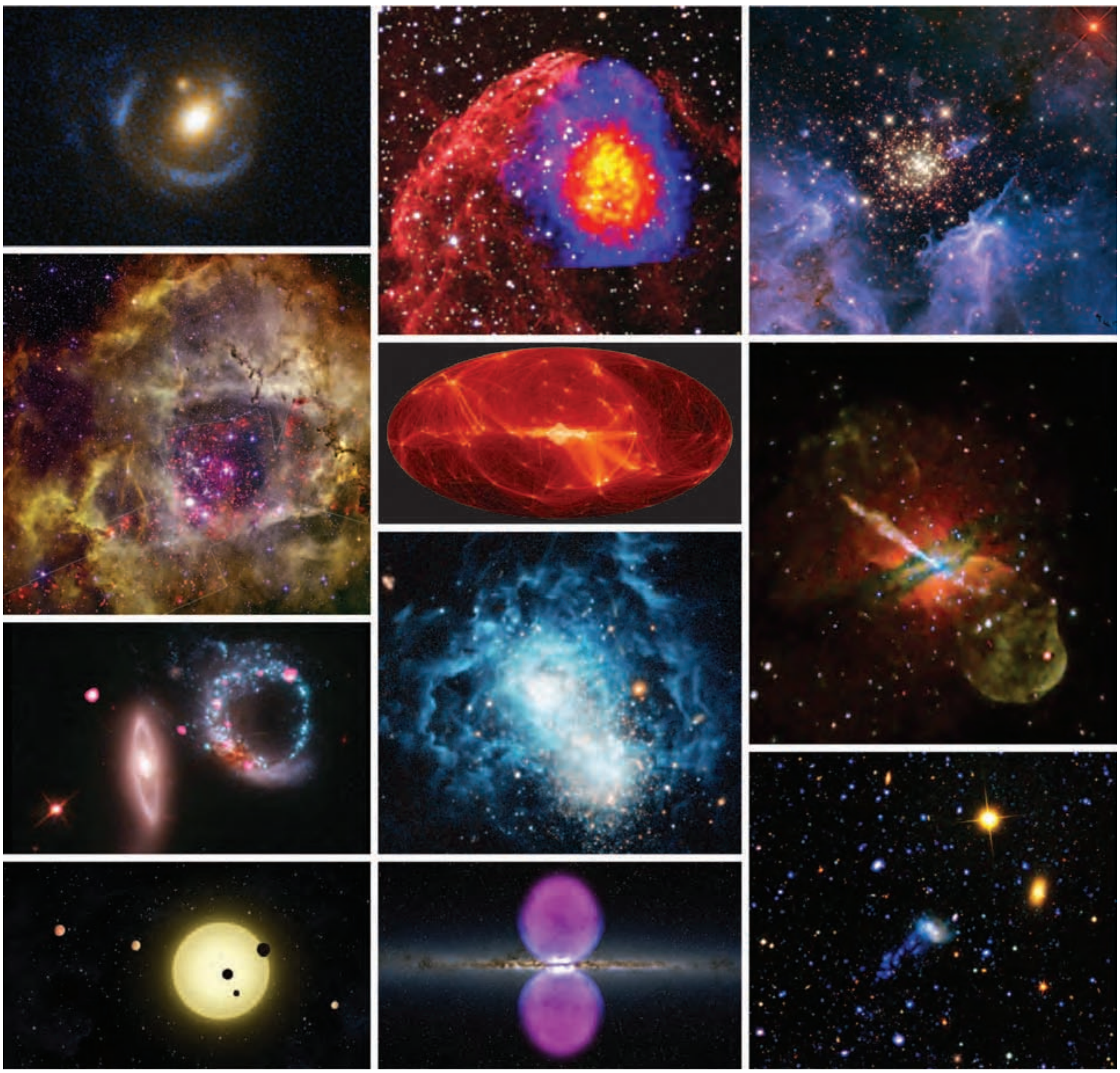
NASA/TM–2011–215870

Goddard's Astrophysics Science Division Annual Report 2010

Joan Centrella and Francis Reddy, Editors
Pat Tyler, Graphical Editor



NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

March 2011

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March 2011

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

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2010: Year in Review

This was the year of the "big wait." After several years of work on mission concept studies and white papers that were submitted to the National Academy of Sciences' Decadal Survey of Astrophysics (Astro2010), the community finally received the report in August 2010. The priorities in the large mission category were: (1) the Wide Field Infrared Space Telescope (WFIRST), a combined dark energy, exoplanet microlensing and Near-IR survey; (2) an enhanced Explorer program; (3) the Laser Interferometer Space Antenna (LISA) and (4) the International X-ray Observatory (IXO). The Astrophysics Science Division (ASD) at Goddard had heavily invested in all of these missions, so this was certainly good news. However, budget realities plus the cost of the James Webb Space Telescope (JWST) implied that none of these big missions were going to start in earnest anytime soon. Complicating the picture was the fact that LISA and IXO relied on partnership with the European Space Agency (ESA), and there is wide-spread opinion that NASA and ESA will eventually collaborate on a dark energy mission. ESA was in the middle of their own Decadal process (Cosmic Visions, 2015–2025), and the results of those deliberations won't be known until late Spring 2011. As we enter 2011, we still seem to be in a "wait" mode—to learn the Fiscal 2012 budget, and the outcome of the Cosmic Visions process. So, check back next year!

The Fermi, Swift, RXTE and Hubble missions all continue to operate well and return spectacular data. A recent highlight from Fermi was the discovery of enormous (~ 8 kpc) lobes of gamma ray emission extending on either side of our Galaxy centered on the Galactic center. Although the exact nature of the emission is not known, it appears to be due to some energetic event in the Galactic center (high-energy electrons scatter lower energy photons up into the gamma-ray regime). Swift has now recorded more than 500 Gamma Ray Bursts (GRBs). The new instruments installed on HST during Servicing Mission 4 are operating wonderfully, although COS has suffered a small loss in sensitivity.

WMAP completed its mission and has been placed in a parking orbit around the sun. The team is completing the data reduction for the last two years of data, and we look forward to the set of papers based on the full nine-year mission. WMAP was a fabulous Explorer mission that has defined our view of the cosmological evolution of the universe. Long time member of ASD, Gary Hinshaw, the Project Scientist for WMAP, has moved to University of British Columbia. We will miss him but of course wish him well in his new pursuits. He will continue to collaborate with our CMB group.

Tremendous technical progress has been made this year in the development of JWST. The microshutters and the NIR focal plane array for ESA's NIRSpec instrument were delivered from GSFC to ESA. Harvey Moseley is the PI for the microshutters and Bernie Rauscher led the development of the focal plane array. The other instruments and the Integrated Science Instrument Module (ISIM), are coming along well, and the mirrors are on schedule and are meeting specifications. Matt Greenhouse is the lead scientist for the ISIM. On the recommendation of an Independent Comprehensive Review Panel, the JWST Project was restructured at NASA HQ and at GSFC, and Mal Neidner was appointed to the project science team as a new Deputy Senior Project Scientist/Technical.

New instruments and missions are under development in the Division for the Explorer program. Development of the Soft X-ray Spectrometer (SXS; Richard Kelley, PI) for the Astro-H mission is proceeding quite well. The first engineering model will be delivered to JAXA in 2011, and preliminary tests show that the instrument exceeds its spectral resolution requirement by healthy margins. SXS employs a microcalorimeter for obtaining spectral information about every X-ray photon received in the field of view (i.e., non-dispersive). Development of the X-ray polarimeter for the Gravity and Extreme Magnetism SMEX (GEMS; Jean Swank, PI) is proceeding toward a Technology Readiness Level 6 status in Spring 2011. Thousands of glass mirror substrates have been produced in the X-ray mirror oven facility at GSFC, led by Will Zhang. These mirrors were delivered to the NuStar Explorer Project (Fiona Harrison, PI). The mirror substrates exceeded the spatial resolution requirement of 40 arcsec. After the mirrors receive a multilayer coating for use in the hard X-ray band, the mirror module will be constructed at Columbia University. Finally, during 2010, much effort was spent on developing several new Explorer and Mission of Opportunity proposals, with both internal and external PIs, that are due in February 2011.

In the Research and Analysis area, Stephen Rinehart was the PI for a newly selected suborbital program—to build the Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII). The BETTII project is a collaboration between NASA's Goddard Space Flight Center and the University of Maryland, with assistance from the Far-Infrared Telescope Experiment team in Japan. It has an 8m boom and operates in the FIR (30–90μm) on a high-altitude balloon. Further information on BETTII is provided in the Suborbital Projects part of this document.

We also partnered with Chuck Bennett (JHU) on a successful proposal to NSF to build the Cosmology Large Angular Scale Surveyor (CLASS) telescope in Chile. This ground-based telescope will search for the imprint of gravitational waves on the CMB polarization (B-mode). GSFC co-Is includes Dave Chuss and Ed Wollack, and collaborators Kogut, Moseley, and Benford. GSFC will provide the 40 and 90 GHz detectors. The modulator is based on the design being used by the PIPER suborbital program (Kogut, PI).

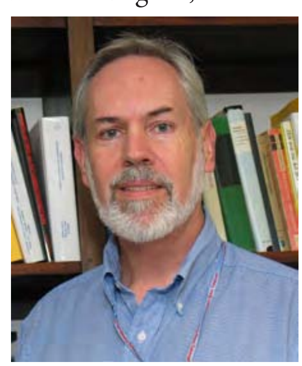
Moseley was selected to carry out a concept study for a potential instrument contribution to JAXA's SPICA mission. SPICA is a ~3m cold (4 K) telescope that is the next generation of far-IR telescopes by JAXA. Moseley's concept is a compact submillimeter spectrometer called Microspec, which operates at wavelengths beyond 250 microns with moderate spectral resolution. In addition, we are significant partners on another successful concept chosen for study. The Wide-field Imaging Spectrograph for the Infrared (WISPIR; Lee Mundy/University of Maryland, PI) has a spectral range from 34–210 microns and a spectral resolving power of R = 1,000 to 6,000, depending on wavelength. WISPIR provides a choice of full-field spectral imaging over a 2' × 2' field or longslit spectral imaging along a 2' slit for studies of astrophysical structures in the local and high-redshift universe.

Rick Lyon and Mark Clampin have made good progress during the year on their Visible Nulling Coronagraph (VNC) testbed. The VNC is one of several promising coronagraph concepts for obtaining high-contrast imaging of exoplanets. Lyon and Clampin were selected for a Technology Demonstration for Exoplanet Missions (TDEM) award to advance the technology readiness of the VNC for use in a potential space flight mission.

