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 technologies and participates in National Aeronautics and Space Administration (NASA) flight missions. Areas of research include extragalactic astronomy and cosmology, galactic astronomy, gravitational physics, the solar system and space plasma physics, and the space life sciences. The Departments of Physics; Earth, Atmospheric, and Planetary Sciences; Aeronautics and Astronautics; and Mechanical Engineering report research conducted at MKI, which 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, 43 graduate students and 29 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 Paul Schechter, MIT director), the Laser Interferometric Gravitational-wave Observatory (LIGO; David Shoemaker, MIT director), and the Chandra X-Ray Observatory (Professor Claude Canizares, associate director). The Magellan Consortium operates two 6.5-m-diameter optical telescopes in Chile. The LIGO Laboratory, a collaboration between Caltech and MIT, is engaged in developing and operating 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 Japan Aerospace Exploration Agency successfully launched the Suzaku (formerly Astro-E2) X-ray astronomy mission (Marshall Bautz, MIT principal investigator) in July 2005. MIT's X-ray imaging spectrometer aboard Suzaku is the prime experiment on the mission and, as expected, is proving especially valuable for soft X-ray spectroscopy of extended sources. The HETE-2 (high-energy transient explorer) mission (George Ricker, Jr., 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: Alan Levine, MIT principal investigator) has entered its 11th 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 cosmic ray telescope for the effects of radiation (CRaTER), 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 the earth's atmosphere to image an extrasolar planet.

Research in MKI's Space Nanotechnology Laboratory (Mark Schattenburg, director) seeks to apply micro- and nanofabrication technology to achieve dramatic improvements in lightweight high-resolution optical components. Recent efforts focus on developing an optical system for the lab's unique nanoruler grating patterning tool that will make it possible to write variable period gratings. This work is targeted toward future NASA X-ray missions.

Research Highlights

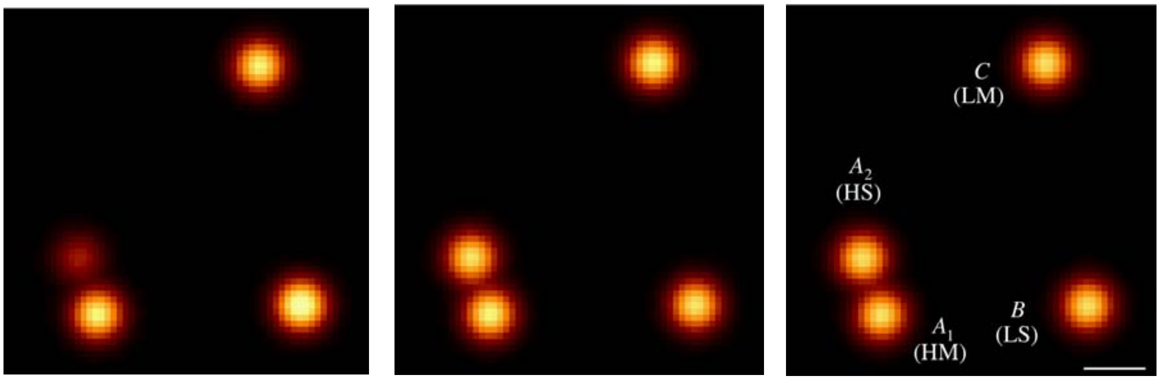
Extragalactic Astronomy and Cosmology

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 spacetime. 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. Until now there has been no way to distinguish between these alternatives. New work shows how long-wavelength perturbations can be combined with other measurements to distinguish these alternatives. 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. Particle physics theories have motivated proposed explanations for dark matter, including one that involves a new version of axion cosmology. Development of a novel dark matter detector based on a gas-phase spin-dependent scheme continues with the successful operation of a laboratory prototype.

Large galaxy surveys are used to test theories of dark energy and dark matter. In the past year, a sixfold increase in the number of galaxies mapped by the Sloan Digital Sky Survey has enabled MKI cosmologists to improve the measurement of cosmological parameters, including the density of dark energy and dark matter.

In collaboration with MIT's Haystack Observatory and the Harvard-Smithsonian Center for Astrophysics, MKI has received funding from the National Science Foundation 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. It will also provide information on how the intergalactic medium became transparent. Design and prototyping are under way.

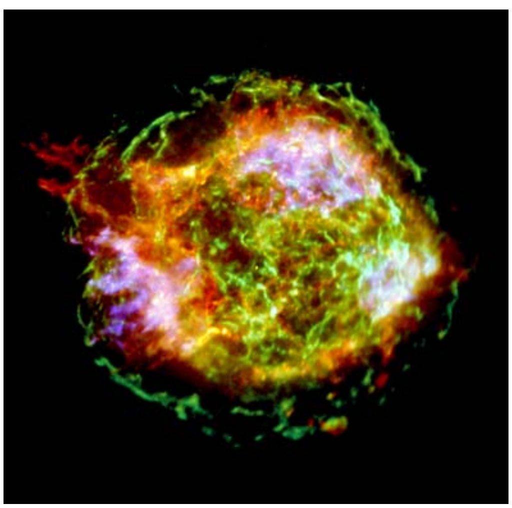
Data from MIT's Magellan telescopes and Chandra have been combined to use the "flux ratio anomalies" in gravitational lenses to probe the "lumpiness" in the dark matter that is a major component of the mass in galaxies. The details of this lumpiness provide clues to the nature of dark matter. The anomalies were found to be more extreme at X-ray wavelengths than at optical wavelengths; this has important implications for the structure of quasars. High-resolution radio studies of lensing galaxies have also placed constraints on the "cuspiness" of dark matter at their centers, another diagnostic of dark matter properties.



