MIT Kavli Institute for Astrophysics and Space Research

The MIT Kavli Institute (MKI) for Astrophysics and Space Research 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 51 graduate students and 28 undergraduate students from five 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-diameter 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 have completed one year of observation in the most sensitive direct search for gravitational wave signals to date and are beginning "Advanced LIGO," a significant upgrade in sensitivity. Advanced LIGO has received full NSF funding with an April 2008 project start and a planned 2014 completion 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. The Chandra X-ray Observatory was recently selected by *Nature* magazine as one of the top 10 highlights of NASA's 50 years of space science and exploration.

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. Suzaku's X-ray Imaging Spectrograph was built at MKI and is enabling sensitive, broadband spectroscopy. The MKI-designed and built All-Sky Monitor (ASM) instrument on NASA's Rossi X-ray Timing Explorer (RXTE) satellite (Dr. Alan Levine, MIT principal investigator) continues to survey the sky for new appearances of X-ray sources as the mission extends its successful operation through 13 years. The results from the ASM provide a unique long-term record of the histories of the flux changes of the bright sources, most of which vary in quite interesting ways. MKI also designed and built the Experiment Data System for RXTE; it allows astrophysicists to choose data compression means that are flexibly optimized for each observation. Finally, NASA recently announced the selection of MKI's Transiting Exoplanet Survey Satellite (TESS; Dr. George Ricker, principal investigator) for a Phase A study. Extrasolar planets that transit (pass in front of and behind) their parent stars are extremely interesting, as the transits allow planetary masses and radii, and absorption spectra of their atmosphere, to be measured. These measurements in turn allow us to infer the composition of the interior of the planet and its atmosphere. TESS has as its goal the discovery, via photometric monitoring, of 1,000 new transiting extrasolar planets.

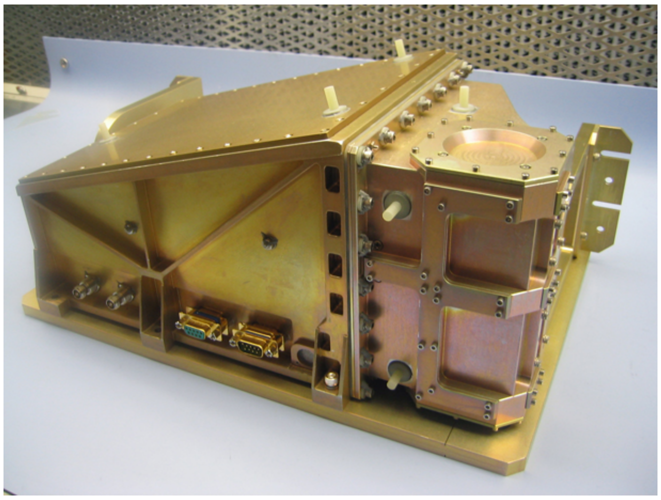


Figure 1. The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument in the laboratory at MIT. CRaTER has been delivered to NASA and is being prepared for launch as part of the Lunar Reconnaissance Orbiter mission. (Provided by Richard Foster.)

In collaboration with Boston University, MKI has developed and built the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument, slated for NASA's Lunar Reconnaissance Orbiter (LRO) Observatory. 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 instrument was delivered to NASA in January and is undergoing integration and testing before the expected LRO launch date of February 27, 2008.

The MKI Optical/Infrared Instrumentation group (professor Robert Simcoe, principal investigator) has begun constructing the Folded-Port InfraRed Echellette (FIRE), an NSF-supported infrared spectrometer for the Magellan telescopes. This versatile instrument will advance MIT-led research on the chemical composition of the early universe and early galaxy formation as well as nearby observations of low-mass stars and remnants from the formation of our own solar system. In developing the first infrared spectrometer for Magellan, the FIRE team has been engineering solutions to the challenges of deploying cryogenic optics, low-background hybrid detectors, and advanced optical materials in a user-oriented package accessible to all our consortium partners.

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 to future missions such as Constellation X, Generation X, and the MicroArcsecond X-ray Imaging Mission. The SNL also is studying ways to apply high-accuracy diffraction gratings to problems of nanoscale metrology and is developing ultra-high-resolution infrared echelle gratings. During the past year, the lab continued to develop 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 also find utility in atom and neutron beam interferometry. The lab has developed a new process for multiple-level interference lithography that was used to demonstrate a grating with 20,000 lines/mm—a major breakthrough. The lab continues to develop the unique Nanoruler grating patterning tool to enable it to write periodic patterns with significantly finer than 100-nm pitch and with improved fidelity.