In 2010, several ASD scientists were selected to serve on important NASA advisory committees or working groups: Jon Gardner was appointed to serve on the Cosmic Origins Program Analysis Group (COPAG), and Liz Hays was selected to serve on the Physics of the Cosmos PAG (PhysPAG), joining Aki Roberge who was selected to serve on the Exoplanetary PAG (ExoPAG) last year. Bernie Rauscher was selected to serve on the Science Definition Team (SDT) for the WFIRST mission. Sally Heap continues to serve on the NASA Advisory Committee (NAC) astrophysics subcommittee (APS). Jennifer Wiseman serves on the AAS Council. Stephen Merkowitz returned to GSFC from a detail to the President's Office of Science and Technology Policy (OSTP), only to then leave on a short detail to NASA Headquarters to work on Policy in the Astrophysics Division. Bill Danchi is also on detail to NASA HQ in the Astrophysics Division, and Padi Boyd just returned from a two-year stint at HQ during which time she served as the Kepler program scientist.

Dr. Jennifer Wiseman was selected as the new Senior Project Scientist for the Hubble Space Telescope, filling the position vacated by Dave Leckrone, who retired from NASA in late 2009. She was previously the Chief of the Exoplanets and Stellar Astrophysics Lab at GSFC. Dr. Joan Centrella was selected as the new Deputy Director of the Astrophysics Science Division. Joan, previously the Chief of the Gravitational Astrophysics Lab, will provide a strong voice for science throughout ASD and the Center.

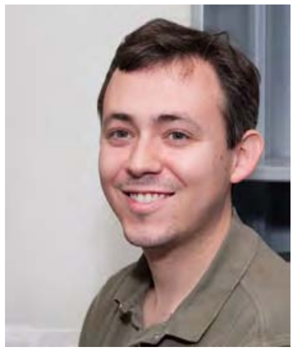
William Oegerle, Director



New Faces in ASD

In 2010, the Division hired many talented new postdocs and civil servants to support its research. Their photos and brief scientific biographies are provided below.

Nicholas Bond



All photos by David Friedlander

Nicholas arrived in November 2010, after working as a postdoctoral associate at Rutgers University for the previous three years. His research interests include selection and morphology of high-redshift galaxies, filaments in large-scale structure, quasar absorption lines and the structure of our galaxy. Nicholas works closely with the Herschel Astrophysical Terahertz Large-Area Survey (H-ATLAS) team, which is producing the world's first large submillimeter survey, as well as NASA's WISE collaboration. He is excited to be taking part in cutting-edge research.

Lindy Blackburn

Lindy Blackburn came to ASD in July 2010 as a NASA Postdoctoral Program fellow. His doctorate work at MIT was on the detection of gravitational-wave bursts with LIGO. He joins the Gravitational Astrophysics Lab here at ASD to begin a joint data-analysis effort on astrophysical transients between NASA's high-energy satellites and the LIGO-Virgo network of interferometric gravitational-wave detectors. He looks forward to drawing heavily on the wide range of X- and gamma-ray expertise in ASD and helping to facilitate communication between the gravitational-wave and broader astrophysics community.

Ori Fox

Ori Fox started his NASA Postdoc Program fellowship with Harvey Moseley and ASD's Observational Cosmology Lab in July 2010. Ori hails from the University of Virginia, where he completed his dissertation work on "An Infrared Study of Dust in Type IIn Supernovae" with advisors Michael Skrutskie and Roger Chevalier. Ori is no stranger to ASD, as some of his dissertation research was spent characterizing detectors for the JWST Near-Infrared Spectrograph with Bernie Rauscher as part of the NASA Graduate Student Research Program (GSRP). His research interests span a wide range, including supernovae and supernova dust, gamma-ray bursts, stellar evolution, infrared instrumentation, and detector development. Ori looks forward to combining all of these interests at Goddard by supporting the construction, observations and science of RATIR, an infrared imager designed to rapidly identify high-redshift gamma-ray bursts.

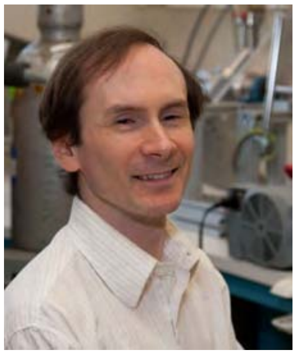
Asami Hayato

Last year, Asami completed her doctorate in physics in Japan with a study about X-ray observations of supernova remnants using Suzaku. She has worked on the satellite's X-ray detector, especially the gas counters, since she was a master's student. She joined the NASA team as a JSPS postdoctoral fellow in June 2010 and is now working on the polarimeter for the GEMS mission. Her goal is to carry out the first X-ray polarimetry observation since the 1970s and discover new science with the detector being developed by the GEMS team.

Joanne Hill

Joanne (Joe) Hill joined the X-ray Astrophysics Laboratory in July 2005 through USRA and became a NASA civil servant in September 2010. She has worked on the development of detectors for astrophysical applications for more than 15 years. She graduated with a Ph.D. from the University of Leicester in 1998 following her research into measuring polarization with small pixel CCDs. She moved to Penn State University, where she became the instrument scientist for Swift's X-ray Telescope. Joe now leads the development of X-ray polarimeters for GEMS, which is scheduled for launch in 2014. Her other interests are in the development of a Gamma-ray Burst Polarimeter and the use of small satellites and human-tended suborbital vehicles as instrument test beds.

Michael Hosack



Michael is a Support Scientist under contract with ADNET Systems, Inc. He arrived at ASD in September 2009 and has been developing an X-ray polarimeter for studying solar flares. For the past 5 years, he has specialized in gas-ionizing X-ray detectors, first at Temple University, then Bruker AXS, Inc., and now Goddard. His graduate and initial postdoctoral work involved high-energy experimental measurements of mixing and charge-parity violation in charm and beauty mesons. Michael enjoys applying knowledge gleaned from one field to other areas. He collaborates closely with members of the X-ray Astrophysics Lab and the Solar Physics Lab to adapt detector technology developed for the GEMS mission—which intends to explore distant objects like black holes and neutron stars—to study the Sun.

Susan Kassin

Susan is a NASA Postdoctoral Program fellow working with Jonathan Gardner on the James Webb Space Telescope. She studies galaxy evolution primarily from the standpoint of galaxy kinematics at low and high redshift. Susan mainly works with data from multi-object and integral field spectrographs in the optical and the near-infrared, in addition to Hubble images. She also collaborates with theorists and numerical simulators to help understand her observations. Most recently she was at Oxford but still has roots in Santa Cruz.

Jeffrey Kruk

Jeffrey came to ASD in June 2010 as the Instrument Scientist for NASA's planned Wide Field Infrared Survey Telescope (WFIRST). Previously, he spent 20 years at Johns Hopkins University, where he worked on instrumentation, systems engineering and far-ultraviolet spectroscopy associated with the Hopkins Ultraviolet Telescope (HUT) and FUSE. His research interests on those programs included chemical abundances in the interstellar medium and hot hydrogen-deficient pre-white dwarf stars. With additional interests in instrument calibration, Jeffrey has been involved with this aspect of both the HUT and FUSE projects and as a co-investigator with the Absolute Color Calibration Experiment for Standard Stars (ACCESS) sounding rocket program now underway at Johns Hopkins. In an earlier life, he was an experimental medium- and high-energy physicist working on numerous experiments at Brookhaven, Los Alamos, and Fermilab. In recent years, his interests have shifted to dark energy, beginning with a MIDEX concept to measure baryon acoustic oscillations and the Advanced Dark Energy Physics Telescope concept study.

Craig Markwardt

Craig joined the ASD X-ray Astrophysics Lab in 2010 as a civil servant. He began his tenure there as a cooperative scientist in 1997 after receiving his Ph.D. from the University of Wisconsin at Madison. As a member of the instrument team for RXTE's Proportional Counter Array (PCA), he studies the timing and spectral properties of stellar-mass black hole and neutron star binary systems in our galaxy. Moving outward, Craig uses the

Swift Burst Alert Telescope (BAT) to examine powerful bursts of gamma rays from distant galaxies and is tabulating a census of X-ray-emitting galactic nuclei in the local universe. Most recently, Craig has joined the GEMS project, which will perform the first systematic survey of X-ray polarization, a new dimension of X-ray astronomy. His primary programmatic role as manager of the GEMS Science Operations Center is to develop science data processing software and science ground systems.

Elisabetta Micelotta

Elisabetta works in the Observational Cosmology Lab and joined the ASD team in June 2010. She received her Ph.D. from Leiden University, The Netherlands, with Prof. A. Tielens, and spent half of those four years collaborating with Prof. A. Jones at the Institut d'Astrophysique Spatiale in Orsay, France. Elisabetta is interested in all stages of scientific research, from the development of models to the testing of models through observations and experiments—and she thinks ASD offers the best opportunity to pursue these interests. Her research focuses on infrared astronomy, with particular interest in the physics of interstellar dust and molecules in various astrophysical environments, including supernova remnants, starburst galaxies and active galaxies.

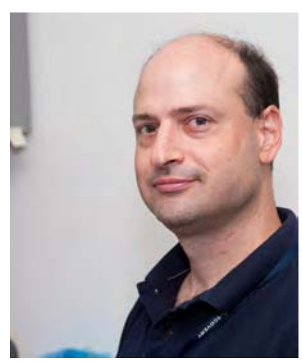
Rodrigo Nemmen

Rodrigo arrived at ASD in August 2010 as a new NASA Postdoctoral Program Fellow and is collaborating with Fermi and Swift researchers in the Astroparticle Physics and X-ray Astrophysics Labs. He came from the city of Porto Alegre ("Happy Harbor"), located in the "deep south" of Brazil. He received his Ph.D. from Universidade Federal do Rio Grande do Sul in 2009, under the supervision of Prof. Thaisa Storchi Bergmann. Rodrigo works at the interface between theory and observations. His research interests include the nature of ultra-high-energy cosmic rays and the connection between the physics of gamma-ray bursts and the central engines of active galactic nuclei (AGN). He is constraining the physics of black hole accretion, outflows and spins in AGN (LINERs, radio galaxies and quasars) using multiwavelength observations (including X-rays and gamma-rays) in order to understand the "astrophysical diet" of supermassive black holes. He's excited to be interacting with so many bright scientists at Goddard and to learn first-hand about updates on NASA missions.

Jeremy Perkins

Jeremy joined the Fermi Science Support Center at NASA in May 2010 after spending four years at the Smithsonian Astrophysical Observatory in Tucson, Ariz., working on VERITAS; he did everything from project management to research on extragalactic TeV emitters such as starburst and active galactic nuclei. Jeremy's research interests are focused on the interplay between GeV (with Fermi) and TeV (with VERITAS) sources, with an emphasis on extragalactic objects, especially AGN. He serves as a member of both the Fermi Large Area Telescope and VERITAS teams, which helps facilitate joint studies. After the recent ice storm, he's really wishing he was enjoying an 80° winter day in Tucson right now.

