# 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. Specific areas of research include cosmology, extragalactic astronomy, galactic astronomy, gravitational physics, extrasolar planets, the solar system, and space plasma physics. MKI is the home of the astrophysics division of the Department of Physics, supporting faculty, postdoctorates, and graduate and undergraduate students. Students actively participate in research; in the past year, 34 graduate students and 27 undergraduate students from three departments worked on projects at MKI. Research at MKI is supported primarily by the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF). In fiscal year 2013, MKI's research volume was $15.7 million, with 59% provided by NASA and 36% provided by NSF. MKI is also supported by a $20 million endowment made possible by gifts from the Kavli Foundation and other generous donors. In April 2013, NASA selected MKI's Transiting Exoplanet Survey Satellite (TESS) for flight, a $200 million mission for which MIT is the lead institution.

A generous gift by Juan Carlos Torres '79 has established the Torres Postdoctoral Fellowship Program. The Torres Fellowships will bring four postdoctoral fellows to MKI to pursue research in astrophysics, with a preference for research in extrasolar planets.

## Observatories

MKI is a partner in six space missions and ground-based observatories that provide MIT access to world-class facilities. The Chandra X-Ray Observatory was launched in 1999 with two MKI-built instruments on board: the Advanced Charge-Coupled-Device (CCD) Imaging Detector (ACIS), and the High Energy Transmission Grating. The Chandra Observatory was recently given the highest ranking in a review of operational NASA astrophysics missions, ensuring priority for continued operation for the next several years. MKI scientists have developed the capability to monitor damaging particle flux with ACIS, enabling operations to continue despite a failed dedicated monitor. The Magellan Observatory provides MIT scientists access to two 6.5-meter–diameter optical telescopes in Chile. Substantial progress was made in the upgrade of the two laser interferometer facilities of the Laser Interferometer Gravity-Wave Observatory (LIGO), with the expectation that Advanced LIGO will be complete in 2014 and will begin operation in 2015. This upgrade will increase the volume of space searched for gravitational wave sources by a factor of 1,000. The two Voyager spacecraft are now 100 and 120 astronomical units (AU) from the Sun. Having already crossed the termination shock caused by the solar wind's interaction with interstellar space, they are now probing the dense outermost layer of the heliospheric bubble. MKI's X-ray Imaging Spectrometer on the Suzaku mission enables spectroscopy of faint extended astronomical objects and continues to operate since Suzaku's launch in 2005. Construction and commissioning of the Murchison Widefield Array, an innovative low-frequency radio telescope array in Western Australia, was completed in June 2013.

## Research Highlights

### Extrasolar Planets

The study of planets orbiting stars other than the Sun ("exoplanets") is a rapidly growing area of research at MKI. A multiyear development program for the Transiting Exoplanet Survey Satellite resulted in the selection of this $200 million mission for flight by NASA. The goals of TESS are: (1) to discover transiting Earths and super-Earths orbiting nearby bright stars, (2) to discover a sample of small planets most suitable for further study, and (3) to survey 500,000 nearby bright stars for planets of all sizes. The expectation is that TESS will discover the planetary systems that will be extensively studied for the next several decades. Because the planets will be hosted by nearby *bright* stars, detailed spectroscopic studies of their atmospheres will be possible. The sample will include habitable planets, and will enable a search for biomarkers in their atmospheres. MKI is the lead institution for the TESS mission, and in collaboration with Lincoln Laboratory will provide the wide-field cameras, CCD detectors, and data acquisition system that make up the payload.

