MIT Kavli Institute for Astrophysics and Space Research

With the receipt of a generous gift from the Kavli Foundation, MIT's Center for Space Research has been renamed the MIT Kavli Institute (MKI) for Astrophysics and Space Research. The MKI is one of 10 centers around the world established by the Kavli Foundation for the study of astrophysics, nanoscience, and neuroscience. Income from the Kavli gift and other gifts is being used to support technology development and the research activities of MKI. The inaugural Kavli research program, described further below, seeks to improve our understanding of the mysterious dark matter and dark energy that are the dominant constituents of our universe.

MKI conducts research in physics, astrophysics, space science, detector engineering, and related technology and participates in National Aeronautics and Space Administration (NASA) flight missions. Specific areas of research include extragalactic astronomy and cosmology, galactic astronomy, gravitational physics, the solar system and space plasma physics, and the space life sciences. Research conducted in MKI is reported by the departments of Physics; Earth, Atmospheric, and Planetary Sciences; Aeronautics and Astronautics; Civil and Environmental Engineering; and Mechanical Engineering, as well as by the Harvard-MIT Division of Health Sciences and Technology. MKI is the home of the Astrophysics Division of the Physics Department, supporting faculty, postdocs, and students. Students actively participate in research; in the past year, 42 graduate students and 28 undergraduate students from four departments and from Wellesley College worked on projects at MKI.

MKI supports MIT involvement in three major observatories: the Magellan Observatory (Professor Schechter, MIT director); the Laser Interferometric Gravitational-Wave Observatory (LIGO, Dr. Shoemaker, MIT director); and the Chandra X-Ray Observatory (Professor Canizares, associate director). The Magellan Consortium operates two 6.5-meter diameter optical telescopes in Chile. The LIGO Laboratory, a collaboration of Caltech and MIT, is engaged in developing and commissioning gravitational-wave telescopes. Recent improvements have made the LIGO instruments the most sensitive gravitational-wave detectors to date. The Chandra satellite was launched as a major NASA mission in 1999 and continues to be extremely productive. Two of the four Chandra scientific instruments were built at MKI: the High-Energy Transmission Grating Spectrometer and ACIS, a Charge-Coupled Device (CCD) imaging spectrometer. MKI is also active in the Chandra X-Ray Observatory Science Center.

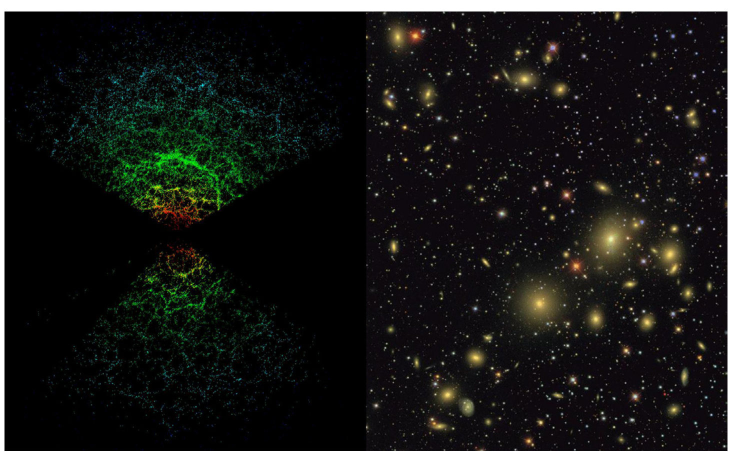
In addition to the major observatories, MKI is involved in several more focused space missions. The Suzaku (formerly Astro-E2) X-ray astronomy mission (Dr. Bautz, MIT principal investigator) was successfully launched by the Japan Aerospace Exploration Agency in July 2005. Commissioning of the instruments, including MIT's X-ray Imaging Spectrometer, is under way. The HETE-2 mission (Dr. Ricker, principal investigator), built and operated at MIT with US and international collaborators, was launched in 2000 and is dedicated to the detection and prompt localization of sources of gamma-ray bursts. The Rossi X-ray Timing Explorer (RXTE: Dr. Levine, MIT principal investigator) has entered its 10th year of successful operation. MKI operates the All-Sky Monitor instrument, which continuously surveys the sky for new sources and finds interesting targets for other observatories. Under development in collaboration with Boston University are the CRaTER instrument, slated for NASA's Lunar Reconnaissance Observatory, and PICTURE, a sounding rocket mission also to be launched by NASA. CRaTER is designed to characterize the lunar radiation environment for assessing its effects on human tissue and for testing models of acceleration processes in the solar wind. The goal of PICTURE is to exploit the high resolution of optical interferometry above the Earth's atmosphere to image an extrasolar planet.