Andy Ptak



Andy joined the X-ray Astrophysics Lab as a civil servant in July after eight years as a research scientist at Johns Hopkins University. He is interested observational extragalactic X-ray astrophysics, with emphasis on active galactic nuclei and starburst galaxies. A key aspect of the future research for both of these source classes is high-resolution X-ray spectroscopy and imaging observations above 10 keV. ASD is at the forefront of those developments thanks to Goddard's involvement in the upcoming NuStar, Astro-H and IXO missions. Andy is also actively involved in wide-area-survey astronomy and astrostatistics—the use of advanced statistical techniques in astrophysics research. He is a member of the Large Synoptic Survey Telescope project's galaxies and astroinformatics science collaborations. He is also a member of the leadership for a wide-field X-ray telescope mission that may be proposed in the future.

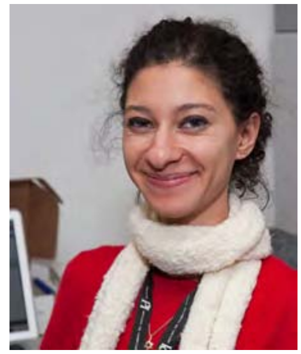
Judith Racusin

Judith came to ASD in August 2009 after finishing her Ph.D. at Penn State University, initially as part of the NASA Postdoctoral Program and later as a civil servant. She directly uses a variety of X- and gamma-ray telescopes and works on multi-wavelength studies to understand the origin and nature of gamma-ray bursts, supernova remnants and other energetic objects. Her research interests also include instrumentation for high-energy astrophysics, and she is an active member of both the Swift and Fermi Gamma-ray Space Telescope teams.

Jane Rigby

Jane came to ASD as a civil servant in 2010 from the Carnegie Observatories in Pasadena, Calif., where she was both a Carnegie and Spitzer Fellow. She works in the Observational Cosmology Lab and serves as the Deputy Project Scientist for Operations for the James Webb Space Telescope. She earned her Ph.D. at the University of Arizona. Her research focuses on galaxies that are rapidly forming stars, as well as galaxies whose central black holes are growing. She uses telescopes spanning a large range of the electromagnetic spectrum, including the Hubble, Spitzer, and Chandra space observatories and the Magellan and Keck ground-based observatories. She uses galaxy clusters as "gravitational telescopes" to push even farther into the era of galaxy growth.

Chanda Prescod-Weinstein



Chanda arrived at ASD in November 2010 as a NASA Postdoctoral Program Fellow. She comes to NASA as the first theoretical cosmology doctorate from Canada's Perimeter Institute for Theoretical Physics and University of Waterloo in Ontario. Chanda is interested in all aspects of cosmic acceleration, from understanding it as a potential quantum gravity phenomenology to using large-scale structure as a test for models of modified gravity and dark energy. Chanda is working with the WFIRST team in the Observational Cosmology Lab with an eye toward identifying the best ways to use weak lensing for precision cosmology. After four years in an extremely theory-oriented environment, Chanda is excited to be home and in a place where data reigns supreme.

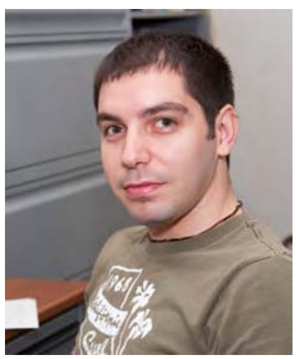
Jeremy Schnittman

Jeremy joined the ASD team as a civil servant in July 2010, coming all the way from Baltimore, Md., where he spent the last three years as a Chandra Postdoctoral Fellow at Johns Hopkins University. His research interests include theoretical and computational modeling of black hole accretion flows, X-ray polarimetry, black hole binaries, gravitational wave sources, as well as planetary dynamics and resonant behavior. He has been described as a "general-purpose astrophysics theorist," which he regards as quite a compliment. Jeremy works closely with members of the X-ray Astrophyiscs and Gravitational Astrophysics Labs on the GEMS and LISA missions, and his office is conveniently located between them.

Tea Temim

Tea joined ASD in November 2010 as a NASA Postdoctoral Fellow. She graduated from the University of Minnesota in 2009, but spent the past three years as a predoctoral (and then postdoctoral) fellow at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., where she worked with Dr. Patrick Slane on the evolution of composite supernova remnants. She is now a part of the James Webb Space Telescope group and works with George Sonneborn. Her research interests include infrared and X-ray studies of supernova remnants, evolution of composite remnants and pulsar wind nebulae, and the production and processing of dust by supernovae.

Francesco Tombesi



Francesco is not completely new to ASD, having visited several times over the past few years. In April 2010, he received his doctorate in Astrophysics from the University of Bologna, Italy. Since August he has worked as a postdoc in ASD and at the University of Maryland. Francesco's main research interests are X-ray spectroscopy of active galactic nuclei and the study of accretion/ejection processes close to their super-massive black holes. He is also interested in developing new X-ray missions and is a member of the Astro-H science team.

Eleonora Troja

Eleonora arrived at ASD in July 2009 as a fellow of the NASA Postdoctoral Program. She received her doctorate in astrophysics at the University of Palermo in Italy with a thesis focused on gamma-ray bursts (GRBs) and their afterglows. Before joining the Swift and Fermi teams at Goddard, she enjoyed working with the GRB groups at the University of Leicester and the Tokyo Institute of Technology.

Adria Updike

Adria joined the Observational Cosmology Lab as a postdoc in November 2010 after completing her doctorate work at Clemson University, where she studied the dust composition of gamma-ray burst host galaxies with Dieter Hartmann. Her research interests include optical and near-infrared observations of gamma-ray burst afterglows, modeling of spectral energy distributions, dust formation and destruction, and galactic evolution. She will be working with Eli Dwek on problems relating to dust and star formation.

Dan Wik

Dan joined the ASD team as a NASA Postdoctoral Position Fellow in September 2010, fresh from completing his Ph.D. at the University of Virginia under the supervision of Craig Sarazin. His dissertation focused on the consequences of galaxy cluster mergers with a particular emphasis on searching for diffuse, non-thermal emission at X-ray energies with XMM-Newton, Suzaku, and Swift. To his great disappointment, Dan failed to detect anything worth admitting to. At Goddard, Dan is particularly excited about having access to a computer directly connected to the HEASARC data archive—allowing him to expand his interest in galaxy clusters—and being a part of the NuSTAR hard X-ray mission, which may one day allow him to detect non-thermal emission from clusters after all.

Awards

In the past year, a number of awards were received by individuals or teams within the Astrophysics Science Division (ASD) for extraordinary contributions to their respective fields.

In April 2010, Neil Gehrels, currently the Chief of the Astroparticle Physics Lab and Principal Investigator of the Swift mission, was elected to the National Academy of Sciences. The award was given for Neil's pioneering contributions to gamma ray astronomy and leadership of the Compton Gamma Ray Observatory and Swift missions to study AGN and gamma-ray bursts (GRB). The results from the Swift mission have been instrumental in advancing our understanding of the nature of GRBs. Neil joins John Mather as the second NASA astronomer in the National Academy. For Neil, election into the National Academy comes on the heels of his being awarded the 2009 Henry Draper Medal by the NAS.

Neil Gehrels

Julie McEnery and Dave Thompson shared the 2010 John C. Lindsay Memorial Award for Space Science. This annual award is presented to a Goddard employee for an outstanding contribution to space science or technology and is one of the Center's highest forms of recognition for a scientific contribution. Julie and Dave are the Project Scientist and Deputy Project Scientist, respectively, for the Fermi Gamma-ray Space Telescope, and the award was presented to them for the key roles they played in significant discoveries made with Fermi. Julie served as the Analysis Coordinator of the Large Area Telescope (LAT) during the first year of flight and was co-lead of the Gamma Ray Burst science group. Dave was the lead for the anti-coincidence detector on LAT, serves as the Multiwavelength Coordinator, and was co-lead of the Catalog science group. Fermi had five of the top-cited papers in all of space science in 2009, and Julie was a leader on one of these papers (announcing extended high-energy gamma-ray emission from GRB 080916C with a Lorentz factor > 600), and Dave was a leader of another (the publication of the LAT Bright Source Catalog). Fermi is revolutionizing our view of the gamma-ray sky, and Julie and Dave contributed significantly to the mission's scientific productivity.

Julie McEnery

Dave Thompson

Mark Clampin was a member of a team receiving the 2009 AAAS Newcomb Cleveland Prize, awarded annually for the most outstanding article published in the journal Science. The paper, "Optical Images of an Exosolar Planet 25 Light-Years from Earth," by Kalas et al., announced the direct detection of an exoplanet in the Fomalhaut system with HST. The award was presented at the 2010 AAAS meeting in San Diego. The Prize was shared between the Kalas/Clampin team and another team led by Christian Marois that reported direct detection with Keck of three exoplanets in the HR 8799 system. Both papers were published in the same issue of *Science*. The Prize was presented to the team at the 2010 AAAS meeting in San Diego. In addition, Clampin received a 2010 NASA Exceptional Scientific Achievement Medal for this work.

Mark Clampin

Numerous members of ASD were on teams that received 2010 NASA Group Achievement Awards for their contributions to the success of operating or future space missions. The awardees include the Fermi Science Team, the Gravity and Extreme Magnetism (GEMS) Explorer Team, and the HST Servicing Mission 4 teams.

Three members of ASD received Robert H. Goddard awards for Science in 2010. Matt Greenhouse was recognized for his excellent leadership of the JWST instrument teams. Matt provides scientific oversight for

Matt Greenhouse

Goddard's contributions to JWST in the area of analysis and testing of detectors and microshutters. He also provides leadership to JWST instrument teams from around the world (U of Arizona, Canada, ESA, Scotland, JPL) to ensure that instrument problems are solved and scientific requirements are met.

Randy Kimble was recognized for exceptional achievement in the development of the Wide Field Camera 3 (WFC3) for HST. The performance of the camera in-orbit is remarkable, fully meeting or exceeding expectations. Randy played a leading role in making sure that high QE NIR detectors were included in WFC3, as well as providing overall leadership of the instrument development.

Randy Kimble

Alexander Moiseev was recognized for his development of analysis methods for measuring high-energy electrons with the Fermi LAT instrument. This led to the unexpected observations that the spectrum of very high-energy electrons is much flatter than expected by conventional models of electron production and diffusion in the Galaxy. The resulting paper in *Physical Review Letters* is the most widely cited Fermi paper to date.

Alexander Moiseev

Finally, Richard Mushotzky received the 2010 Goddard Award of Merit, the highest award given out by Goddard, and is usually reserved for sustained and significant achievement over the span of a career. Richard has been at the forefront of work interpreting observations of AGN and clusters of galaxies for the last 30 years. His research has used data from numerous NASA and international missions including OSO-8, HEAO-1, HEAO-2, BBXRT, ASCA, ROSAT, Einstein, Chandra, XMM and Suzaku missions. Over his career, Richard has authored or co-authored an astounding 343 refereed papers with over 21,000 citations. In the past year, Richard left government service and is now a professor at the University of Maryland in College Park. Luckily for us, he continues to work with scientists in ASD through the Joint Science Institute, a collaboration between GSFC and University of Maryland.