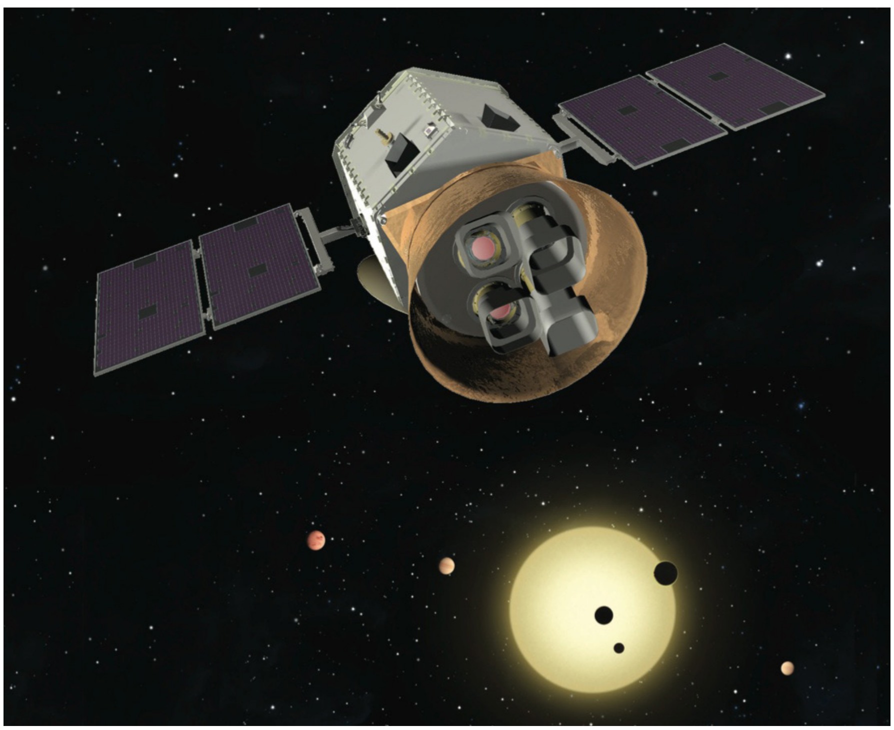

*Figure 1. Artist's conception of TESS. Four wide-field cameras provide the large field of view necessary for monitoring 500,000 nearby bright stars in a search for transiting exoplanets. Source: C. Beals, Lincoln Laboratory*

MKI researchers were part of a team that used NASA's Kepler satellite to discover a system of five planets orbiting a star other than the Sun. The star is of type K2V, not too different from the Sun, and is at a distance of 1,200 parsecs. The planets were detected because they transit the star as viewed from Earth and cause a slight dip in the brightness of the star as they block out its light. The "habitable zone" of a star is the range of distances from the star at which the temperature of a planet is such that it is possible there is liquid water on its surface. The newly discovered five-planet system is particularly interesting because two of its planets are in the habitable zone of the star. Furthermore, they are the smallest planets so far discovered in a habitable zone, which indicates that they may be composed mainly of rock and iron and be similar to Earth.

Extensive photometric monitoring of a recently discovered binary brown dwarf system, located only two parsecs from our solar system, has revealed unusual variability believed to be associated with weather patterns in the atmospheres of the objects. Remarkably, clouds are forming and disappearing on a timescale of 10 hours, and provide an opportunity to explore the dynamics of brown dwarf atmospheres.

### Gravitational Physics

The Advanced LIGO project, an upgrade of the four-kilometer interferometer detectors in Hanford, WA, and Livingston, LA, has moved forward significantly since its start in 2008 and is now 85% complete.

A fundamental limit to the sensitivity of gravitational wave detectors is caused by the quantum nature of light, manifesting itself as photon shot noise and radiation pressure noise due to quantum fluctuations in the photon flux. It has been demonstrated in the laboratory and in the European GEO gravitational wave detector that injecting "squeezed light" into an interferometer can reduce the shot noise below the quantum limit. The MIT LIGO Laboratory has adapted this technology to the lower gravitational wave frequencies to which LIGO is sensitive (150–300 Hz), where it is expected that many astrophysical sources of gravitational waves will be found. In an experiment proving the viability of this technology for the next generation of gravitational wave detectors, the Hanford LIGO interferometer was used to demonstrate improved performance with squeezed light, achieving the best broadband sensitivity to gravitational waves to date.

### Extragalactic Astronomy and Cosmology

An extensive study of distant clusters of galaxies identified in millimeter-wave surveys has been carried out with the Chandra X-ray telescope. The millimeter-wave selection ensures that the survey includes both nearby and distant clusters, enabling a simultaneous probe of the large-scale structure of our universe and the physics of galaxy clustering. Significant evolution of cluster properties with distance (and hence age) and cluster concentration was discovered. Another probe of the young universe was done in a survey of the magnesium II absorption line in galaxies, made possible by the capabilities of the new Folded-port InfraRed Echelette (FIRE) instrument built by MKI scientists for the Magellan telescopes. This survey revealed that the evolving chemical abundances of the more massive galaxies are consistent with their measured star formation rates, as expected. However, a population of less massive systems that did not show evolution was also discovered, indicating a subset of the population that has existed for some time. These results provide evidence for significant chemical evolution early in the history of our universe.