The three X-ray space missions bearing MKI instruments were evaluated by NASA's biennial senior review. Both the Chandra X-ray Observatory and the Suzaku satellite were recommended for continued operations over the next two to four years. Despite the highly rated scientific record of the RXTE, the senior review was unable to allocate funds to support this mission, now in its 13th year, after 2009.

Research Highlights

Extragalactic Astronomy and Cosmology

Studies continue of the mysterious dark matter and dark energy that apparently make up most of the energy density of the universe. Dark energy may be either a novel substance filling space (such as a cosmological constant) or it may indicate that Einstein's theory of general relativity needs revision. Development work continues on large X-ray calorimeter arrays that make use of transition-edge sensors. These will form the heart of future space-based X-ray cameras, and a laboratory version of the detector array was recently demonstrated. The long-term goals include X-ray surveys of clusters of galaxies that will probe the properties of dark energy, and it is anticipated that their first demonstration in space will be on a rocket flight in 2011 or 2012. Laboratory searches for dark matter are now also being pursued with the development of new detectors sensitive to nuclear recoils. Under development is a gas-phase detector 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. The goal is to increase their sensitivity over the current state of the art by a factor of 20, enabling tests of candidate dark matter models.

A recent observing campaign that combined data from the Chandra X-ray Observatory and several radio and optical observatories around the world collected an unprecedented wealth of spectral information from the central source of galaxy M81, believed to be a supermassive black hole. Comparison with time-varying spectroscopic data for known smaller black holes in our galaxy shows that the accretion and emission processes for this supermassive black hole (several tens of millions of solar masses) are remarkably similar to those of galactic black holes (a few solar masses). Models constructed within the context of general relativity are consistent with the observed properties of these black holes on size scales spanning many orders of magnitude. In a spectroscopic study carried out with the Suzaku telescopes, data on extragalactic supermassive black holes and smaller black holes in our galaxy provided further evidence for their very similar properties over a large range of X-ray energies, both in the continuum and in the details of certain line shapes. Furthermore, details of the shape of the iron line provide evidence for significant spin in some black holes. The broadband coverage of the Suzaku instruments made such studies possible for the first time.

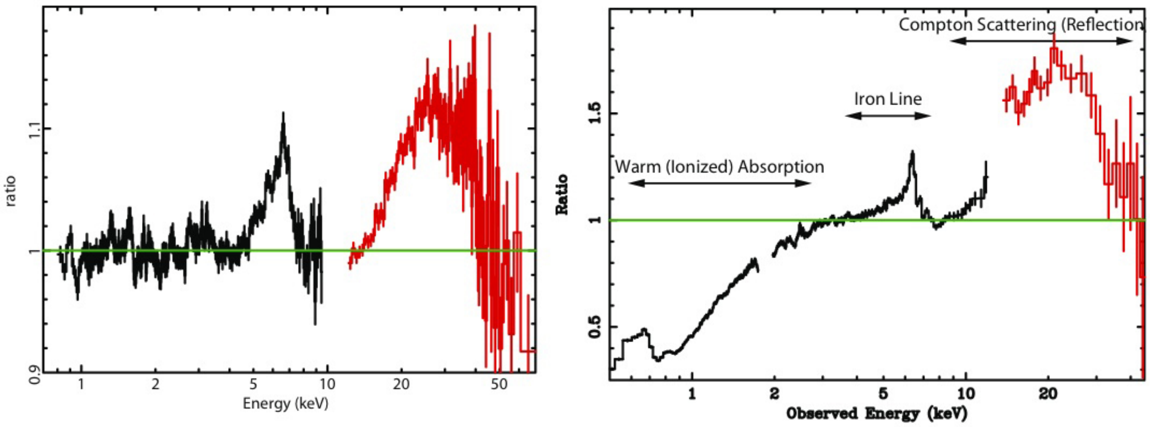


Figure 2. Broadband X-ray spectra measured using the X-ray Imaging Spectrometer and the Hard X-ray Detector, both instruments on the Suzaku satellite. The spectrum on the left is that of a galactic black hole of about 10 solar masses; the spectrum on the right is that of an extragalactic supermassive black hole of about 100 million solar masses. The similarities between these spectra argue for a common mechanism for the energy output. Furthermore, the shape of the iron line in the spectrum on the left provides evidence that the black hole has significant spin. (Provided by J. Miller.)