Richard Mushotzky

Research Highlights

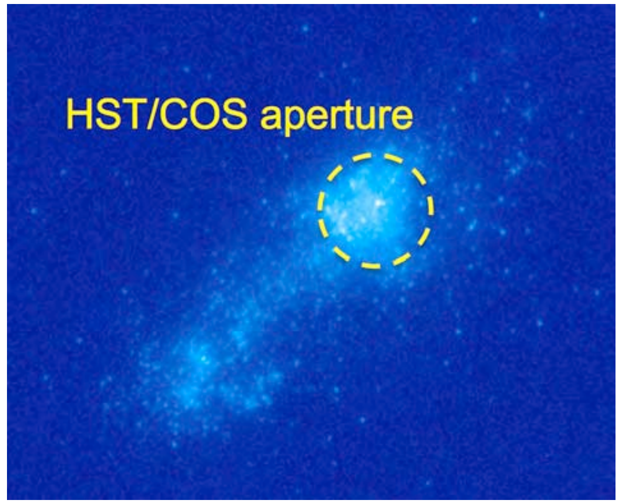
Exploring I Zw 18, a Blue Compact Dwarf Galaxy

The blue compact dwarf galaxy I Zw 18 is one of the most metal-poor star-forming galaxies known. In fact, it is a probably a more primitive galaxy than the high-redshift (z=7–8) galaxies now being explored with Hubble's Wide Field Camera 3 (WFC3). Because of its low stellar mass and low nebular metallicity, I Zw 18 offers an excellent laboratory for studying star formation, metal enrichment and galaxy evolution in the early universe ($z \geq 9$).

Recently, Sally Heap and colleagues obtained far-UV spectra of I Zw 18-NW using Hubble's Cosmic Origins Spectrograph (COS) in order to learn about evolutionary processes operating in primitive galaxies. They found that the observed properties of stars in I Zw 18 are consistent with models of stellar evolution at very low metallicity, which can be *qualitatively* different from those at higher metallicity due to the effects of rapid rotation, and/or the evolutionary paths of close binary systems containing massive stars, as shown in the table below.

They also find that the stage of star formation as measured by the ratio $M_*/(M_{gas} + M_*)$ is important, affecting the UV slope parameter (β), the dynamical evolution of the galaxy, and the dispersal of newly synthesized elements into the interstellar and intergalactic medium.

Observed Feature	Fast-Rotating Single Stars	Interacting Binary Stars
Presence of Wolf-Rayet (H-rich envelope removed)	Mixing from core to surface Rotation-enhanced mass-loss	Roche-Lobe overflow
Low velocity of wind lines	Rotation-induced “mechanical” mass-loss	Radiative inhibition
Broad stellar spectral lines	High rotational velocity	Spin-up of mass-gainer star
Strange, emission-line stars; CNO abundance anomalies	Rotation-induced mixing of newly synthesized CNO to the surface	Transfer of newly synthesized CNO from original primary star in Roche-Lobe overflow



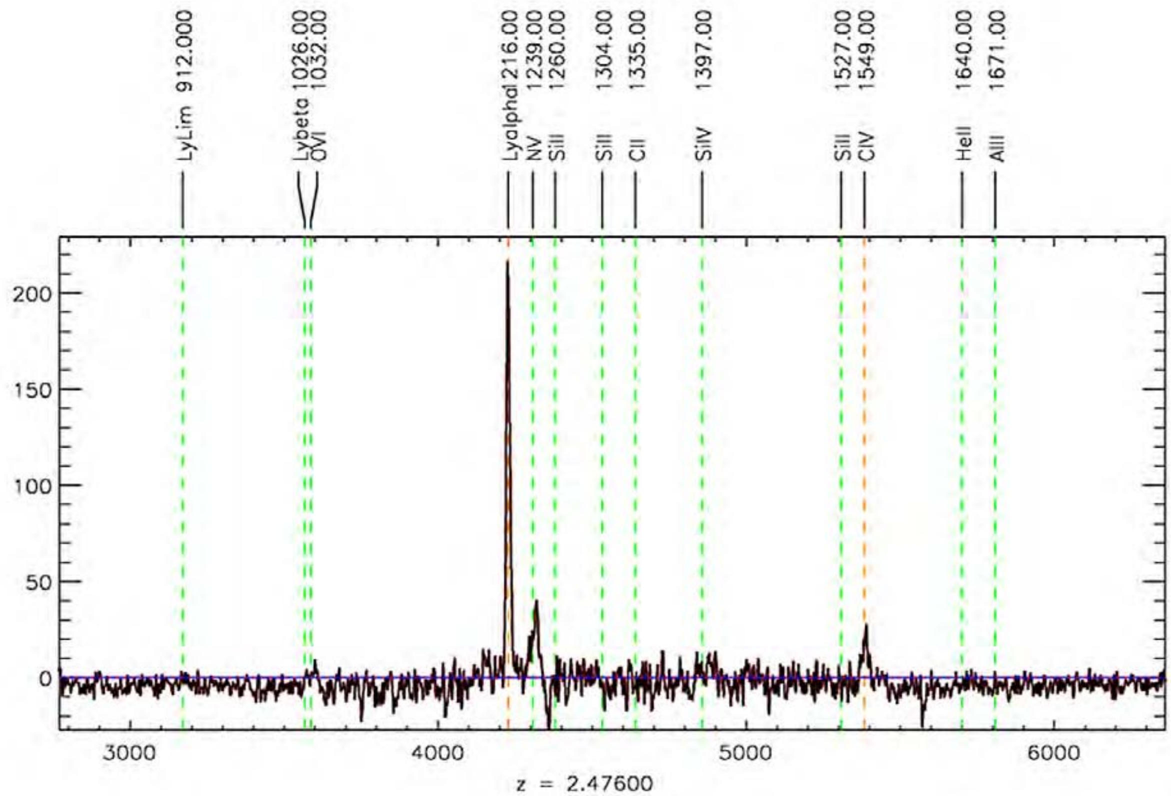
I Zw 18 as seen in the far-ultraviolet by Hubble's STIS. The broken circle indicates the region studied using the Cosmic Origins Spectrograph.

The Discovery of Lyman-alpha-emitting Galaxies

Bruce Woodgate, Carol Grady, Don Lindler, and collaborators at Goddard, the University of Indiana, University of Chicago, and the University of Hertfordshire in the UK have discovered 50 galaxies with strong Lyman-alpha emission between redshifts 2.3 and 3.4 in the last two years. Their new method is to exploit the huge cosmic volume covered by recent deep, wide photometric surveys, such as the CFHT Legacy Survey, and select those objects with excess flux in a single band, such as the green band, in the expectation that it is due to the strong Lyman alpha line shifted into that wavelength range. Then these candidate excess-green objects are observed spectroscopically to confirm or deny that they are line emitters.

Most of those found (44 of 50) have been in two deep fields of the Legacy Survey, using the WIYN telescope on Kitt Peak with the multi-fiber Hydra spectrograph, by graduate student Brian Baptista of the University of Indiana, and the remaining six have been found using the Dual Imaging Spectrograph at the Apache Point Observatory, N.M. They plan to follow up investigating the spatial and spectral structure of these objects using the new Integral Field Spectrograph currently being installed at the Apache Point Observatory.

The use of the strong Lyman alpha emission line enables the galaxies to be picked out of millions of other galaxies in the field and their redshifts deter-



Blue camera extracted spectrum of target CFHT Legacy Survey Wide3-73617, showing the possible detection of oxygen VI emission at 1032 Angstroms.

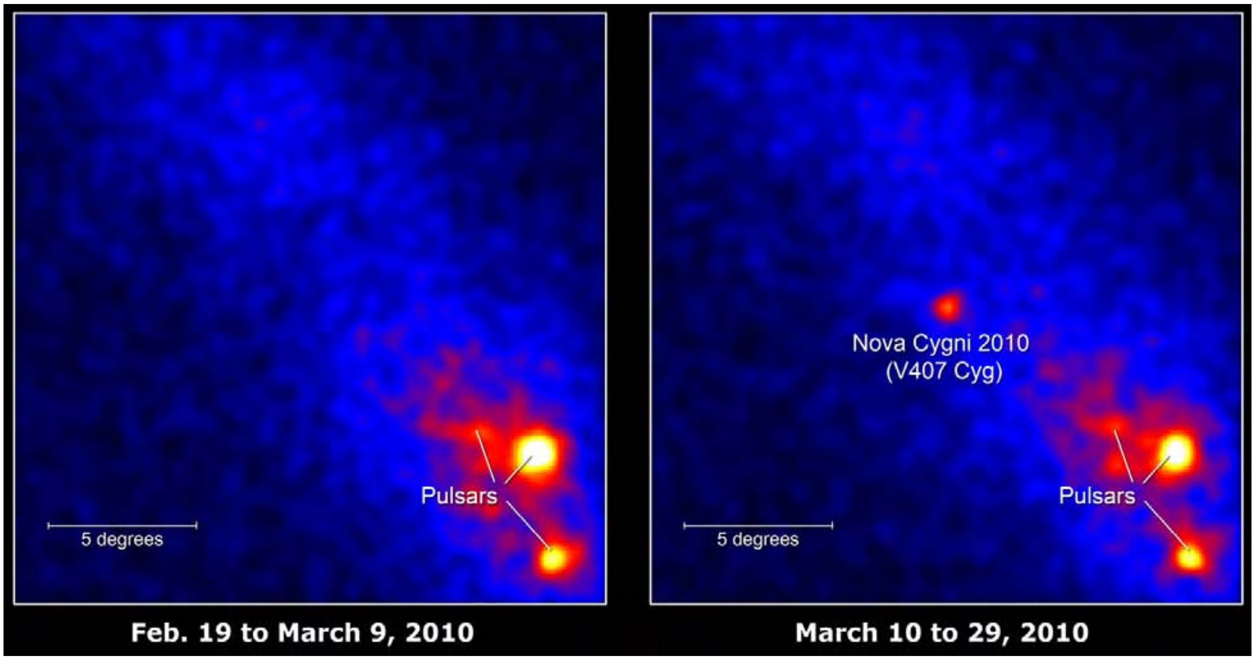
mined, so that they can be placed within the cosmic web as indicators of large scale structure, and the shapes and spectra used to determine the mechanisms of their interactions with the intergalactic medium as they emerged from their dark matter haloes 11 to 12 Gyrs ago. This is a pilot program for use of deeper and wider surveys associated with Dark energy missions, and for studies even earlier in cosmic time using JWST.

Fermi: Gamma-ray Flares from Surprising Places

The Fermi Gamma-ray Space Telescope carries the Large Area Telescope (LAT), an instrument offering unmatched sensitivity in the MeV- GeV band, a very wide field of view (~2.4 sr), and a three-hour cadence of all-sky coverage. After more than two years of observations, the LAT is revolutionizing gamma-ray variability studies and revealing some surprising results.

