Center for Space Research

The Center for Space Research (CSR) conducts research in physics, astrophysics, space science, detector engineering, and related technology, and participates in various National Aeronautical and Space Administration (NASA) flight missions. Specific areas of research include extragalactic astronomy and cosmology, galactic astronomy, the solar system and space plasma physics, and the space life sciences. Research conducted in CSR is reported by the departments of Physics, Earth Atmospheric and Planetary Sciences, Aeronautics and Astronautics, and Civil and Environmental Engineering, as well as by the Harvard-MIT Division of Health Sciences and Technology. CSR 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, 39 graduate students and 30 undergraduate students from four departments worked on CSR projects.

CSR 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. The observatories in Washington and Louisiana have attained astrophysically interesting sensitivity and are alternating data-taking runs with detector commissioning. New upper limits have been placed on the gravitational waves incident on the Earth. 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 CSR: the High-Energy Transmission Grating (HETG) Spectrometer and the Charge-Coupled Device (CCD) Imaging Spectrometer. CSR is also active in the Chandra X-Ray Observatory Science Center.

One of four flight sensors comprising the Astro-E2 X-ray Imaging Spectrometer. The CCD X-ray detector (the shiny rectangle in the center) was fabricated at MIT Lincoln Laboratories. This CCD has the same basic architecture as those used in many commercial digital cameras, but a variety of enhancements developed jointly at Lincoln and at CSR provide the capability not only to detect individual X-ray photons but also to measure photon energy very precisely. Photo courtesy of Dr. Marshall W. Bautz.

In addition to the major observatories, CSR is involved in several more focused space missions. The Rossi X-ray Timing Explorer (RXTE; Dr. Levine, PI) has entered its 9th year of successful operation. CSR's All-Sky Monitor instrument continuously surveys the sky for new sources and finds interesting targets for other observatories. The High-Energy Transient Experiment 2 (HETE-2) mission (Dr. Ricker, PI), built and operated at MIT with US and international collaborators, was launched in 2000 and is dedicated to the detection and prompt localization of the

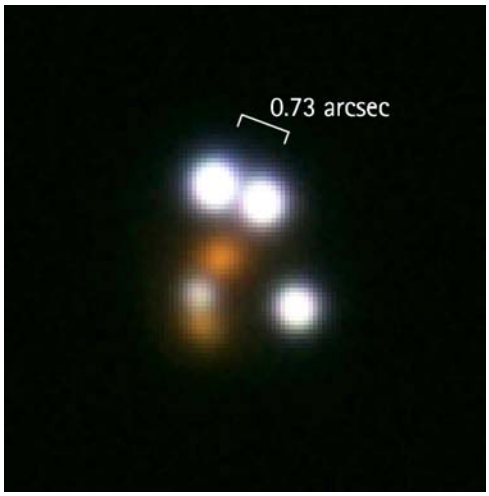
sources of gamma-ray bursts. The Astro-E2 X-ray astronomy mission is to be launched by the Japan Aerospace Exploration Agency in February 2005. Detectors built by CSR (Dr. Bautz, PI) were delivered on schedule in August. Approved by NASA for formulation and now under development is a new remote sensing satellite mission (HYDROS; Professor Entekhabi, PI) that will measure the state of the land hydrosphere, an important component of the Earth's water and energy cycles.

Research in CSR'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. In 2003 the SNL completed construction and testing of a revolutionary new grating patterning tool called the Nanoruler, which writes gratings orders of magnitude faster and more precisely than previous tools. The laboratory has received *R&D Magazine*'s 2004 R&D 100 Award in recognition of this work.

Research Highlights

Extragalactic Astronomy and Cosmology

With its discovery of a bright, nearby gamma-ray burst (GRB), HETE and optical follow-up observations conclusively established the link between these bursts and core-collapse supernovae. The long-standing "dark burst" problem has also been solved by showing that 90 percent of the HETE-localized GRBs have optical or near-infrared counterparts. As a result of these discoveries, the satellite's results were highlighted by *Science Magazine* in December 2003 as being among the 10 most important discoveries in all fields of science during the year 2003.



A gravitational lens imaged by the Walter Baade 6.5-m telescope, one of the two Magellan telescopes at Las Campanas Observatory in Chile. The four images of a background quasar are clearly visible, along with two reddish foreground galaxies responsible for the lensing. MIT is a partner in the Magellan Consortium that built and now operates the telescopes. The CCD camera used to capture this image was built at CSR by Professor James Elliot. Photo courtesy of Professor Scott M. Burles.