Progress continues on Magellan observations of the chemistry of intergalactic matter in the early universe. Absorption lines in the spectra of distant quasars (galaxies harboring supermassive black holes) reveal information about the density and chemical composition of intervening gas clouds along the line of sight. MKI researchers have performed a census of carbon absorption in these clouds, at an epoch when the universe was approximately 10% its present age. Carbon atoms represent the "pollution" by-products of nuclear fusion in the universe's first stars, since the Big Bang only lasted long enough to create hydrogen, helium, and lithium on the periodic table.

In collaboration with MIT's Haystack Observatory and the Harvard–Smithsonian Center for Astrophysics, and with the support of the NSF, MKI is building a low-frequency radio array in western Australia. By mapping radio emissions 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.

The first antennas have been deployed on site, and they are currently being instrumented and tested.

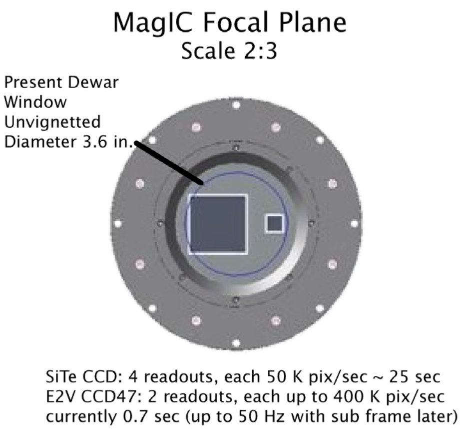
Galactic Astronomy

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. Our understanding of the important details of the nature of galactic X-ray sources is often based on difficult-to-interpret observations. When periodic intensity changes are seen, the interpretation is generally clear and unambiguous. Changes with periods below 1,000 seconds generally prove that the source is a spinning neutron star. Periods in the range of 1,000 seconds to days generally reveal the period of a binary orbit. Thus, it is important to improve the sensitivity of searches for pulsations in bright X-ray sources that are suspected of having a neutron star accreting material from a normal-type stellar companion. It is also important to determine the periods, radii, and eccentricities of the orbits of the binary X-ray sources. It is even conceivable that the knowledge of the pulsation and orbital periods of the very brightest X-ray sources could help lead to a detection of gravitational waves with LIGO. MIT is leading or participating in searches designed to achieve these objectives. One of these searches involves looking for millisecond pulsations in data from RXTE observations of the very bright source Sco X-1. Another search involves looking for the signatures of orbits in the results from the ASM on RXTE.

Extrasolar Planets and Substellar Objects

A new program in the study of extrasolar planets and substellar objects has been established at MKI. Among the new initiatives is a campaign to search for "misaligned" planetary systems, in which the planetary orbital axes do not line up with the stellar rotation axis. The solar system is very well aligned, as are many of the exoplanetary systems, but some theories of planet formation predict occasionally large misalignment. This year, MKI scientists were part of a team that discovered the first possible case of a strongly misaligned system. The discovery is potentially important but the data have modest statistical significance; follow-up observations to improve the data have been scheduled. These studies are possible only with transiting extrasolar planets. As described above, work is under way on the TESS mission to discover many new examples of such systems.

Work continues on identifying spectroscopic diagnostics of physical parameters—mass, age, brightness, and atmospheric composition—of the lowest mass stars and brown dwarfs. This work includes studies to characterize the composition and thickness of "metal" clouds (made up of minerals and liquid iron) in brown dwarf atmospheres; to measure the surface gravities of young, very low mass brown dwarfs in the nearest stellar associations; and to determine the luminosities and galactic orbits of the oldest