Research in MKI's Space Nanotechnology Laboratory (SNL, Dr. Schattenburg, director) seeks to apply micro- and nanofabrication technology to achieve dramatic improvements in lightweight, high-resolution optical components. Recent efforts focus on developing a new optical system for the lab's unique Nanoruler grating-patterning tool that will enable writing variable period gratings. This work is targeted toward future NASA X-ray missions. The SNL was recently awarded a NSF Nanoscale Interdisciplinary Research Team grant to seek ways of applying high-accuracy diffraction gratings to problems of nanoscale metrology.

Research Highlights

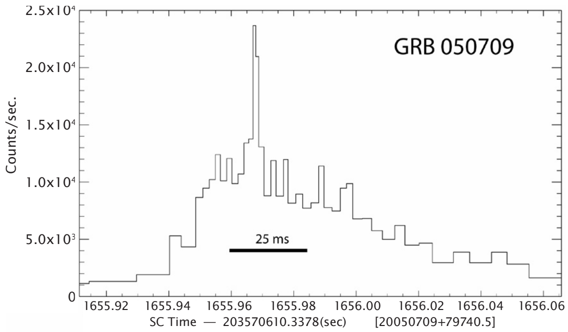
Extragalactic Astronomy and Cosmology

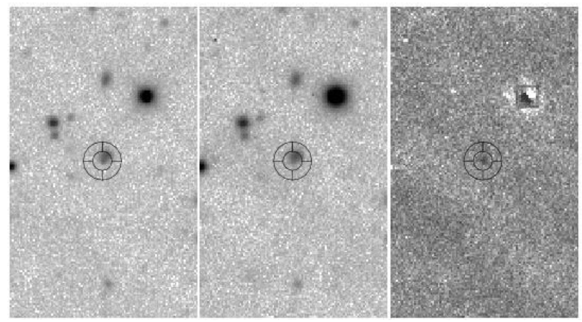
MKI's first Kavli research program is focused on studies of dark matter and dark energy in the context of the evolution of the universe and our understanding of the structure of matter and spacetime. The Sloan Digital Sky Survey has been used to create the largest three-dimensional map of the universe to date. A paper describing its use in the measurement of cosmological parameters, including the density of dark energy, was the most cited paper in 2004 in all areas of physics. Other studies of dark matter have investigated the decoupling of the dark matter in the early universe and the substructure of the dark matter in clusters at the present time. A new calculation of inflationary perturbations and their quantum to classical transition has been made that drops the usual slow-roll approximation.



On the right is an image from the Sloan Digital Sky Survey that shows a field of galaxies detected in the survey. Galaxies discovered in images such as this are examined spectroscopically to determine their redshift and hence their distance. From this information, a three-dimensional map of the galaxy distribution can be derived. On the left is a slice of the universe that shows the distribution of 67,000 galaxies. Each galaxy is shown as a single point with the color representing luminosity. Using data on 205,000 galaxies, Professor Max Tegmark and colleagues derived the power spectrum of matter in the universe. Different cosmological models predict different power spectra. Tegmark's work shows that a model that includes dark energy and dark matter is required to produce the spectrum observed. (Credit: Professor Max Tegmark, MKI)

The HETE satellite localization of a short, hard gamma-ray burst, combined with optical and radio follow-up measurements, have resulted in the first secure determination of the source of this type of burst. The energy scale established by these measurements and the identification of the galaxy host as an old elliptical galaxy support the picture that these bursts are caused by the inspiral of a pair of neutron stars. Information on neutron-star inspiral rates has important implications for predictions of gravitational-wave sources. In a related area, the study of core-collapse supernovae, both as gamma-ray bursts and as X-ray sources, is continuing.





Left: X-ray light curve for the short-hard gamma ray burst GRB050709 discovered by the HETE satellite on July 9, 2005. Features as brief as ~3 msec are detected in the 6-400 keV X-ray emission. (Credit: Dr. George Ricker, MKI). Right: Optical afterglow detected from GRB050709. The bull's-eyes in the three panels indicate the following: left panel, afterglow 1.4 days after the burst; center panel, afterglow 2.4 days after the burst; right panel, image subtraction of left and center panels. The residual image in the right panel indicates that the afterglow has faded, confirming the discovery. (Credit: J. Hjorth and the Danish 1.5 m telescope)

Chandra spectroscopy has provided the first convincing evidence that most of the baryons in the present-day universe are in the form of a heated gas, possibly solving the "missing baryons" problem in cosmology. Chandra X-ray observations of galaxy clusters have been combined with microwave-decrement measurements to constrain the three-dimensional shape of these objects, providing information on cosmic structure formation. Comparison of Chandra X-ray and weak-lensing mass estimates shows that X-ray measurements of clusters can yield accurate masses even when the clusters are not relaxed. This result suggests that an X-ray survey of clusters could provide useful constraints on the properties of dark energy.