Representations of X-ray data (a),optical data (b), and a theoretical model (c) of a four-image gravitational lens. These images show that the optical fluxes of the four images agree well with the model and that the X-ray fluxes do not. The model assumes that the mass distribution responsible for the lensing is smooth. The disagreement between the X-ray data and the model shows that it is not smooth. Furthermore, the much better agreement between the optical data and the model shows that the source of optical emission in the quasar is much larger than the source of X-ray emission. Credit: D. Pooley, S. Rappaport, J. Blackburne, P. Schechter.

Data accumulated from five years of successful gamma-ray burst (GRB) observations by MIT's HETE are proving to be critical in calibrating the use of GRBs as new cosmological yardsticks. The extreme brightness and penetrating power of long GRBs permits their use over a very broad range of distances, extending back to the first few hundred million years after the Big Bang.

Galactic Astronomy



A Chandra image of a supernova remnant, formed in the explosion of a massive star that leaves behind a neutron star. Some neutron stars appear to us as pulsars, compact stars that emit a rapid stream of radio pulses. Timing of the pulses from one of these systems has revealed the presence of planets in orbit about the pulsar. MKI infrared observations of a similar pulsar have detected a debris disk from which planets might form. Credit: U. Hwang et al.

The Magellan telescopes have been used in studies of low-mass stars and brown dwarfs. The coolest brown dwarfs that have been discovered represent a new, unstudied stellar population. Considerable effort has gone into understanding these as a class, involving the establishment of a new classification system. Several extreme cases have been found, including some that are very cool and metal-poor, with implications for our understanding of how star formation proceeded early in the Galaxy's history.

In 1992, three Earth-sized planets were discovered orbiting a pulsar. It was proposed then that such planets form from a debris disk left behind after the parent star exploded. Using NASA's Spitzer space telescope, MKI researchers have discovered excess infrared emission from such a pulsar, providing strong evidence for the debris disk scenario for this type of planetary system.

The high time resolution and operational flexibility of the RXTE satellite continue to be applied to exploit the time variability of cosmic X-ray sources in the exploration of black holes and neutron stars, particularly those in binary systems in the galaxy. A systematic investigation of the occurrence rates of thermonuclear explosions in assorted categories of sources quantified the differences between the X-ray binaries that contain stellar-mass black holes and those containing neutron stars, and thereby built confidence in the theoretical description of a black hole as a collapsed object without a surface. The broadband spectral properties of the X-rays from black hole binaries were used to estimate the masses and, possibly more reliably than previously, the spins of black holes. In complementary theoretical investigations, new capabilities for studying the formation and evolution of these binary systems have been developed. Using MKI's Beowulf computer cluster, entire populations (more than 100,000 systems) can be modeled.

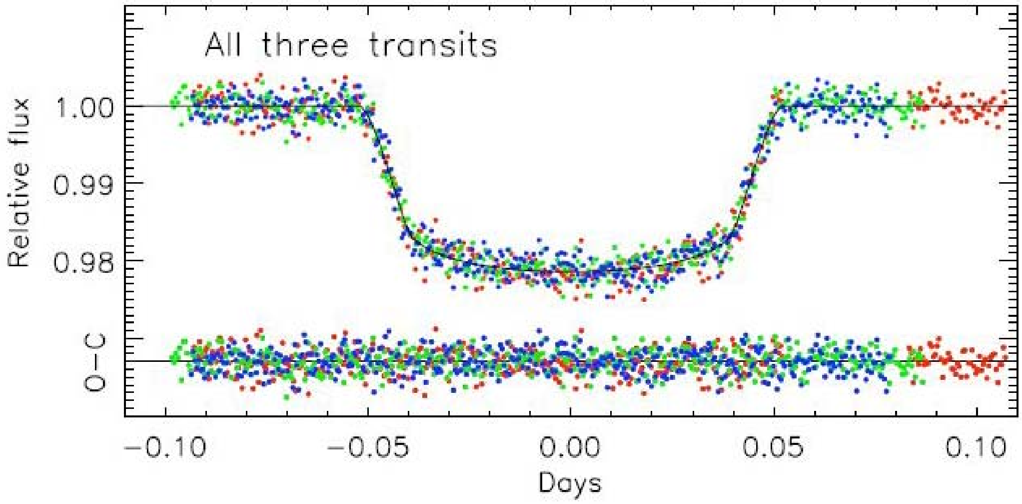
The high-energy transmission grating on Chandra continues as the premiere high-resolution X-ray spectrometer. Chandra spectroscopic measurements were used to test the physical model of the relativistic jets in the galactic X-ray binary SS-433. If the model is correct, the study indicates that the compact object is a black hole and that accretion occurs through a wind process. Spatially resolved spectroscopic measurements done with Chandra, combined with advances in modeling techniques, have verified that particles are accelerated as fast as possible in accordance with our understanding of acceleration mechanisms and plasmas. 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, neon, and iron.