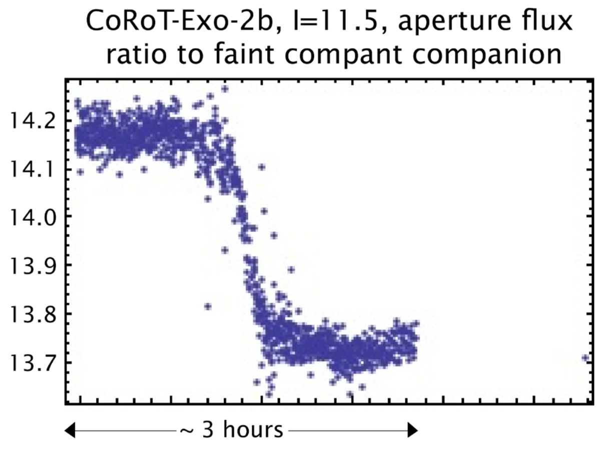


Figure 3. (Left; provided by Steve Kissel) Schematic diagram of the focal plane of the MagIC camera as mounted on one of the Magellan telescopes. A recent upgrade has added a second charge-coupled device detector capable of rapid readout. (Right; provided by E. Adams) Flux of the light from a star as a planetary companion transits, eclipsing a portion of the disk of the star, as measured by the new detector.

known brown dwarfs. One highlight in particular this term was the discovery, on the basis of its unusual spectrum, of a nearby, unresolved binary system, 2MASS 0320-0447. This binary was subsequently shown to have a very small, eight-month orbit, as revealed from Doppler shift velocity variations of the kind used to find extrasolar planets around nearby stars. 2MASS 0320-0447 is the first so-called "radial velocity binary" to be found near the Sun and will enable important constraints on theoretical models of brown dwarf atmospheres and evolution.

Gravitational Physics

The LIGO gravitational wave detectors completed their planned integrated year-long main observation run with the initial instruments. Analysis of these data continues. No gravitational waves have been identified so far in the data, but some challenging nondetections and upper limits have been published. For example, a failure to detect gravitational waves from the pulsar at the center of the Crab Nebula implies that the surface of the neutron star is very smooth. Enhanced instruments will undertake a second year-long observation run starting in 2009. Advanced LIGO is the current focus of development efforts. MKI scientists are in the leader and chief scientist roles of Advanced LIGO, and the MIT Lab is a hub of development, design, and testing.

In next-generation gravitational wave detectors, quantum noise is expected to limit the sensitivity at most frequencies. This quantum limit arises from the Heisenberg uncertainty principle applied to light. The discrete nature of photons sets a limit on how precisely the amplitude and phase of light can be measured simultaneously. The MIT LIGO group has been studying ways to characterize and circumvent this noise limit. One technique for reducing the quantum optical noise is to inject so-called squeezed states of light into the interferometer output port. The MIT group led an experimental demonstration of this technique on a prototype gravitational wave detector and is now in the planning stages for a possible implementation in the LIGO interferometers. Another aspect of this quantum limit arises from the radiation pressure that laser light exerts on the (movable) mirrors

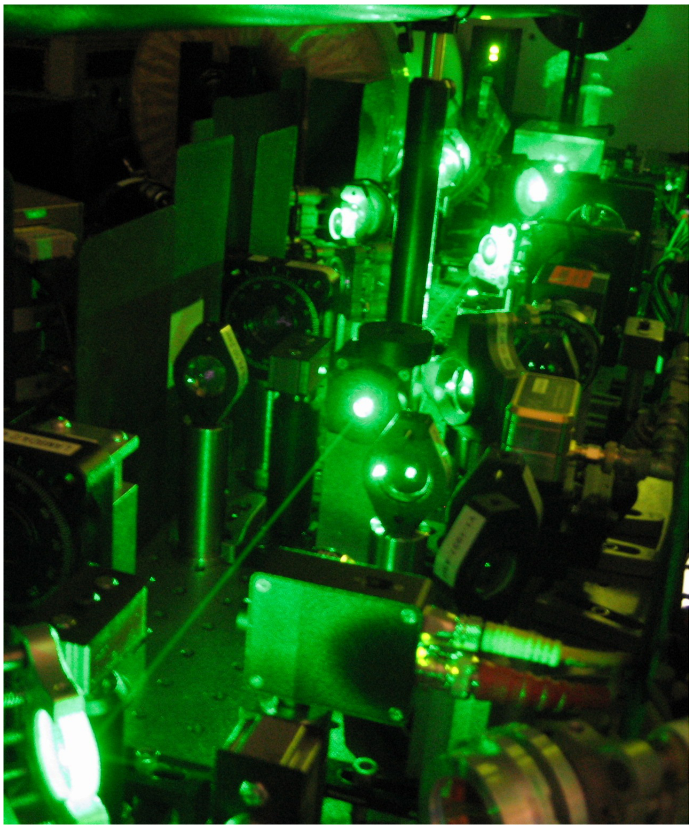


Figure 4: This experiment, operating at MIT's LIGO Laboratory, has demonstrated that a "squeezed state" of light can reduce the quantum optical noise in a gravitational wave interferometer. (Figure provided by Nergis Mavalvala.)