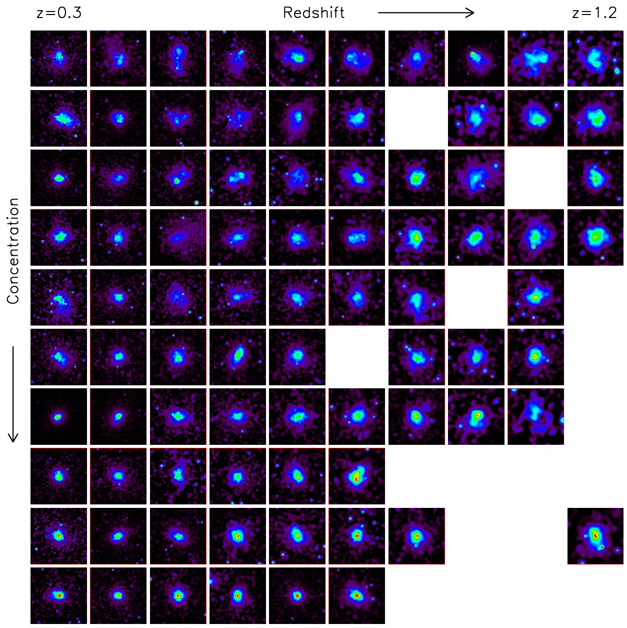


*Figure 2. X-ray images of 83 galaxy clusters arranged in order of increasing distance (horizontal axis) and degree of concentration of their structure (vertical axis). Source: M. McDonald*

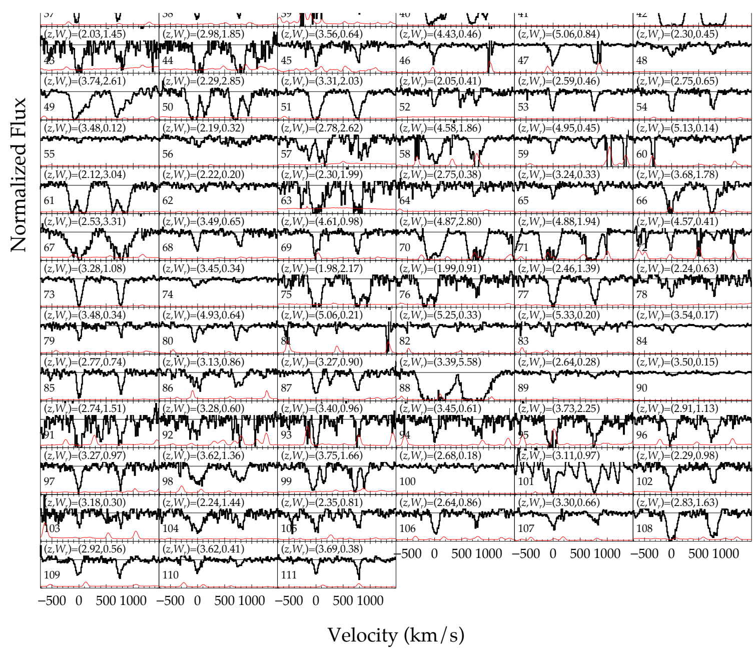


*Figure 3. A montage of characteristic double-lined magnesium II absorption spectra in quasar light measured with the FIRE instrument on a Magellan 6.5-meter telescope. Source: R. Simcoe*

Probing even earlier cosmological epochs, the FIRE instrument was also used in a detailed spectroscopic study of a very bright, distant quasar. The spectrum is remarkably different from the spectra of more nearby quasars. In particular, it shows a great deal of absorption by neutral hydrogen, and extremely low abundances of the heavier elements iron, carbon, magnesium, silicon, and oxygen. The implication is that scientists are seeing the composition of the intergalactic medium at a time in the history of the universe *before* star formation enriched the intergalactic medium with the heavy elements that are formed in stars.

### Galactic Astronomy

Precision timing of X-ray pulsars can be used to study neutron stars in detail, probing the physics of ultra-dense matter, the radiation in the extreme magnetosphere of the neutron star, and the physical composition and dynamics of these fascinating objects. MKI scientists have been developing instrumentation based on silicon drift detectors to improve the precision of timing measurements, and this technology formed the basis for a successful proposal to NASA for the Neutron-star Interior Composition Explorer (NICER). NICER is led by NASA's Goddard Space Flight Center; MKI is responsible for the detector subsystem and will participate in the scientific program. The MKI detectors will form the heart of a bundle of 56 telescopes that will collect the X-rays emitted from the hot surfaces of neutron stars. The instrument is scheduled for launch in 2017, and it will be deployed on the International Space Station.