Galactic Astronomy

Investigations into the nature of black holes, neutron stars, and related objects continue with emphasis on exploration of the detailed properties of such objects in binary systems in the galaxy. The high time resolution of the RXTE satellite was used to establish a link between the well-known quasiperiodic oscillations in suspected black hole binary systems and the existence of iron lines broadened by kinematic and gravitational effects. These measurements support the interpretation that infalling matter is forming an accretion disk with properties that are characteristic of the environment immediately surrounding a black hole. Other recent experimental work has focused on new sensitive techniques to unveil basic properties of binary systems, such as orbital periods and pulsations. The past year notably saw the orbital properties of one system revealed through absorption by a stellar wind. The hot-spot model for quasi-periodic oscillations of accretion disks in black hole binary systems has been extended to provide tentative explanations for some of the timing phenomena of these systems. Chandra observations have revealed a remarkable overabundance of transient X-ray binaries in the central parsec of our galaxy, providing evidence that tens of thousands of stellar-mass black holes and neutron stars may be swarming about our galaxy's central supermassive black hole.

Chandra spectroscopic measurements have solved the "solar model problem" by showing that the abundance of neon in sunlike stars is larger than previously thought, removing a troubling discrepancy between models and inferences of the depth of the convective layer. Searches for gravitationally redshifted lines from the atmospheres of neutron stars are under way, a probe of the stars' compactness. Detailed spatially resolved spectroscopic measurement done by Chandra of supernova remnants is unraveling the dynamics of these systems and testing long-standing theories concerning the mechanisms responsible for accelerating particles to high energies. Studies of the interstellar medium combined with new atomic cross-section models have yielded an unprecedented understanding of the abundance and ionization states of oxygen.

Gravitational Physics

Data from LIGO have been analyzed for gravitational waves from a variety of astrophysical sources, including compact binary coalescences, periodic sources, impulsive sources, and a stochastic background. A directed search for waves from gamma ray bursts was also undertaken. No gravitational waves have yet been detected, but the first papers reporting upper limits have been published. Complementing the ground-based LIGO detectors, a space-based interferometric gravitational-wave mission (LISA) is being planned by NASA for launch early in the next decade. Extensive theoretical studies predicting the properties of gravitational-wave sources detectable by LISA are under way. Results are promising for the mergers of black holes at the centers of galaxies and for the inspiral of stars into these black holes. Detailed study of the waveforms of these objects will test general relativity and reveal the evolution of supermassive black holes at the centers of galaxies.

The Solar System and Space Plasma Physics

A rare alignment of Pluto's moon Charon with a background star was captured by a number of telescopes, including one of MIT's Magellan telescopes. The dimming and brightening of the starlight by Charon was recorded in high-speed photometric measurements that will be used to determine whether Charon has an atmosphere. In continuing studies of the giant planets, simultaneous observations have been made of the X-ray, ultraviolet, and radio flux from Jupiter and Saturn, constraining models of their magnetospheres and their interaction with the solar wind.

