes, housed in a single spacecraft, which will combine to produce an effective area at 6.4 keV (the Fe K line) that is 40 times larger than Chandra. It will bring X-ray spectroscopy to a new level of performance with resolution of $300 < R < 2000$ over the energy band 0.25 keV to 15 keV. Con-X will obtain unprecedented high resolution and high signal-to-noise spectra for sources as faint as 2×10^{-15} erg cm⁻² sec⁻¹ (0.25 – 2.0 keV), *i.e.*, every source in the ROSAT All Sky Survey.

Con-X is a jointly led by SAO and GSFC and is estimated at \$1.5 -1.6B in real year dollars through launch (2016/2017), and \$25M annually once in operation. The success of the Chandra X-ray Center places SAO in an excellent position to play a major role in the development and operation of Con-X. Current SAO involvement includes 6.7 FTE (3 scientists, 1.6 engineers, 2.2 managers). During the various mission phases, this will increase as follows: Phase A (FY07-10): 9.2; Phase B (FY11-13): 12.5; Phase C/D (FY13-17): 51.7; Phase E (FY17-22): 100 FTE/year.

Con-X science is very broad and far-reaching, covering all four science themes in this report. It will address fundamental questions such as: What happens at the edge of a Black Hole? What is the mysterious Dark Energy, which is pulling the Universe apart? Con-X science includes studies of active galaxies: we will be able to observe in detail quasars out at very high redshift to study the evolution of their spectral properties when the Universe was very young. Investigations of cosmic feedback, probing both quasars and star formation galaxies at high redshift will provide constraints on the growth of Black Holes over cosmic time and the relation to galaxy evolution and star formation. Cosmological studies include measuring distances to clusters of galaxies out to very high redshift along with their number and mass distributions to provide unprecedented constraints on cosmological parameters and thus on dark energy and dark matter. Observations of supernova remnants utilizing the spatial and spectral resolution of Con-X will enable determination of the composition, ionization state and velocity of SNR material and the building of a complete model for their structure. Studies of stars will examine the X-ray emission processes in the outer atmospheres of stars and access the effects of these X-rays on planet formation and evolution.

PanStarrs and Large Synoptic Survey Telescope (LSST)

Recognizing the power of combining a large collecting area, a wide field of view, and the growing capabilities of high throughput computing facilities, the most recent decadal survey of astronomy and astrophysics highly ranked the concept of a Large Synoptic Survey Telescope (LSST). Moving from astronomical photography into the regime of celestial cinematography, in which most of the accessible sky is scanned every few days, will provide unprecedented scientific opportunities that range from the solar system to cosmology.

Specific examples include 1) mapping out the expansion history of the Universe with thousands of type Ia supernovae, thereby probing the nature of dark energy, 2) detecting the optical transients that accompany extreme astrophysical events, 3) detecting lensed supernovae, probing the dark matter distribution in the lensing galaxy, and 4) mapping the orbits of Kuiper belt objects, obtaining important clues to the formation of the solar system, and 5) using co-added images, with photometric redshifts, to search for the weak lensing signature of the foreground mass distribution. These measurements each have a direct bearing on the science priorities laid out earlier in this document.

CfA astronomers are presently at the forefront of time domain astronomy, in both cosmological and planetary science. We intend to build upon this strength, and to leverage Harvard's investment in the Initiative for Innovative Computing (IIC), to play a leadership role in the ambitious projects that will open up this new era of ground-based astronomy. The CfA is a member of the LSST Corporation, which has embarked upon the construction of an 8.5 meter telescope that will be equipped with a camera that images 10 square degrees. CfA scientists are working in conjunction with detector and camera development, supported with DOE funding, housed in Harvard's Department of Physics. The LSST is currently scheduled for first light in 2013.

In the interim we have joined the PanStarrs-1 survey, which will address these same science goals with telescope systems of more modest aperture, but sooner. We are focusing on hardware and software developments that will benefit both PanStarrs and LSST, such as detector technology, precision calibration schemes, and database implementation. The initial PanStarrs system began operation in Fall 2006.

The data reduction of both PanStarrs and LSST images is challenging. These projects will generate tens of Terabytes of data per night. In order to capitalize on rapid transients, the variable sources must be detected and classified in near real time, and disseminated to the broader astronomical community. We intend to partner with the IIC as a pathbreaking campus project in high throughput computing, extending the benefits of our participation in these projects well beyond the domain of astronomy. We will also make use of our expertise in handling very large data sets, pipeline data processing and archives as exemplified in the Chandra X-ray Center Data Systems Division.