of the LIGO interferometers. The MIT LIGO group has carried out experiments in which the light force dominates the mechanical forces to such an extent that the mirror is optically trapped and cooled. Ultimately reaching the quantum limit and studying quantum noise in these experiments will not only lead to more sensitive gravitational wave detectors but will also provide a test bed for studying quantum behavior of very large objects—macroscopic mirrors.

Theoretical studies of the capabilities of planned future gravitational wave detectors are under way. These studies include assessing the ability of a future ground-based network of LIGO-like detectors to exploit gravitational wave sources as probes of cosmology. Complementing the ground-based LIGO detectors, a space-based interferometric gravitational wave mission (LISA) is being planned by NASA. The expected sensitivity of LISA to very low frequency gravitational waves allows investigations of the small masses orbiting large black holes and the merging of supermassive black holes at the centers of galaxies. Both these phenomena will test previously unexplored aspects of gravitational theory and cosmic structure formation.

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.

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. As predicted, Voyager II crossed the termination shock in late 2007. Unlike Voyager I, the Voyager II spacecraft was carrying a functioning Plasma Science instrument, built at MIT. The spacecraft in fact crossed the termination shock several times, as the shock front moved back and forth in response to changes in the solar wind. Measurements with the Plasma Science instrument and other instruments aboard Voyager II revealed that the detailed properties of the plasma outside the termination shake were not as predicted, launching new studies of this unique corner of the solar system.

MKI is a member of the science operations team of the NASA Interstellar Boundary Explorer (IBEX) project led by Boston University. This mission will analyze the neutral ion flux from the heliospheric termination shock and provide a first global look at the structure of the boundary between our solar system and the surrounding interstellar medium. IBEX is scheduled for launch in October 2008.

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. A new "parametric rank-ordered multifractal spectrum" method was developed recently. This method accurately and quantitatively characterizes the observed intermittent fluctuations with unprecedented precision and has been applied by researchers in various fields of space and astrophysical plasmas.

Instrumentation for the Future

Looking toward future missions, high-performance X-ray sensors are being investigated in collaboration with MIT's Lincoln Laboratory. New highly linear output amplifiers are being developed for the TESS CCD detectors that will extend the linear signal range by a factor of 500, enabling photometric precision approaching 1 part in 10,000. Avalanche photodiode arrays are being developed to provide submicrosecond X-ray photon timing. Fully depleted silicon-on-insulator active pixel sensors have demonstrated spectral resolution better than 300 electronvolts for 6-kiloelectronvolt X-rays.

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 for Boston area youths. In collaboration with the Harvard–Smithsonian Center for Astrophysics Science Education Department, the MKI group is continuing its association with Citizen Schools to create a curriculum for an astronomy apprenticeship for middle school students. This year four Citizen School campuses (after-school sites) implemented the curriculum and 28 participants carried out projects. The Youth Astronomy Apprenticeship (YAA) program, in its second year of operation, promotes science learning among urban teenage youth and their communities. YAA youth apprentices developed new astronomy outreach activities. For example, the YAA program has purchased a portable planetarium that the youth apprentices used to create and perform planetarium shows at a variety of venues in the Boston area. The Chandra Astrophysics Institute, in its fourth year of operation, continues to provide an opportunity for students underrepresented in science and technology to build the background skills and knowledge necessary to understand how research science is done—by actually doing it. This year 14 high school students practiced these abilities during a summer session hosted in one of the two Technology Enabled Active Learning Project (TEAL) classrooms here at MIT. Two students participating in this program won first and second prizes in the Massachusetts state science fair. MKI's third annual Astronomy in the City event took place in May 2008. 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. Finally, as in previous years, MKI hosted several 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/.