Although some gamma-ray populations, such as pulsars, appear steady over time, much of the gamma-ray sky changes on timescales from minutes to hours, days, weeks, and beyond. The first Fermi LAT catalog found significant monthly variability in about 30 percent of 1,451 sources. The vast majority of those are confirmed or suspected to be associated with blazars, active galactic nuclei with the particle jet close to our line of sight. However, the conditions that generate flaring and transient gamma-ray emission are not exclusive to extragalactic objects. LAT flare advocates, who monitor the sky for new and interesting outbursts, keep daily watch for activity that could be associated with phenomena occurring in our Galaxy.

V407 Cyg is the first confirmed Galactic gamma-ray transient discovered by the LAT. This symbiotic binary system contains a white dwarf with a red giant companion. On March 10, 2010, the white dwarf shed the outer layers of material accumulated over the past decades in a thermonuclear explosion, a nova. V407 Cyg appeared suddenly and for the first time as a gamma-ray source on the same day as the optical detection. The gamma-ray emission peaked within a few days, and then faded away completely by March 25. Davide Donato played a key role as the LAT flare



The gamma-ray images (E > 100 MeV) show a large section of the Cygnus region of the Galaxy for 19 days before (left) 2010 V407 Cyg, and for 19 days after the onset of the nova (right). The color scale indicates higher gamma-ray intensity. The diffuse gamma-ray emission along the Galactic Plane is visible as the blue diagonal stripe. Other bright sources are gamma-ray pulsars.

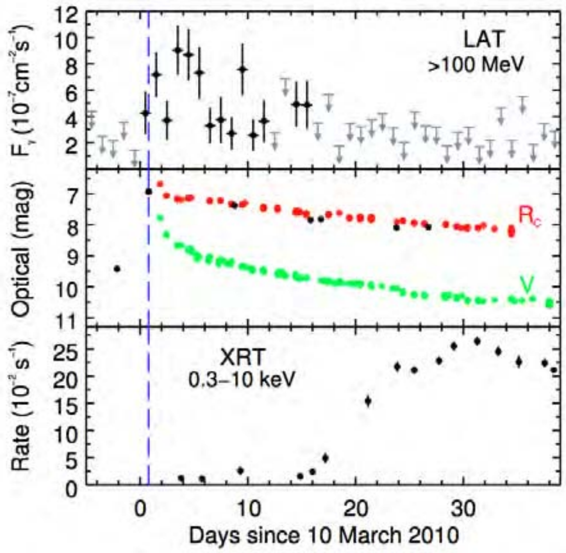
advocate during the event. While monitoring the automated data processing, he noted the presence of a new, unidentified source and alerted other team members, including former Goddard NPP Fellow Teddy Cheung, Elizabeth Hays, and Robin Corbet. The following hunt included examining Swift XRT data of the region and led to identifying the nova as the most likely counterpart. This brought in another Goddard scientist, Glenn Wahlgren, who contributed to the LAT publication and has also conducted high-resolution studies of the optical spectra of the system.

Although surprising, the association is not unreasonable. The V407 Cyg system is a great candidate for high-energy emission because it is a symbiotic binary. This means that the white dwarf accumulates material from the wind of the red giant. The resulting density and radiation gradients around the star set the stage for an asymmetric expansion of the nova shockwave and efficient conversion of the shock energy into gamma radiation. A previous nova, 2006 RS Oph, demonstrated that the expanding shock of a nova in a symbiotic binary system generates non-thermal X-ray emission. However, the presence of gamma rays above 100 MeV in V407 Cyg came as an exciting surprise and established novae as a new type of gamma-ray emitter.

The X-ray development follows an entirely different timeline from the gamma-ray emission. The initial X-ray signal was weak and then increased rapidly around 20 days after the nova. The X-ray emission not only started much later, but also continued for a longer duration than the gamma ray outburst. This is consistent with the scenario of an asymmetric shock expansion into the complex environment of the white dwarf-red giant system. The origin of the X-rays and the gamma rays are both instigated by the energy release of the nova, but are separate mechanisms

The shock created by the nova explosion may initially be symmetric, but it will not remain that way as it encounters mass at different rates in different directions as it expands outward from the white dwarf. This means that the time evolution of the expansion will have a directional dependence. The environment in the direction of the red giant favors gamma-ray production most strongly. The increasing density of the stellar wind and atmosphere allows the Sedov condition, where the swept-up mass exceeds the ejected mass, to be reached relatively quickly. The gamma-ray production should peak within a few days and then decline as the shock loses energy.

Protons and electrons undergo Fermi acceleration in the shockwave. Accelerated protons collide with



The gamma-ray (top), optical (middle), and X-ray (bottom) lightcurves show the wavelength dependence of the nova development. The blue line marks the nova appearance. The optical peak leads and fades slowly with the gamma-ray flux, binned per day, peaking a few days later. Gray arrows indicate 2 sigma upper limits. The X-ray emission brightened weeks later. The timeline reflects the progression of the shockwave into the asymmetric environment surrounding the white dwarf.

other protons to produce pions that decay to gamma rays. Accelerated electrons inverse-Compton scatter infrared radiation into the gamma-ray band. Both processes can become efficient during the adiabatic expansion and the early deceleration of the shock. The total energy released in gamma rays above 100 MeV during the outburst, 3.6 x 10^{41} erg, implies that about 9 percent of the kinetic energy of the explosion (estimated at about 10^{44} ergs) could be in accelerated protons (assuming 20 percent average efficiency for gamma rays via pion decay). This is similar to the percentage of energy transferred in supernova explosions. Although supernovae are much more energetic (~10^{51} erg) and produce a shell expansion that lasts for much longer (thousands of years), the physical conditions in the expanding shockwave of the V407 Cyg nova are similar but evolve far more rapidly.

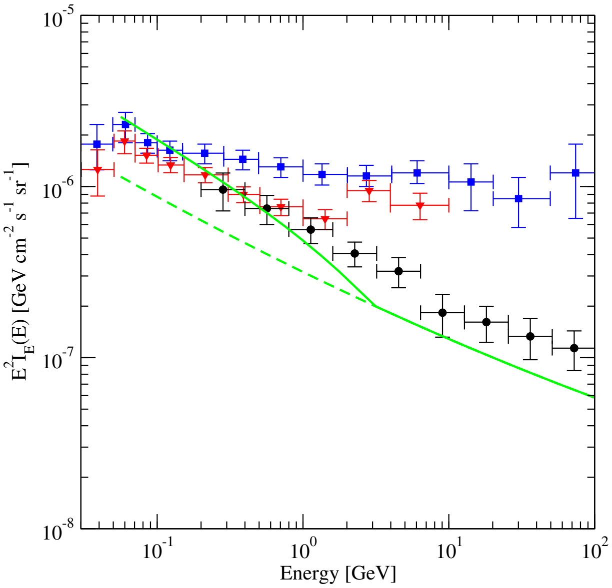
If we assume that electrons are the primary means for producing gamma rays, then the total energy in the electrons only needs to be 0.4 percent of the kinetic energy of the explosion. Both the proton and electron mechanisms are viable options to generate the observed gamma-ray lightcurve and spectrum. Despite debates about fine details of the gamma-ray production, the event clearly demonstrates the potential for significant acceleration to high energies in this class of novae. Although these events are rare, the vigilance of the LAT flare advocates guarantees discovery of future nova candidates and other exotic gamma-ray transients.

Understanding the Extragalactic Gamma-Ray Background

Floyd Stecker and Tonia Venters have made new theoretical calculations of the contributions of unresolved blazars and star-forming galaxies to the extragalactic gamma-ray background (EGB) observed by Fermi Large Area Space Telescope (LAT). Previously, the Fermi results appeared to indicate an unknown origin for the bulk of the EGB. Stecker and Venters have now shown that most of this background is consistent with being from faint unresolved sources. Of these unresolved sources, the class of active galactic nuclei known as blazars appears to supply the dominant contribution to the EGB. Blazars are by far the most numerous extragalactic sources that have been detected by gamma-ray telescopes such as the Fermi LAT and EGRET. There is also a contribution to the EGB from unresolved galaxies. This is an expected result since galaxies such as our Milky Way produce gamma-radiation through the interaction of cosmic rays with interstellar gas and radiation.

Any analysis of the contribution of extragalactic sources to the background requires some way of modeling the source count distribution to account for the number of sources below the effective sensitivity of the telescope. Determining the contribution of faint, unresolved extragalactic sources from observations relies on the ability to associate such sources with their astronomical counterparts for which redshifts can be measured. In the case of blazars, Fermi data have shown a correlation between gamma-ray brightness and radio brightness. Since source counts of radio blazars are complete to relatively much fainter luminosities, Stecker and Venters have used the radio/gamma-ray correlation to construct theoretical extensions of gamma-ray source counts to fluxes below the sensitivity for individual detection by Fermi.

The angular resolution of the telescope must also be taken into account in the analysis of the EGB. In an optical telescope, the theoretical limit to the angular resolution is determined by the wave nature of a pho-



The collective spectrum of the EGB from blazars compared with the data (solid line). The dashed line shows the spectrum derived without accounting for source confusion. The black data points are derived the new Fermi measurements; the red and blue points are based on EGRET data.

ton, i.e., the diffraction limit. For the Keck telescope this limit is 1.4 × 10^{-2} seconds of arc . However, in a gamma-ray telescope such as Fermi and EGRET, the angular resolution is determined by the particle (photon) nature of the gamma-ray. Each photon interacts in the detector and is converted to an electron-positron (e^+e^-) pair. The e^+ and e^- tracks have the rough shape of an upside-down V. Because the Coulomb scattering of the e^+ or e^- that affects its track depends on its energy, the angular resolution of a gamma-ray detector is strongly dependent on energy; it goes from ~5 deg at 100 MeV to ~0.2 deg at 10 GeV. Owing to this effect, Fermi would not resolve out as many faint steeper spectrum sources at 100 MeV than at 1 GeV; below about 1 GeV source confusion would limit the reduction of the EGB, provided that the dominant EGB is from as many unresolved point sources as estimated by Stecker and Venters. This effect, appears to be roughly manifested in Fermi and EGRET spectra, supporting the point source origin hypothesis.

The figure shows the calculated contribution of unresolved blazars to the EGB. Stecker and Venters have also calculated the component of the EGB from unresolved star-forming galaxies. There is a large uncertainty in the galaxy calculation (results not shown) owing to uncertainties in modeling cosmic ray intensities and gas densities in other galaxies. However, all such models result in a galaxy component that is lower than the blazar component. Also, the spectrum of the EGB component, which is dominated by secondary pion production and decay, falls off below 200 MeV and therefore cannot account for the EGB found by EGRET at energies between 50 and 200 MeV. In contrast, the spectrum of unresolved blazars, when accounting for the energy-dependent effects of source confusion, is consistent with the combined spectrum of both the low-energy EGRET measurements and the Fermi-LAT measurements. Interestingly, the model spectrum may account for only ~50 percent of the EGB at energies above 10 GeV. This is the energy range where gamma-rays from the annihilation of dark matter particles may contribute significantly to the EGB.