Mileura Widefield Array (MWA) and Square Kilometer Array (SKA)

The Mileura Wide-field Array(MWA)/Low Frequency Demonstrator (LFD) is a proposed high-redshift HI imaging array that will enable forefront study of the Epoch of Reionization ($z > 6.2$). At present the EOR represents an almost 1 billion year gap in the cosmological record. Few data are available to constrain theories of structure formation, which began during this time. The MWA/LFD is a first step in the anticipated progression of instruments leading to the low-frequency portion of the Square Kilometer Array, and early development at the CfA will enable substantive participation in later instruments.

The demonstrator is designed to test new hardware and software techniques with the possibility of detecting the power spectrum of HI brightness fluctuations at $z < 8$. Detection of discrete shells of warm HI that are anticipated to surround known quasars may also be possible. These are key science targets for the MWA/LFD. Secondary key science includes space weather and heliospheric imaging, and all-sky monitoring of transients, as from GRBs or extrasolar planets.

MWA/LFD key science is directly related to Themes 1, 2, 3, and 4. The CfA role in MWA/LFD construction is assembly of the critical high-speed data processing pipeline that will feed each of the back-end science packages. The CfA will also play a key role in analysis and interpretation of MWA/LFD data, leveraging the expertise of SSP members (*e.g.*, heliospheric shock modeling) and the unique concentration of intellectual and computing resources (through the ITC) that exists in the Theoretical Astrophysics Division. TA members have written many of the seminal papers about re-ionization. Because the CfA is a full partner in the MWA/LFD, CfA scientists working with members of the several declared science collaborations will have full access to MWA/LFD data.

An SAO federal scientist leads MWA/LFD work at the CfA. Several postdoctoral positions will be filled over the 4 years of the current funding profile. Additional positions may be obtained through collaboration with the Harvard IIC for work on high throughput computing and database tools, or through additional proposals to NSF via Harvard. Staffing beyond the first three to five years will depend on the success of the MWA/LFD. Three to five post-doctoral fellows per year will probably be required if there is expansion of the instrument to achieve higher sensitivities.

The MWA/LFD together with the European LOFAR are the first in a progression leading ultimately to the low frequency portion of the SKA (2020). Five SKA key science projects have been defined internationally, including structure during the Dark Ages and Epoch of Re-ionization. If successful, the MWA/LFD program will enable construction and operation of larger, more capable instruments. The initial configuration comprises 1% of a square kilometer. Expansion to 10% is hoped for early in the next decade. CfA work on the MWA/LFD programs will enable strong participation in the later instruments, and the magnitude of effort may be expected to increase by factors of at least a few with each bump in array size. The importance of studying high redshift HI is plain, and competition among institutions to join efforts worldwide will be fierce. Present investments of resources by the CfA have established an early presence. Sustained leadership and participation will require re-investment of institutional resources from time to time, in support of radio astronomical technique development and associated computing.

The MWA/LFD is a \$10M collaboration between MIT/Haystack, CfA, a consortium of Australian universities led by U. Melbourne, ANU, ATNF, and the Western Australian Government. The US share requested from the NSF is \$4.9M over four years (split between the AST, ATM and multidisciplinary sciences divisions), with a supplement of \$0.3M by the Air Force Office of Sponsored Research. Partnership requires investment of institutional resources. The CfA investment will be \$610k, and the CfA share of the NSF grant will be \$595k.

Centers at the CfA

On-Going Projects:

The Institute for Theoretical Atomic, Molecular and Optical Physics (ITAMP)

The Institute for Theoretical Atomic, Molecular and Optical Physics (ITAMP) is located both at the CfA and the Harvard Physics Department. It was created in 1988 to support the theoretical AMO Physics community and to stimulate research in theoretical AMO Physics. ITAMP carries out its mission through a variety of programs, including the education of postdoctoral fellows and students, organizing and hosting workshops on forefront topics in AMO Physics and related fields, and hosting visiting scientists and scholars from around the world. ITAMP is funded by the National Science Foundation (approximately \$750 K per year). There are seven staff scientists (including two in the Harvard Physics Department), approximately five to seven postdoctoral fellows, and an ITAMP Office Administrator.