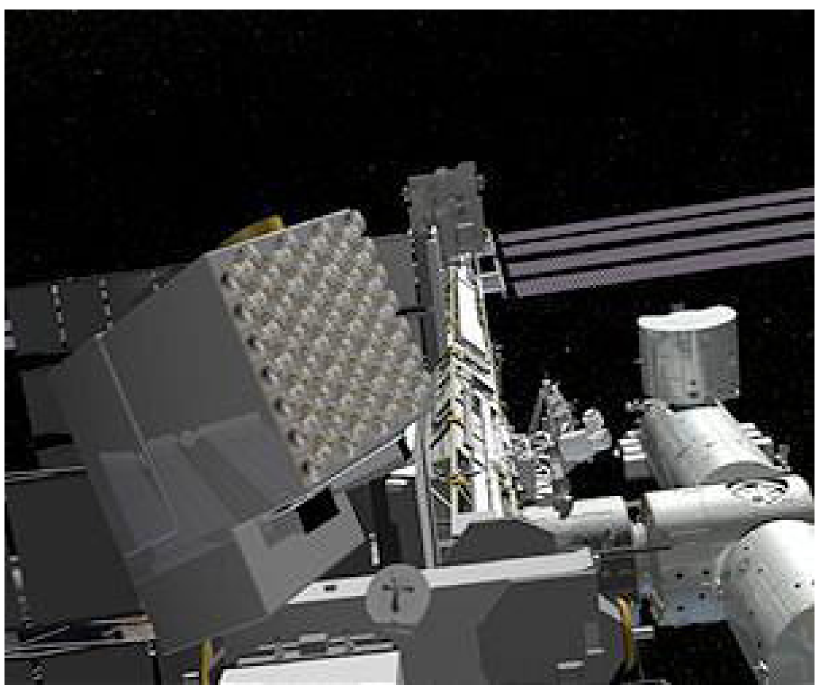

*Figure 4. Artist's conception of the NICER instrument mounted on the International Space Station. Source: NASA*

MKI scientists were part of a team that discovered a new magnetar (a highly magnetized pulsar) in the direction of the center of our galaxy. Detailed studies with Chandra, other X-ray telescopes, and radio telescopes refined the position of the source. Its dispersion and the rotation of the polarization axis of its radiation provide evidence that the pulsar is physically located in the region of the center of the galaxy and not simply seen in projection. This source was discovered during a temporary outburst and it is believed that many other similar objects may exist in the region that may also become visible in the future. The center of our galaxy harbors a massive black hole. Detailed studies of pulsars near the black hole would provide a way to test general relativity in the strong-field regime. Understanding the mechanism underlying the X-ray emission is also of interest; measurements such as these from compact objects have stimulated theoretical work that includes for the first time consideration of plasmas with anisotropic particle distributions.

Chandra and Suzaku spectra of X-ray emission from the O-type star μ Columbae have revealed a wind of material emanating from the star that shines in X-rays, rather than in ultraviolet and optical radiation, as is normally the case for such stars. This discovery largely resolves the long-standing "weak-wind problem" by recognizing that the wind is hot and not simply absent, as previously thought.

## The Solar System and Space Plasma Physics

As the Sun moves through the interstellar medium, the solar wind plasma flowing outward from the Sun is expected to form a bullet-shaped boundary, the heliopause, which separates the solar plasma from the much cooler interstellar medium. The first indication that Voyager 1 may have crossed the heliopause was in July 2012, at 121 AU, when instruments on that spacecraft detected an abrupt decrease in the intensities of termination shock particles and anomalous cosmic rays, and a coincident increase in the galactic cosmic ray intensity and the magnetic field magnitude. These are the changes expected at the heliopause boundary but, surprisingly, there was no concurrent change in the magnetic field direction. Because the magnetic field in the local interstellar plasma is not in the same direction as in the solar field, the absence of a significant change in the magnetic field direction has led to doubts about whether this boundary was indeed the heliopause. These doubts can be resolved by measurements by the MIT low-energy plasma detector on the Voyagers. Unfortunately, the detector stopped working on Voyager 1 many years ago. The question of whether the heliopause boundary has been crossed by Voyager 1 will be definitely decided by the MIT instrument when Voyager 2 crosses into the same region of space that Voyager 1 is now in, within the next three years. (Voyager 2 is about 20 AU closer to the Sun than Voyager 1).