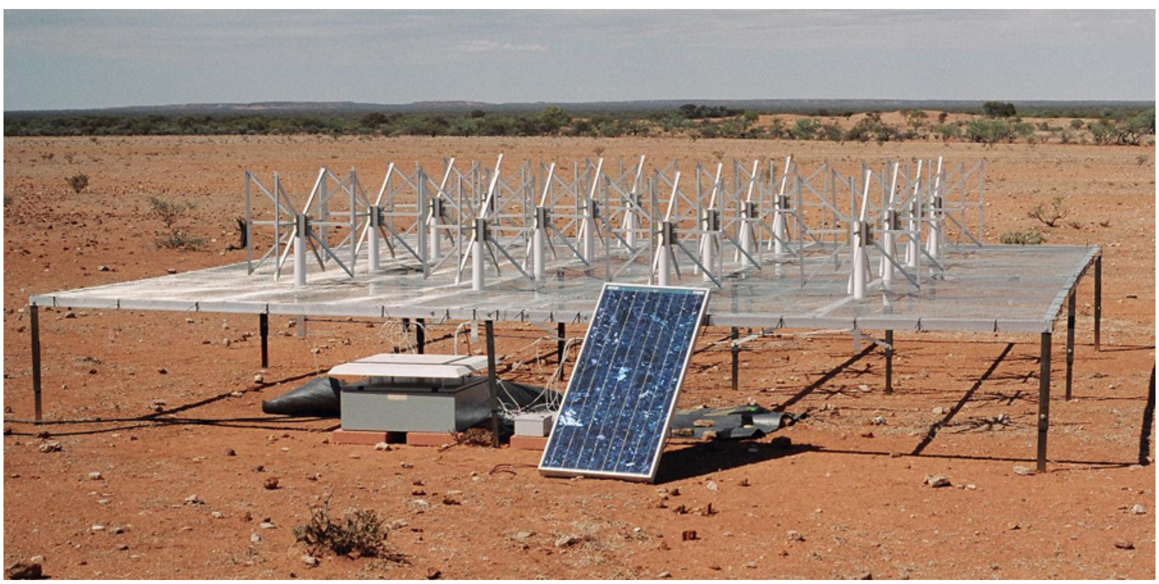
MKI scientists study plasma in the solar wind using instruments on three spacecraft: IMP 8, WIND, and Voyager II. In December 2004, the Voyager I spacecraft entered the solar system's final frontier, a vast turbulent expanse where the sun's influence ends as the solar wind crashes into the thin interstellar plasma. Future measurements by this spacecraft and by Voyager II will, remarkably, provide an in situ probe of the shocked interstellar medium. An innovative theory of complexity in space plasmas in the Earth's magnetosphere and ionosphere, the solar corona, and the solar wind has been developed using the concepts of forced and self-organized criticality, topological phase transitions, and multifractal measures.

Human Space Flight

The Man Vehicle Laboratory continues active ground-based research programs on artificial gravity, disorientation countermeasures, and the study of locomotion in partial gravity. Research on concepts for advanced space suits continues with the development of several technology prototypes for producing mechanical counterpressure. Physiological tests are being conducted to determine suitability for use in planetary surface exploration space suits. Investigations of visuomotor and orientation functions in astronauts on the International Space Station are planned.

Instrumentation for the Future

Looking toward future missions, high performance X-ray sensors are being investigated in collaboration with MIT's Lincoln Laboratory. Event-driven CCD's are under development for NASA's Constellation X mission and promise to reduce greatly the power requirements for future astronomical X-ray CCD cameras. In another development with astronomical applications, single X-ray photon counting by a complementary metal-oxide semiconductor active pixel sensor has been demonstrated at room temperature. A new program directed toward the use of X-ray sensors for celestial navigation has been initiated. Two new spectrometers and an adaptive optics system for the Magellan telescopes are under development. With Haystack Observatory, work



One of three test antenna "tiles" at Mileura Station in Western Australia. Built at Haystack Observatory, these tiles are being tested in the field in preparation for the construction of an array of 500 elements. Each tile consists of 16 crossed-dipole, low-frequency antennas, connected together electronically to form a single unit. The operating frequency range is 80–300 megahertz. The Mileura Widefield Array has as one of its goals the detection of the neutral hydrogen gas that is believed to have existed in the universe before the formation of stars and galaxies. Mapping this primordial hydrogen will give us important information about the process of structure formation and about the initial conditions of fluctuations established during the inflationary epoch of the early universe. (Credit: Dr. Brian Corey, Haystack Observatory) continues on the development of a large low-frequency radio array, with the design being optimized for cosmological studies. The design and development of the next-generation Advanced LIGO detector is continuing; it received National Science Board approval this year and appears in the president's budget for 2008 funding. The timetable calls for starting the installation of the new detectors in 2010. Studies for future NASA gravitational wave missions are under way, including LISA and the Big Bang Observer. Research continues on sub-quantum-limited interferometric detectors that make use of squeezed states of light or vacuum.

Education and Public Outreach

The MKI Education and Public Outreach Office (Dr. K. Flanagan, director) has built on existing partnerships with community-based organizations in Boston to provide new opportunities for science learning to underserved communities. To this end, a new program was developed to train professionals in the use of the Chandra After School Astronomy Project curriculum and make the program available at many sites. A development based on previously successful summer programs, the new Chandra Astrophysics Institute makes use of the MIT Technology Enabled Active Learning studio to stimulate in-depth learning in astrophysics and data analysis for students from underrepresented groups and their teachers. As in previous years, MKI hosted high school students participating in the Research Science Institute program at MIT.

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More information about the MIT Kavli Institute for Astrophysics and Space Research can be found online at http://space.mit.edu/.