Although many of the forefront areas of Atomic, Molecular, and Optical Physics research at present include topics which are not relevant to astrophysics, ITAMP has continued to promote theoretical atomic and molecular astrophysics through the research of its staff, the organization of workshops, and the support of visitors and postdocs who work in this area. Recent workshops on astrophysical topics include: "EUV and X-Ray Emission from Comets, Planets and Heliospheric Gas" (January, 2003); "X-Ray Diagnostics for Astrophysical Plasmas" (November, 2004); "Collisional Calculations and Non-LTE Modeling of Molecular Hydrogen in Astrophysical Environments" (June, 2005).

Because of the exciting intellectual environment at ITAMP and the success of former ITAMP postdocs at securing research and teaching positions in physics, the competition for an ITAMP postdoctoral appointment is very stiff. Leading scientists from all over the world have come to the CfA to take part in ITAMP programs. ITAMP has fostered strong intellectual ties with the Harvard Physics and Chemistry Departments, especially with the NSF-funded Center for Ultracold Atoms (at Harvard and MIT), as, well as with the Physics Department at the University of Connecticut.

The Institute for Theory and Computation (ITC)

The Institute for Theory and Computation (ITC) is a CfA center of excellence in theoretical astrophysics that integrates conceptual theory and computational modeling. Its annual operational cost ranges between \$600k (existing, Harvard funds only) and \$1.4M (desired). The budget supports postdocs, staff, an extensive program for short-term visitors, and computer hardware. The people involved include 12 senior scientists, 16 postdocs, and 15-20 theory students. While there are other institutions in North America that host focused efforts in theoretical astrophysics (e.g., CITA, IAS, and KITP), at the moment none blend theory and computation in the same way.

The ITC is intended to be a long-term fixture at the CfA. Existing support will be subject to an external review after five years from its start in 2003. The establishment of a long-term ITC would entail the need for other CfA resources, such as office space.

The presence of the ITC at the CfA provides numerous benefits to the scientific environment here, aside from the immediate boost to theoretical and computational astrophysics. The postdoctoral fellows are exposed to a stimulating environment where they have the opportunity to interact and work with leading authorities in theory and computation. For a sufficiently large program, the ITC will comprise a critical mass of expertise among the postdocs, meaning that their own interactions will spark new developments in their fields of research. The concentrated, high profile nature of the ITC will greatly enhance postdoc training, especially since the reputations of Harvard and the CfA will enable us to draw from among the best available people.

The existence of the ITC promotes interdisciplinary interactions with other departments at Harvard University, especially between Astronomy and Physics and/or between Astronomy and Earth and Planetary Sciences. It also promotes interactions with the CfA science divisions, e.g., OIR scientists are using Spitzer observations in synergy with ITC cosmological simulations of galaxy evolution.

New Projects:

The Center for X-ray Technology (CXT)

The Center for X-ray Technology is an SAO initiative within the HEA Division that was originally proposed in the late 1990s in order to re-invigorate the development of new techniques for X-ray observations. In 2002, the CXT was formally announced by then Director Shapiro, but

remains essentially unfunded.

The CXT goals are to provide a focus for the efforts of individual scientists working on optics, sensors, or future facility or mission concepts, primarily (but not exclusively) related to X-ray astronomy. The long term vision is for the CXT to have a base of funding that could support about 15 FTEs consisting of a mix of staff scientists, postdocs, graduate and undergraduate students, engineers and technicians. Also included are funds for equipment, supplies and materials, etc. Overall, an operating budget of \$2-3M/year is needed to reach this level. To obtain this funding, the CXT "business plan" is to have a mix of core funding in the Federal base, contract and grant funding from NASA, NSF, etc., and private funds through endowments, foundations and gifts.

Thus far the CXT has been able to enlist science time from people at CfA. Some are federal scientists, some are fully supported on a science center contract who are allowed independent research time that can be for CXT activities, and some have a variety of contracts and grants that involve CXT related activities. Using SAO IR&D/REF funding for equipment, materials, and limited engineering support, several projects have been started - these include Active Pixel Sensors (a follow up to X-ray CCDs), Active X-ray Optics (examining how to modify an X-ray optic in a controlled manner), High Energy Reflectivity (how to improve X-ray reflectivity above about 10 keV, to make hard X-ray optics), Magnetic MicroCalorimeter X-ray Absorber (how to make arrays of Bi absorbers to be used with mag-cal readouts), Slumped X-ray Optics (how to make light weight optics by slumping thin glass on a figured mandrel), and High Speed Optical Imaging Detectors (how to monitor 1000's of stars for occultations by small bodies in order to carry out a census of the Kuiper Belt and Oort cloud).

