# MIT Kavli Institute for Astrophysics and Space Research

The MIT Kavli Institute for Astrophysics and Space Research (MKI) conducts research in physics, astrophysics, space science, detector engineering, and related technology. This research is carried out in part through participation in National Aeronautics and Space Administration (NASA) flight missions and in National Science Foundation (NSF) Major Research Equipment and Facilities Construction activities. Specific areas of research include extragalactic astronomy and cosmology, galactic astronomy, gravitational physics, extrasolar planets, the solar system, and space plasma physics. The Departments of Physics; Earth, Atmospheric, and Planetary Sciences; Aeronautics and Astronautics; and Mechanical Engineering report research conducted in MKI. 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, 46 graduate students and 34 undergraduate students from four departments worked on projects at MKI.

MKI supports MIT involvement in three major observatories: the Magellan Observatory (Professor Paul Schechter, MIT director), the Laser Interferometric Gravitational Wave Observatory (LIGO; Dr. David Shoemaker, MIT director), and the Chandra X-ray Observatory (Professor Claude Canizares, associate director). The Magellan Consortium operates two 6.5-meter optical telescopes in Chile. The LIGO Laboratory, a collaboration of Caltech and MIT, is engaged in developing and operating gravitational wave telescopes. The LIGO instruments are completing one year of observation in the most sensitive direct search for gravitational wave signals 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. Marshall Bautz, MIT principal investigator) was successfully launched by the Japan Aerospace Exploration Agency in July 2005. MIT's X-ray Imaging Spectrometer (XIS) aboard Suzaku completed its second year of successful operation. The XIS continued to perform very well thanks to the unique radiation-tolerant properties of its CCD detectors, developed at MKI and Lincoln Laboratory. The Rossi X-ray Timing Explorer (RXTE; Dr. Alan Levine, MIT principal investigator) has entered its 12th 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 Orbiter, 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 Earth's atmosphere to image an extrasolar planet.

Research in MKI's Space Nanotechnology Laboratory (SNL), Dr. Mark Schattenburg, director, seeks to apply micro- and nanofabrication technology to achieve dramatic improvements in lightweight high-resolution optical components. The advanced X-ray optics and diffraction gratings developed by the lab are targeted toward future NASA space missions; SNL also has NSF support to seek solutions to problems of nanoscale metrology. During the past year, the lab invented and tested a new type of X-ray transmission grating called the critical-angle transmission grating. This breakthrough design allows much higher diffraction efficiency than previous technology, which should find utility in astronomy and in atom and neutron beam interferometry.

## Research Highlights

### Extragalactic Astronomy and Cosmology

MKI's first Kavli research program (supported by a gift from the Kavli Foundation and led by Professor Edmund Bertschinger) 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 space-time. Dark energy may be either a novel substance filling space (e.g., a cosmological constant) or it may indicate that Einstein's theory of general relativity needs revision. MKI has received funding from NASA to develop large X-ray calorimeter arrays. Such arrays will make possible X-ray surveys of clusters of galaxies that will probe the properties of dark energy. Research on dark matter in the early universe indicates that our galaxy may be filled with numerous clouds of dark matter weighing less than the earth but having a size larger than the solar system. Despite their low density, such clouds might be detectable through particles produced by dark matter annihilation. Searches for dark matter are now being pursued with the development of new detectors sensitive to nuclear recoils. A prototype gas-phase detector has been constructed that records information on the direction of motion of the dark matter particles, an important discriminant against backgrounds and a tool for studying dark matter phase space structure. Work also proceeds with the cryogenic dark matter search collaboration on the design, construction, and testing of silicon detectors with superconducting transition-edge sensors.