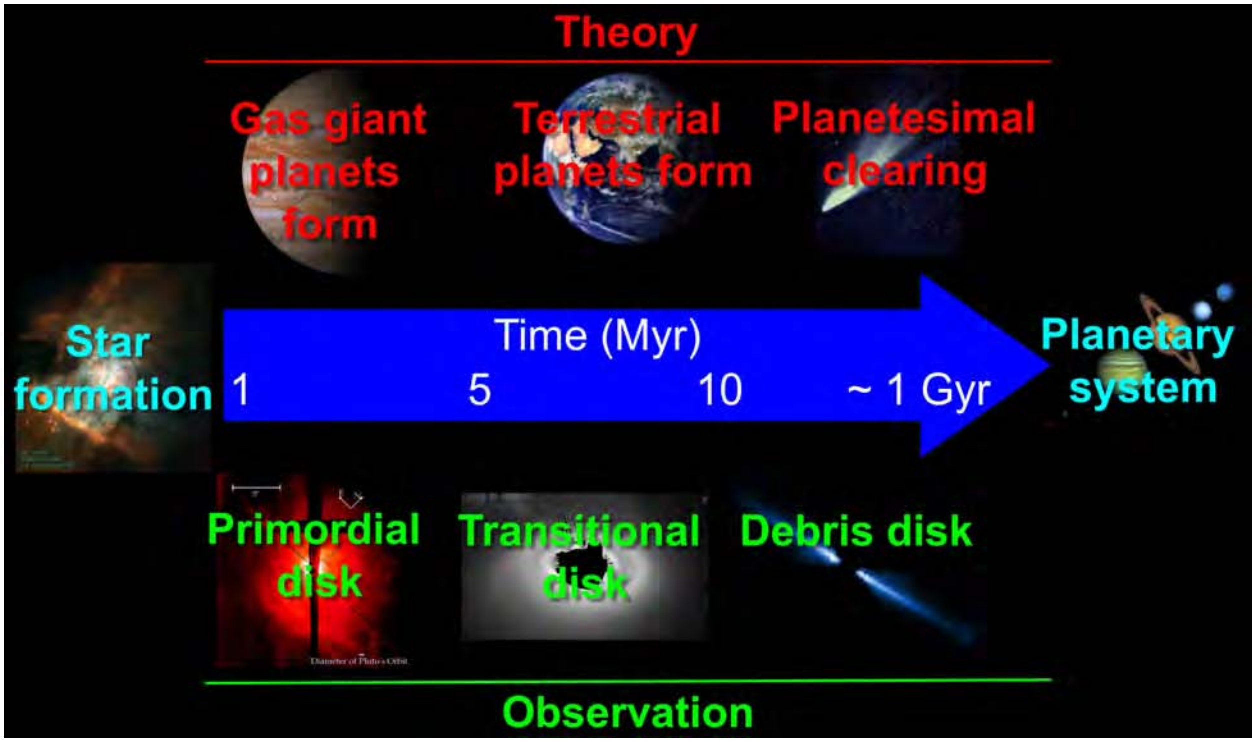
The results of this study support the hypothesis that most of the extragalactic gamma-ray background is made up of thousands of unresolved blazars, many more than have been individually observed by astronomers at other wavelengths. This result also has implications for star formation and cosmic ray production in young galaxies and for estimating the number of active galaxies in the universe. Such galaxies have supermassive black holes at their centers.

The Evolution of Planet-Forming Disks with the Herschel Space Observatory

The Herschel Space Observatory, a far-infrared/submillimeter telescope launched in May 2009 by the European Space Agency, is eminently well suited to spearhead the next big advances in our knowledge of planet formation, protoplanetary disk evolution and debris disks. Drs. Aki Roberge, William Danchi, and Carol Grady are participating in two Herschel Open Time Key Programs aimed at these topics. One project, GASPS, will study gas abundances and chemistry in protoplanetary disks over the planet-forming phase. The other, DUNES, will sensitively probe the Sun's nearest neighbors for signs of cold debris disks associated with extrasolar Kuiper Belts.

Gas in Protoplantary Systems (GASPS)

Herschel provides the first opportunity to sensitively measure gas abundances in a large number of disk systems. To this end, the GASPS project is executing a survey of young stars for far-IR gas emission lines using the PACS spectrograph on Herschel. GASPS will



Schematic illustrating the stages in formation of a mature planetary system (top) and the evolution of young circumstellar disks in which planets form (bottom). Credit: A. Roberge

observe roughly 200 targets, which were carefully chosen to span a wide range of spectral types. The stellar ages are between 1 million and a few tens of millions of years, covering the critical gas dissipation phase into the young debris disk phase. It's during this phase that protoplanetary disks transform from disks of interstellar material left over from star formation to young planetary systems in the late stages of terrestrial planet formation.

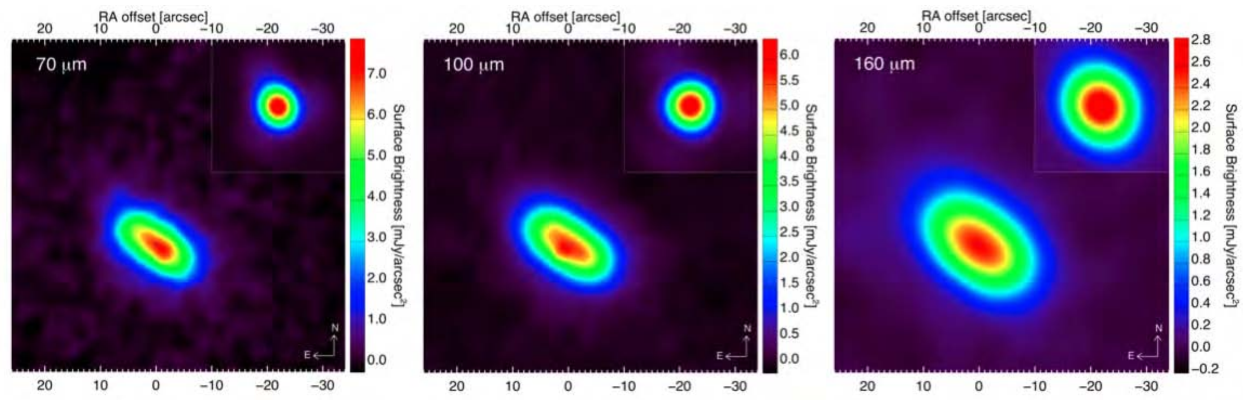
The GASPS spectra will focus on detecting one ionized carbon emission line and two neutral oxygen lines, as well as several water vapor lines. The first result will be direct measurement of relative gas abundances as functions of age and stellar mass. The team plans to use sophisticated new thermochemical disk models to convert relative abundances into actual gas masses. A detailed description of the team's disk modeling code, called ProDiMo, may be found in Woitke et al. (2009).

To date, the GASPS project has been detecting neutral oxygen emission from disk systems spanning a wide range of parameters, including spectral type, disk mass, and accretion rate. The emission tentatively appears correlated with the strength of the dust continuum emission, but no other parameters so far. Ionized carbon emission, on the other hand, is weaker than expected based on pre-launch modeling, providing a challenge to the disk thermochemical model described above. The GASPS team has published four refereed journal articles during the last year (Mathews et al. 2010, Thi et al. 2010, Meeus et al. 2010, Pinte et al. 2010) and several others are close to submission.

Dust Around Nearby Stars (DUNES)

The DUNES project is using the PACS instrument to obtain far-IR photometry of nearby solar-type stars, sensitively probing them for circumstellar dust coming from planetesimal collisions within extrasolar Kuiper Belts. This survey will push to unprecedentedly low dust levels and provide the most sensitive census to date of planetary material around the Sun's nearest neighbors. These stars will be the primary targets of future efforts to directly detect and characterize potentially habitable terrestrial planets (i.e., exoEarths).

Already, the DUNES project has been highly successful. As of the end of 2010, about 65 percent of the data have been obtained and every target has been detected at the expected level. Many targets show excess emission coming from cold circumstellar dust, at a higher rate than seen in earlier surveys of F, G, and



DUNES imaging of q[1] Eri, a planet-hosting star (HD10647, type F9V). For the first time, this debris disk is resolved at far-IR wavelengths. Each panel shows a basic calibrated PACS image, with the point-spread function in the inset panel at the upper right. The disk is resolved at all three wavelengths and appears to be a roughly 40 AU-wide ring located ~ 85 AU from the star (Liseau et al. 2010).

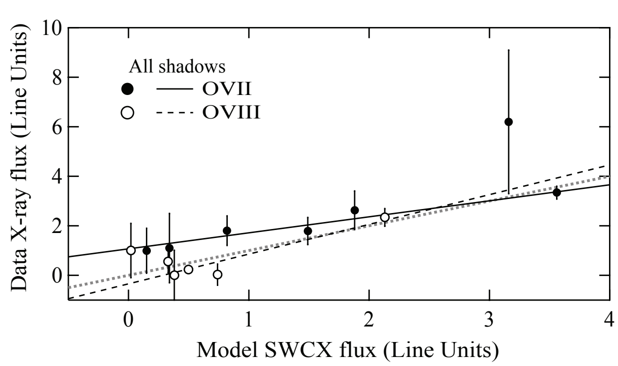
K stars with the Spitzer Space Telescope. Furthermore, about half of detected disks are spatially resolved at one or more wavelengths; in most cases, these are the first images of these disks in thermal emission. Most notably, DUNES appears to have discovered a new class of ultra-cold debris disks that present a severe challenge to both debris disk modeling codes and to theories of debris disk evolution.

Charge Exchange X-ray Emission in the Heliosphere and Beyond

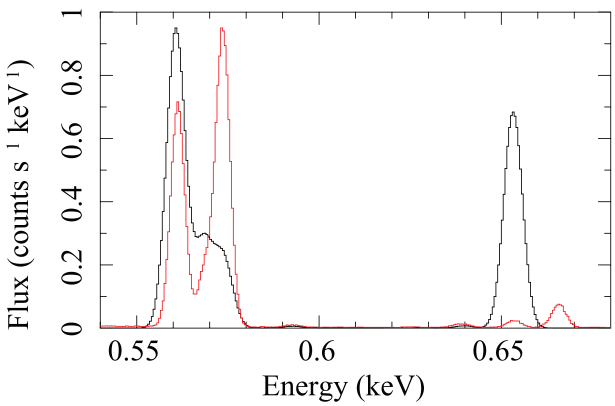
The importance of charge-exchange (CX) emission in X-ray astrophysics emerged about 15 years ago with the discovery of bright X-ray emission from comet Hyakutake, which arose as a result of processes between neutral atoms in the comet's atmosphere and highly charged ions in the solar wind; a number of comets are now known to exhibit X-ray emission via CX processes.