In the CXT model, long term goals are identified, for example the need for a higher angular resolution, larger area successor to Chandra. To address this goal, several technologies are selected that work on different scales of approximation to making an ideal optic. Slumping may achieve a 5 arc second figure, selective deposition could improve this performance to 1 arc second, and finally active control could tune mirrors to the desired 0.1 arc second level. Each technology has an identified PI responsible for the work. The CXT provides some common infrastructure - lab space (currently the HRC lab), tools, equipment (e.g., our optical interferometer metrology station), and management oversight. For each technology, the first goal is to understand the basic physical processes governing performance rather than trying to meet a specific specification. This approach emphasizes a strategic approach to technology rather than a more immediate tactical approach. Initial studies are designed to see what can be accomplished and find out where the technology is heading.

Potential applications include instruments for new missions that span all time frames. For example Active Pixel Sensors could be used for Con-X's grating readout, or in the focal plane of a possible X-ray Cluster Survey Mission in support of dark energy studies. The Active Optics are targeted to more distant missions such as Generation-X which is a NASA Vision Mission slated for the 2025 and beyond time frame.

The CXT is included in the SI Science Strategic Plan, with a five year goal (starting last year) of being fully staffed and funded. So far there has been no direct funding for CXT from SI itself, although an augmentation request was presented to SI as part of the SI Science Strategy (\$500K in year 1, \$1M in year 2, and finally a steady state of \$1.5M starting in year 3). However, SI has been working with SAO's Development Office to help obtain private funds. SAO's Advancement Office has been pursuing support for an CXT Postdoc from the aerospace industry, and has been helping with potential donors. The CXT will submit a NASA SR&T proposal for Active Pixel Sensors. CXT will also submit a work task for slumped X-ray optics as part of the Con-X technology development effort at SAO.

Acronyms:

21CMA – 21 Centimeter Array
ALMA – Atacama Large Millimeter Array
APEX – Atacama Pathfinder Experiment
ASCE – Advanced Solar Coronagraph Explorer
BHFP – Black Hole Finder Probe
CANGAROO – Collaboration of Australia and Nippon for a Gamma-Ray Observatory in the Outback
CARMA – Combined Array for Research in Millimeter-wave Astronomy
Chandra – Chandra X-ray Observatory
CIP – Cosmic Inflation Probe
CMB – Cosmic Microwave Background
Con-X – Constellation-X
CSO – Caltech Submillimeter Observatory
CXT – Center for X-ray Technology
DEP – Dark Energy Probe
EOR – Epoch of Reionization
EUSO – Extreme Universe Space Observatory
EXIST – Energetic X-ray Imaging Survey Telescope
Gen-X Generation-X
GLAST – Gamma Ray Large Area Space Telescope
GMT – Giant Magellan Telescope
GRB – Gamma Ray Burst
HESS – High-Energy Stereoscopic System
IGM – Intergalactic Medium
IIC – Initiative for Innovative Computing
IMF – Initial Mass Function
ISM – Interstellar Medium
ITAMP – Institute for Theoretical Atomic, Molecular, and Optical Physics
ITC – Institute for Theory and Computation
JCMT – James Clarke Maxwell Telescope
JWST – James Webb Space Telescope
KEPLER – Kepler Mission
LBT – Large Binocular Telescope
LFD – Low Frequency Demonstrator
LMT – Large Millimeter Telescope
LOFAR – Low Frequency Array
LSST – Large Synoptic Survey Telescope
LWA – Long Wavelength Array
MMT- Multiple Mirror Telescope
MWA – Mileura Widefield Array
QCD – Quantum Chromodynamics
QPOs – Quasi-Periodic Oscillations
RXTE – Rossi X-ray Timing Explorer
SAFIR – Single Aperture Far Infrared Observatory
SDO – Solar Dynamics Observatory
SMA – Submillimeter Array
SMBH – Supermassive Black Holes
SKA – Square Kilometer Array
SOFIA – Stratospheric Observatory for Infrared Astronomy
SOHO – Solar and Heliospheric Observatory
Spitzer – Spitzer Space Telescope

SPT – South Pole Telescope

VERITAS – Very Energetic Radiation Imaging Telescope Array System

VLA – Very Large Array

VLBA – Very Long Baseline Array

VLT – Very Large Telescope