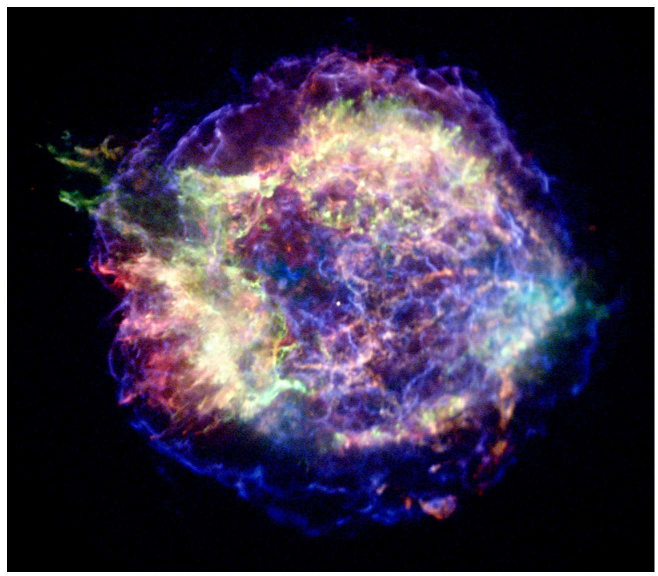
Gravitational lensing, a phenomenon in which gravitating matter alters the propagation of light, is an important tool for studying dark matter and gravitation. Through studies of quadruply lensed quasars the microarcsecond structure of quasar accretion disks, as well as the dark matter fraction in lensing elliptical galaxies, has been probed. Comparison of the measured Einstein radii of lensed galaxies with the directly measured dispersion velocity of the stars in the lensing elliptical galaxies has yielded constraints—for the first time on galaxy scales—on the post-Newtonian parameter gamma, thereby testing general relativity. Finally, the smoothness of the dark matter distribution in clusters of galaxies is being investigated with the Hubble Space Telescope through studies of giant lensed arcs.

In collaboration with MIT's Haystack Observatory and the Harvard-Smithsonian Center for Astrophysics, MKI has received NSF funding to build a low-frequency radio array in western Australia. By mapping radio emission from neutral hydrogen that existed in the universe before and during the time when the first stars and galaxies formed, this array will elucidate the process of structure formation mediated by dark matter. Deployment of the first antennas in western Australia is planned for fall 2007.

## Galactic Astronomy

Astrophysical jets, jets of relativistic particles emerging in a narrowly collimated beam, are a common but poorly understood phenomenon. It has long been believed that they are associated with black holes and that the black hole phenomenon is somehow responsible for the particle acceleration and collimation. Using data acquired with the Chandra X-ray Observatory, a jet was discovered in the Circinus X-1 binary system that consists of a neutron star, not a black hole, in orbit with a more ordinary star. This discovery calls for a reexamination of theories of jet formation.

The Chandra X-ray telescope was also used to obtain an extremely deep exposure of the Cassiopeia A supernova remnant, the youngest supernova remnant in our galaxy. The high quality of the data made possible a detailed spectroscopic analysis that identified electrons that have been highly accelerated by interaction with shock waves in the system. The data support long-standing but untested theories of the mechanism of cosmic ray acceleration.



*A deep exposure of the Cassiopeia A supernova remnant acquired with the Chandra X-ray telescope. The different colors correspond to X-ray photons of different energies. X-ray spectroscopy makes possible the reconstruction of the energy spectrum of the electrons accelerated in the supernova remnant. Credit: M.D. Stage, G.E. Allen, J.C. Houck, J.E. Davis.*

The physics of galactic X-ray sources comprising neutron stars and black holes in binary systems continues to be a major focus of the RXTE satellite. A long-term pulse-timing study has revealed another system with a wide yet circular orbit that is hard to understand in the conventional picture that predicts that the supernova that made the neutron star would also have left the system with an eccentric orbit. In another study, spectra obtained from RXTE observations of X-ray transients containing accreting neutron stars were used to propose a resolution of a decades-old problem concerning empirical models of X-ray source spectra. Only one type of model yields results that are consistent with predictions of accretion disk theory. In addition, the characteristics of the accretion boundary layer on the neutron star surface, as inferred from the successful model, can be interpreted to suggest that the surfaces of neutron stars lie within the radius of the innermost stable circular orbit predicted by general relativity.

A multiwavelength campaign utilizing many of the world's largest telescopes, including the Chandra X-ray Observatory, was organized by MKI researchers to study the physical properties of and the mechanisms by which flares are formed by the supermassive black hole at the center of our galaxy. This campaign was the centerpiece of the PBS/Nova television program "Monster of the Milky Way."