Charge exchange (CX) is a basic physical process involving the transfer of bound electrons between colliding particles. CX X-ray emission through decay of excited states of highly-charged recipient ions occurs in many astrophysical circumstances. Diffuse CX emission from the heliosphere and geocorona (solar wind charge exchange, SWCX) adds a variable background to essentially all X-ray observations at energies below 1.5 keV. It is a significant contributor to the diffuse soft X-ray background (SXRB) in competition with the Local Hot Bubble (LHB) thought to be a hot plasma cavity of about 100 pc around the Sun. The LHB, galactic halo emission and unresolved extragalactic sources constitute the invariable cosmic SXRB, while the SWCX varies because of geometric effects and changing solar activity.

Dimitra Koutroumpa, Steve Snowden, and collaborators have been studying the heliospheric SWCX contribution to the SXRB through several observational campaigns. Most recently, they analysed XMM-Newton observations toward the nearby molecular cloud MBM 12, which absorbs distant galactic diffuse emission. This allows a direct comparison of the local SWCX and LHB emission (Koutroumpa et al. 2011). Repeated observations toward the same field of view allow detection of both temporal and geometric SWCX variations, and Koutroumpa et al. have compiled a summary of seven observations toward three different shadowing fields observed with XMM-Newton, Chandra, and Suzaku from 2000 to 2008.



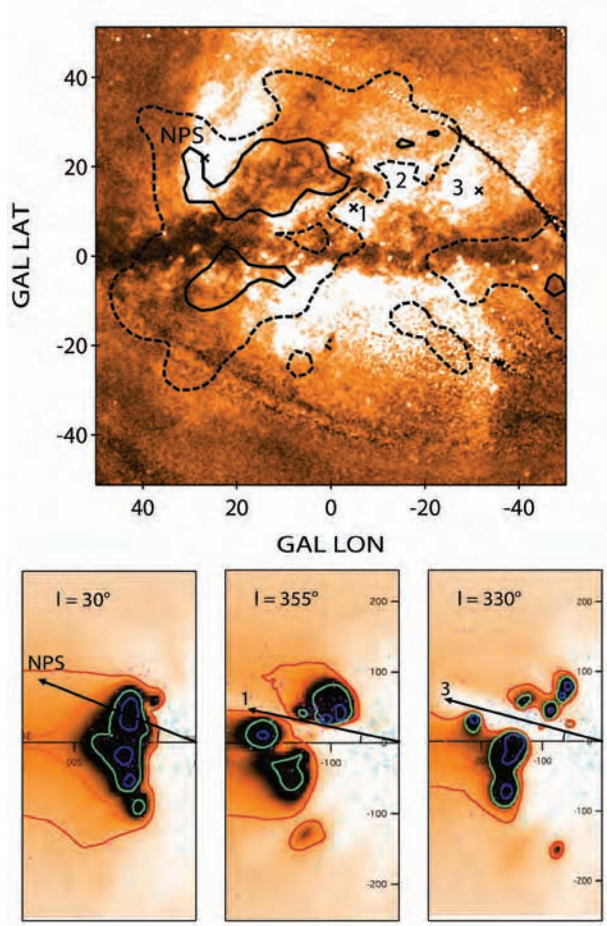
Data vs. SWCX model correlation for shadowing observations with Chandra, Suzaku, and XMM-Newton. The filled circles and plain line represent OVII while the open circles and dashed line stand for OVIII. The gray dotted line traces the y=x line.



Model thermal (red) and model charge exchange (black) spectra of the O VII and O VIII lines folded through the Spectrum Röntgen Gamma calorimeter response.

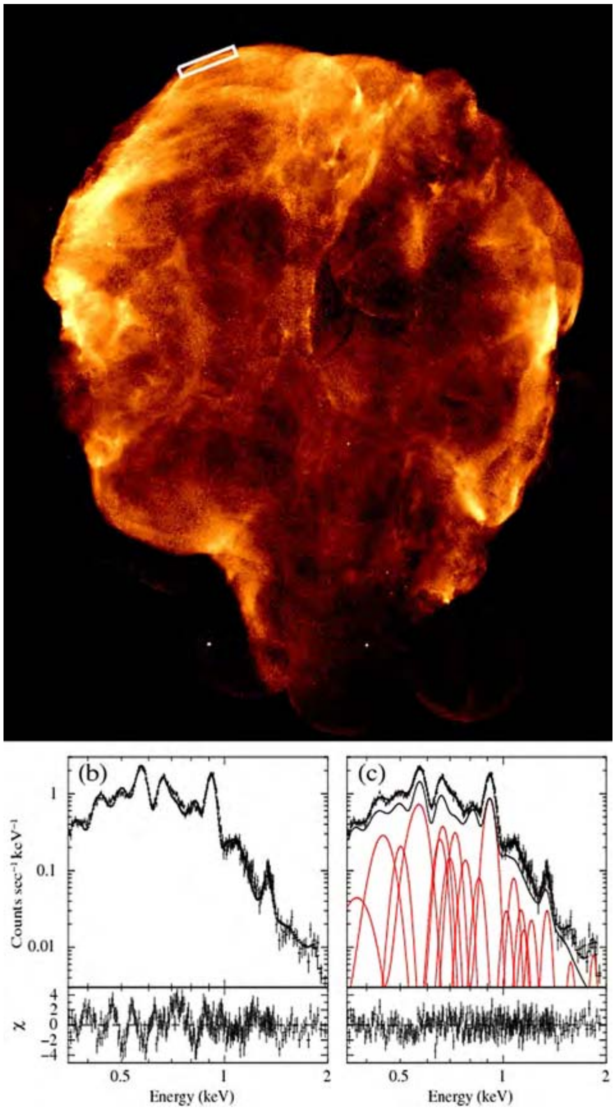
In the soft X-ray energy range of XMM-Newton (as well as Chandra and Suzaku), SWCX emission mainly contributes to the two oxygen lines at 0.57 keV (OVII triplet) and 0.65 keV (OVIII Lyman-alpha). Koutroumpa modeled the SWCX oxygen emission variations with a heliospheric SWCX code (taking into account solar activity and observation geometry) and compared the observed flux values. The heliospheric SWCX emission may account for the entire observed local OVIII background, and there is no need for emission from the LHB in this line. For OVII, in general, the model predictions suggest that at least half of the observed values are due to SWCX emission from the heliosphere. A new series of XMM-Newton observations toward MBM 12 (in collaboration with the University of Miami) will improve the statistical significance of this comparison.

In a different context, Koutroumpa, Snowden, and collaborators have been investigating the CX X-ray emission from interstellar interfaces between hot and cool gas. The team has been using the characteristic spectral signature of the OVII triplet to identify the emission mechanism. Indeed, although both CX and thermal plasma emission produce the same spectral lines in the soft X-ray band (because both mechanisms involve de-excitation of the same highly charged ions), line intensity ratios in triplets of the He-like ion OVII (and NeIX) are very different. While thermal emission has a very strong resonance OVII line (574 eV) SWCX emission favours the forbidden transition (560.9 eV). For diffuse sources, with the spectral resolution of current missions, it is very difficult to measure the individual line ratios, but it is possible to detect an apparent displacement in energy of the unresolved centroid.



Top: ROSAT 3/4 keV emission map displaying the central region of the NPS/Loop I feature. Superimposed are sodium isocolumn density contours at two levels that correspond to 30- percent and 70-percent absorption of 3/4 keV photons, respectively. The three crosses show the directions of the observations analyzed. Bottom: Inverted Na I volume density in vertical half-planes containing the Sun (on the right) and directed approximately towards the galactic longitude of the observations. White is low density, and black represents dense neutral gas.

In principle, CX-induced X-ray emission could be produced at any astrophysical site where hot plasma interacts with (partially) neutral gas. One very promising site is the thin post-shock layer in supernova remnants (SNRs). SNR shocks are collisionless and both unshocked cold neutrals and shocked hot ions can be present just behind the shock front. In fact, observational evidence of CX emission has been obtained as the broad component of Ha emission in many SNRs



Top: Direct ROSAT image of the Cygnus Loop, a middle-aged (~10,000-year-old) Galactic supernova remnant. Spectral data from the region within the white box is shown below. Bottom left: Suzaku/XIS spectrum, along with the best-fit model consisting of a pure thermal emission model. The lower panel shows the residuals. Bottom right: The same data, but with the best-fit model consisting of a pure thermal emission model (a solid curve in black) plus a number of Gaussian components (in red) for CX line emission.

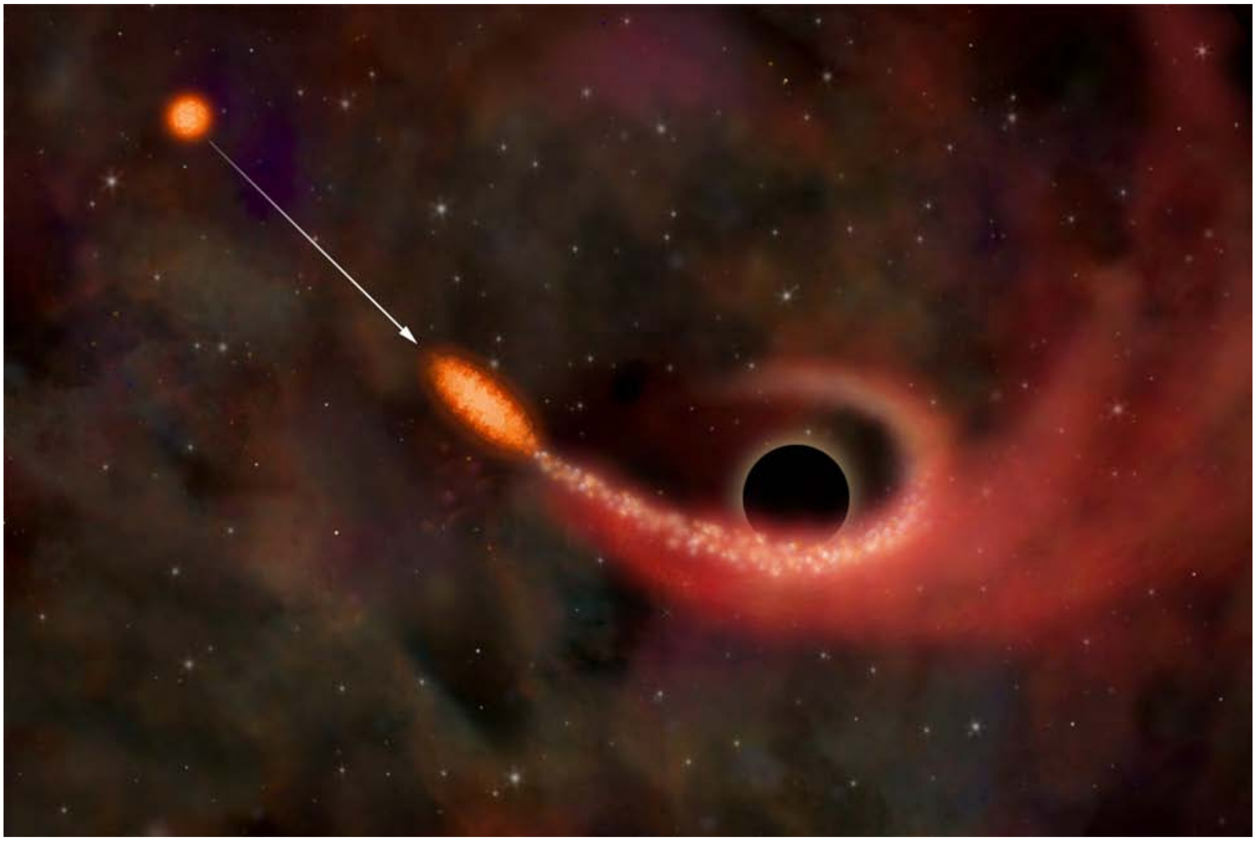
for more than 30 years. On the other hand, CX-induced X-ray emission has not yet been detected firmly. Taking account of the CX emission could be extremely important for understanding the true properties of the shocked plasma, since the undetected presence of CX emission leads to incorrect plasma parameters (e.g., the metal abundance and the electron temperature) if we interpret the CX-contaminated X-ray spectra with pure thermal emission models.