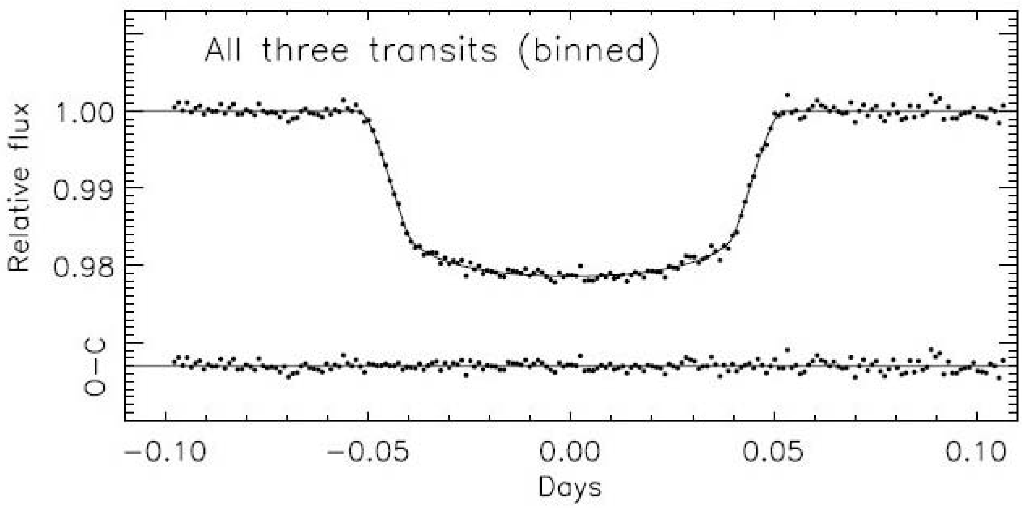
Suzaku observations of diffuse galactic X-ray emission have determined relative abundances of carbon, nitrogen, and oxygen for a number of structures for the first time. The North Polar Spur, for example, shows a surprisingly large nitrogen-oxygen ratio, reflecting its peculiar enrichment history.

In further studies of the supermassive black hole at the center of our galaxy, Chandra observations of its X-ray flares were highlighted in the television program "Supermassive Black Holes," which aired on The Science Channel in fall 2005.

Extrasolar Planets

A program in the study of extrasolar planets is being established at MKI. Early results involve planets that pass in front of their parent stars. In particular, high-precision photometry with the Magellan and other telescopes has provided estimates of the sizes of these planets, which, when combined with theoretical models, can give an indication of their composition (rocky or gas giants). Technology development in this area is focused on space-based photometric techniques, which, when implemented on a future satellite, will make it possible to detect many new extrasolar planetary systems.





Plots of transits of a planet in orbit about a bright nearby star. The light from the star is eclipsed as the planet passes in front of it. At the top of each plot are measurements of the brightness (points) as a function of time and a model (solid line). At the bottom are the residuals after subtraction of the model. These data have been used to infer the radius of the planet. This fundamental measurement sets the stage for future studies of the planet's atmosphere and the orbital dynamics of the planet and other possible planets in the system. Credit: J. Winn, M. Holman, A. Roussanova.

Gravitational Physics

The LIGO gravitational wave detectors are now operating at, and at times exceeding, their targeted sensitivity. Although no gravitational waves have yet been detected, the search continues with unprecedented sensitivity and with collaborative measurements from other gravitational wave observatories around the world. The sensitivity is now such that the range of the instrument is 45 million light years for detection of the coalescence of two neutron stars. At the same time, significant progress has been made in developing technologies for improving the instruments, and plans for enhancements to initial LIGO and for advanced LIGO are being finalized. Complementing the ground-based LIGO detectors, a space-based interferometric gravitational wave mission, the Laser Interferometer Space Antenna (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. 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 2006. Future measurements by this spacecraft 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. Theoretical techniques using the dynamic renormalization group have been incorporated into the analytical calculations of the details of such multifractal and intermittent turbulent processes.

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 counter pressure. 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 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 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 has received funding from the National Science Foundation to develop and build a novel infrared spectrometer for the Magellan telescopes.

Education and Public Outreach

The MKI Education and Public Outreach Office (Kathryn Flanagan, director) continues to build on existing partnerships with community-based organizations in Boston to provide new opportunities for underserved communities. MKI hosted “Astronomy in the City,” an event showcasing initiatives that engage underrepresented groups at the K-12 level. MKI also developed further its multitiered approach to science education in out-of-school time. The training of after-school instructors was extended to four new sites in Boston. The Chandra Astrophysics Institute, which makes use of the MIT Technology Enabled Active Learning studio, recruited students from five new schools. 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 at http://space.mit.edu.