### Extrasolar Planets

A new program in the study of extrasolar planets has been established at MKI. It focuses on planets that pass in front of their parent stars and produce eclipses. Studies of eclipses allow much to be learned about the planets, including their size, their composition, and the temperature and composition of their atmospheres.

Of general interest is learning whether planetary systems like our solar system are common or unusual. For example, a striking pattern in the solar system is the close alignment between the rotation axis of the Sun and the orbital axes of the planets. Presumably this close alignment exists because the Sun and planets condensed from a single spinning disk. This year, MKI scientists made the most accurate measurement yet of the spin-orbit alignment for a planetary system around another star, finding it to be aligned within two degrees.

### Gravitational Physics

The LIGO gravitational wave detectors are now observing at a level of sensitivity exceeding their design goal and have nearly completed their planned integrated year-long main observation run with these instruments. While no gravitational waves have been detected, the search continues with unprecedented sensitivity and with collaborative measurements from other gravitational wave observatories around the world. Enhancements to the instruments have been designed and are in fabrication, with installation to start in fall 2007. Advanced LIGO, with MKI scientists in the leader and chief scientist roles, is in the president's and the NSF budget for a FY2008 start, with the MIT testbed for full-scale prototypes fully occupied with integration and characterization.

Complementing the ground-based LIGO detectors, a space-based interferometric gravitational wave mission (LISA) is being planned by NASA. Extensive theoretical studies predicting the properties of gravitational-wave sources detectable by LISA are under way.

## The Solar System and Space Plasma Physics

MKI scientists study plasma in the solar wind using instruments on three spacecraft: IMP 8, WIND, and Voyager II. Studies using WIND have found that helium may act as a throttle for the solar wind, setting its minimum speed. 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. Voyager II is expected to cross the same region by the end of 2007. MKI has recently joined the science operations of the Interstellar Boundary Explorer project, a mission to study the boundary between the local interstellar medium and the solar wind.

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. Theoretical techniques using the dynamic renormalization group have been incorporated into the analytical calculations of the details of such multifractal and intermittent turbulent processes.

## 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 CCDs are under development for NASA's Constellation X mission and promise to reduce greatly the power requirements for future astronomical X-ray CCD cameras. MKI has demonstrated that active-pixel sensors are capable of detecting single X-ray photons when operating at room temperature. It was also demonstrated that back-illuminated CCDs, when operated with low-noise electronics developed at MKI, are sensitive at low energies, extending the low-energy limit of the passband by a factor of three. MKI is building a novel infrared spectrometer for the Magellan telescopes and has recently received funding to develop gratings for the next generation of large ground-based telescopes. The LIGO Quantum Measurement group has demonstrated laser cooling of a coin-sized mirror down to 1 Kelvin, an important breakthrough for cooling such large objects to the point where they exhibit quantum behavior normally obscured by thermally driven motion.

## Education and Public Outreach

The MKI Education and Outreach Group (Dr. Irene Porro, public education and communications officer) continues to focus its efforts on responding to the need for quality out-of-school science programs, in particular to reach out to underserved youth. This year MKI was able to implement three major initiatives that together illustrate the multitiered approach to science learning that has been developed in recent years. "Kids Capture the Cosmos" reaches out to middle school students through an apprenticeship model developed by a leading organization in the field, Citizens Schools. The Youth Astronomy Apprenticeship program promotes science learning among urban teenage youth and their communities. High school students from community centers across Roxbury attended an after-school astronomy training program during the school year and then, during the summer, worked informally with education professionals to create and contribute to astronomy outreach events and informal science initiatives directed to their own communities. Finally, the Chandra Astrophysics Institute, in its third year of operation, continues to provide an opportunity for students underrepresented in science, technology, engineering, and mathematics to build the background skills and knowledge necessary to understand how research science is done, by actually doing it. Students practice these abilities during a summer session hosted in one of the two Technology Enabled Active Learning Project classrooms here at MIT. MKI's second annual "Astronomy in the City" took place on May 12. The urban youth engaged in MKI education initiatives gathered at the MIT Stata Center to showcase their accomplishments to a large audience of family members and representatives of the MIT community. As in previous years, MKI also 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 at http://space.mit.edu/.*