The Chandra HETG Spectrometer is being used to probe the warm-hot intergalactic medium, which is thought to contain a large fraction of the "missing" baryons in the nearby universe. Chandra studies also show quantitatively that substructure in galaxies is higher at high redshift, consistent with expectations of cluster evolution. Further studies of the relationship between the X-rays and light emitting by high redshift clusters indicate the light may not be a reliable tracer of mass at that epoch, with important implications for our understanding of structure formation. In theoretical cosmological studies, a new parallel dark matter simulation code has been developed and run on the newly constructed 48-processor Astrophysics Beowulf Cluster. The effects of dark energy on the microwave background fluctuations was used to constrain quintessence models. A study of gravitational lensing by the

supermassive black holes at the centers of galaxies makes quantitative predictions of the lensing signatures that will be observed by next-generation telescopes.

Galactic Astronomy

RXTE and Chandra investigations into the nature of black holes, neutron stars, and related objects continue. Studies of fast oscillations from millisecond X-ray pulsars, both in and out of the stellar thermonuclear explosions known as X-ray bursts, provide insight into the physics of neutron stars. In one highlight this year, timing studies of the pulsations of X-ray pulsars have revealed a change in the spin rate of a neutron star. This may represent the first detection of a sudden change in the structure of an accreting neutron star. Theoretical exploration of the progenitors of hypernovae demonstrates that massive binaries provide an ideal environment for the development of rapid rotation in their cores, a possible site of gamma-ray burst emission. A new model describing orbiting clumps in a relativisitic accretion disk has been developed and shows promise for explaining the quasiperiodic oscillations of black hole binaries.

Chandra studies of globular clusters have demonstrated that the large number of X-ray binaries in the clusters were formed inside the cluster due to tidal interactions and close encounters. This was suspected for decades, but it has now been demonstrated in a quantitative manner. Innovative software is being developed to exploit the exquisite X-ray spectra provided by the Chandra HETG Spectrometer. These studies are mapping the dynamics and composition of supernova remnants and providing a detailed investigation of cosmic ray electrons. Chandra spectra were also used to look for absorption in the atmospheres of neutron stars in order to determine their surface redshifts, which provide a strength of the surface gravity and a measure of these stars' compactness.

The Solar System and Space Plasma Physics

It has recently been recognized that some Kuiper Belt (trans-Neptunian) objects exist in binary systems, allowing new studies of the mass distribution and dynamics of this important component of the solar system. A survey with the Magellan telescopes has resulted in the discovery of a new binary system. This system and others previously known are being studied. Studies of plasma in the solar wind continue from three spacecraft: IMP 8 and WIND, Near Earth, and Voyager 2. Modeling of the neutral and plasma environment near Saturn has shown that the recent discovery by the Cassini-Huygens spacecraft that the outer edges Saturn's rings are water rich could result from the deposition of material from near the moon Enceladus. An innovative theory of complexity in space plasmas in the Earth's magnetosphere, the solar corona, and the solar wind has been developed using the concepts of forced and/or self-organized criticality and topological phase transitions.

Human Space Flight

CSR is developing virtual reality display devices, restraint systems, and software tools for the International Space Station (ISS) Human Research Facility. The system supports

VOILA (Visuomotor and Orientation Investigations in Long-Duration Astronauts), a set of flight experiments planned for 2007. These experiments use virtual reality techniques to study three-dimensional spatial orientation and navigation abilities of astronauts. Other experiments being developed for the ISS include the Cell Culture Unit for biological experiments and an astronaut microgravity disturbance experiment.

Instrumentation for the Future

Looking toward future missions, high-performance X-ray sensors are being developed in collaboration with MIT's Lincoln Laboratory, including a new process in the fabrication of photon-counting CCD's that greatly improve their sensitivity and resolving power at low energies. X-ray polarimetry is being developed, a potentially powerful tool for studying neutron stars and quasars. Work continues in the Space Nanotechnology Laboratory on advanced X-ray optics with applications targeted to future missions such as Constellation X, Generation X, and the MicroArcsecond X-ray Imaging Mission. An adaptive optics system for the Magellan telescopes is under development. Haystack Observatory work continues on the development of a large, low-frequency radio array. The Advanced LIGO proposal for a second generation of gravitational detectors to be installed in the LIGO infrastructure is being reviewed by the NSF. Research continues on techniques to improve the quantum limits to gravitational-wave detector sensitivity.

Education and Public Outreach

The CSR Education and Public Outreach Office (EPO; Dr. K. Flanagan, director) further developed existing partnerships with community-based organizations in Boston to further formal education in science among underserved communities. Among the most successful initiatives were the Chandra after-school Astronomy Project and the Chandra Science Summer Program. Other EPO initiatives such as the HETE Summer Institute are designed to support the professional development of Massachusetts science teachers. CSR also hosted students from the Research Science Institute program at MIT.

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More information about the Center for Space Research can be found on the web at http://space.mit.edu/.