## Instrumentation for the Future

The MIT Experimental Cosmology and Astrophysics Laboratory develops and deploys new experimental techniques to address the nature of dark matter and the formation and evolution of our universe. MKI is the lead institution for the Micro-X High-resolution Microcalorimeter X-ray Imaging Rocket, a sounding rocket payload that will fly a new high-resolution X-ray imaging spectrometer. An extensive study of the resonance modes of the Micro-X flight cryostat and detector systems was undertaken, and vibration tests at NASA's Wallops Flight Facility have demonstrated successful performance. The Micro-X rocket payload is now entering its final integration in preparation for a spring 2014 launch to obtain a high-spectral-resolution X-ray image of the Puppis A supernova remnant.

Research in MKI's Space Nanotechnology Laboratory seeks to apply micro- and nanofabrication technology to achieve dramatic improvements in lightweight high-resolution optical components. Development of the novel Critical Angle Transmission (CAT) grating for X-ray spectroscopy continues. Current emphasis is on the fabrication of dispersive gratings with 200-nanometer period, and on the development of techniques to integrate these gratings into a hierarchical coherent structure with size scales of centimeters. The CAT technology will enable future X-ray spectroscopy missions with very large collecting area.

In collaboration with Lincoln Laboratory, the Detector Development Laboratory continues to develop technology for future X-ray astrophysics missions, including three-dimensional active pixel sensors, modular wide-field detectors, and optical blocking filters. The Chandra X-Ray Center supports the development of technology for measurements of the polarization of astrophysical X-ray sources. A new polarized X-ray source has been built and will be used in the testing of these systems.

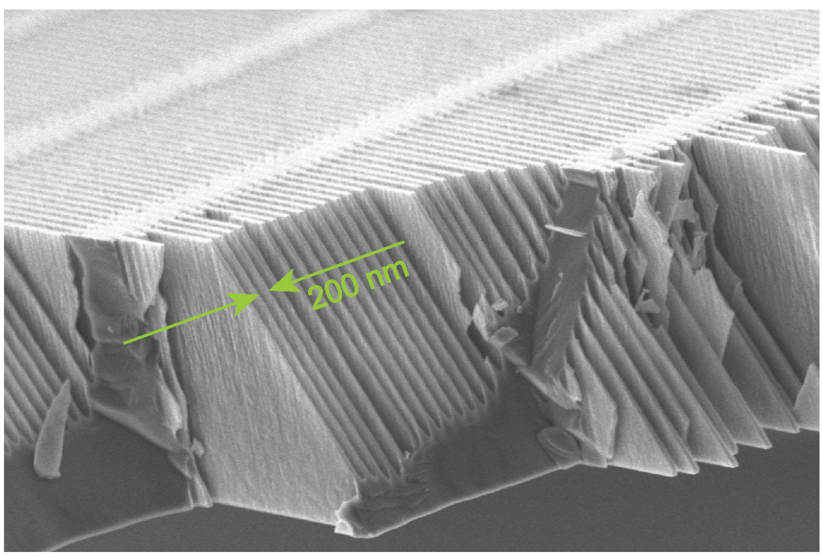


*Figure 5. Scanning electron micrograph of a 200-nanometer period, 4-micrometer thick, freestanding CAT grating membrane with integrated support bars. Source: Space Nanotechnology Laboratory*

## Awards

A number of MKI researchers have received special recognition for their accomplishments. These include the American Physical Society (APS) Joseph F. Keithley Award for Advances in Measurement Science to professor Nergis Mavalvala, the International Union of Pure and Applied Physics Young Scientist Prize in Relativity and Gravitation to research scientist Lisa Barsotti, an NSF CAREER Award to professor Anna Frebel, the Latinos in Science and Engineering (MAES) Outstanding MAEStro Award to professor Edmund Bertschinger, APS Fellowships to professors Scott Hughes and Max Tegmark, a School of Science teaching award to Professor Mavalvala, an Office of Undergraduate Advising and Academic Programming Outstanding Freshman Advisor award to Professor Bertschinger, and the School of Science Infinite Kilometer Award to postdoctoral fellow Chanda Prescod-Weinstein.

**Jacqueline N. Hewitt**
**Director**
**Professor of Physics**