X-ray spectroscopic measurements of the Cygnus Loop SNR indicate that metal abundances throughout most of the remnant's rim are depleted to ~0.2 times the solar value. However, recent X-ray studies have revealed in some narrow regions along the outermost rim anomalously “enhanced” abundances (up to ~1 solar). The reason for these anomalous abundances had been puzzling. Satoru Katsuda and a team of scientists (Katsuda et al. 2011) examined X-ray spectra in annular sectors covering nearly the entire rim of the Cygnus Loop using Suzaku (21 pointings) and XMM-Newton (1 pointing). They found that spectra in the "enhanced" abundance regions commonly show a strong emission feature at ~0.7 keV, which is most likely a complex of He-like Oxygen K($\alpha+\beta+\gamma$) lines. The intensity of this emission relative to the He-like Oxygen Kα complex appears to be too high to be explained as thermal emission.

This fact, as well as the spatial concentration of the anomalous abundances in the outermost rim, led the team to propose an origin from CX processes between neutrals and H-like Oxygen. The team then interpreted that the ~0.7 keV emission and possible other CX line emission could lead to the inference of apparently “enhanced” metal abundances using pure thermal emission models. In fact, this model can represent the data much better than the pure thermal emission model. The Astro-H soft X-ray spectrometer with superior spectral resolution is eagerly awaited for further studies of the Cygnus Loop and other SNRs.

Trojan Analogs in Binary Black Hole Systems

Astrophysics research at Goddard spans an enormous variety of objects, from extrasolar planets to supermassive black holes—celestial bodies that are separated by more than ten orders of magnitude in mass and distance from the Earth. Though vastly different in size, both exoplanets and black holes have the ability to capture the public’s imagination and fascination with astronomy, a point not lost on the authors of the recent decadal report, *New Worlds, New Horizons*. They may be at opposite extremes of the cosmic growth chart, yet it turns out that these systems may not be so different in their underlying dynamics, according to new work by Jeremy Schnittman, a researcher in ASD’s Gravitational Astrophysics Lab.

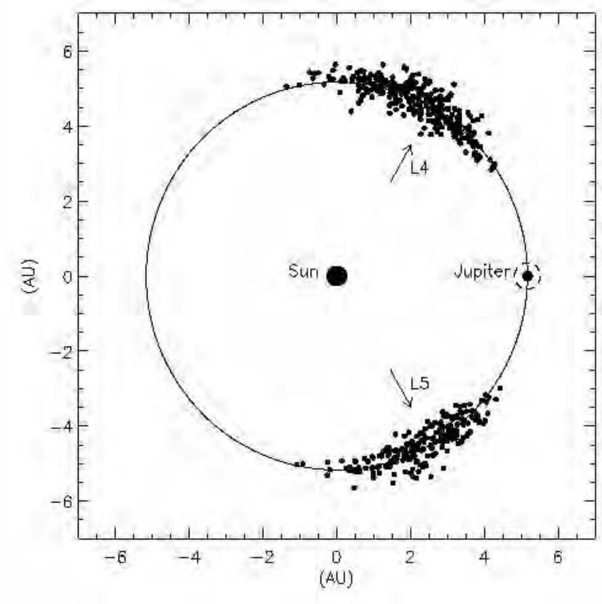


Artist's concept of a star being tidally disrupted by a supermassive black hole. Some of the gaseous debris is ejected while the rest forms a hot, dense accretion disk around the black hole. Credit: M. Weiss/Chandra X-ray Center/NASA

Just as exoplanets are most often discovered by observing their host stars, black holes must also be seen indirectly, by measuring the light from the surrounding stars and gas. Taking the analogy one step farther, we know from our own solar system that, in addition to the planets, a considerable amount "junk"—asteroids and comets—also orbits the sun. The orbits of these asteroids are strongly influenced by resonant interactions with Jupiter, the dominant player in solar system dynamics, second only to the Sun. One particularly interesting family of asteroids, called the Trojans, move in near-perfect synchronicity with Jupiter, always just one step ahead or behind in their orbit around the Sun.

Schnittman showed that in many binary black hole systems, where two supermassive black holes orbit each other like Jupiter and the Sun, similar resonant orbits may be populated by Trojan analogs. Yet instead of small, irregular asteroids a few kilometers across, the black hole system is be able to capture and shepherd entire stellar systems locked into stable orbits around the L4 and L5 Lagrange equilibrium points. While there is an undeniable beauty underlying the self-similar behavior and symmetry of these vastly different systems, there are also important astrophysical implications of the Trojan analogs. Foremost among these is the promise of using the trapped stars and gas as sources for electromagnetic counterparts to the underlying (and otherwise invisible) black holes. During their final inspiral and merger, the black holes emit copious amounts of energy in the form of gravitational radiation—but these waves are almost as difficult to see as the black holes themselves. LISA will be able to detect just such gravitational waves with great sensitivity, but will be able to identify the location of the waves' origin with only moderate accuracy. To more precisely determine the host galaxy—which may likely be billions of light-years away—we ideally need a flash of light that can be seen by more conventional telescopes with high spatial resolution.

One of the most promising sources that could actually produce such a bright signal at cosmological distances is the tidal disruption of a main sequence star by a supermassive black hole. In such an event, any



The distribution of Trojan asteroids in the Sun-Jupiter binary system. More than 5,000 objects are now known to occupy stable orbits around the L4 and L5 Lagrange points. Credit: Scott S. Sheppard/Carnegie Institution of Washington

star that approaches too close is torn apart by the enormous gravitational forces near the black hole. Some of the resulting gas is ejected, and some gets swallowed promptly by the black hole. The rest forms a massive accretion disk that can easily outshine the entire galaxy for weeks afterwards, briefly surpassing the black hole's Eddington luminosity by factors of 10–100, primarily in the soft X-ray band.

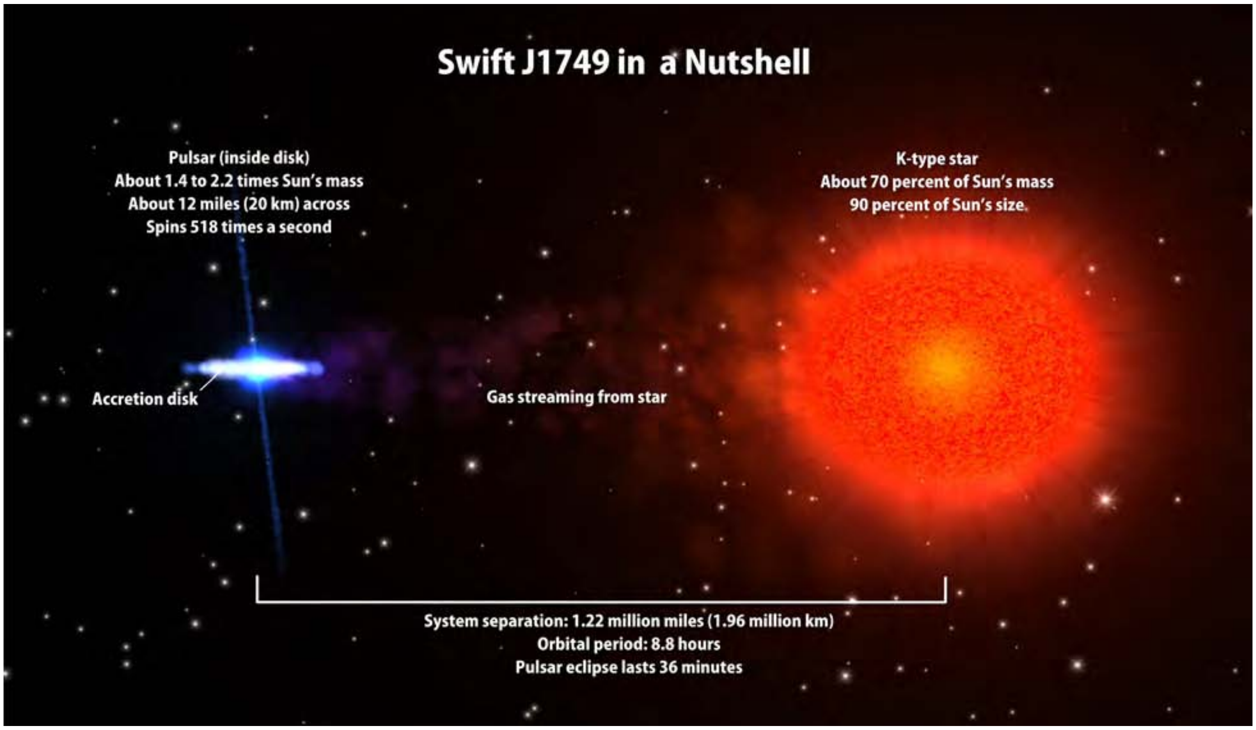
While these extraordinary events occur in ordinary galaxies hosting single black holes, they are rare and unpredictable (roughly one per galaxy per 10,000 years). However, in a black hole binary system, they may well be unavoidable consequences of the merger process. Following the merger of two galaxies, each of their black holes will sink towards the center of the new galaxy via dynamical interactions with the surrounding stars and gas, eventually forming a tight binary system with orbital separation of ~10 milliparsec. As we know from our own galactic center, there are dozens of stars present on such scales, not to mention a great deal of gas and dust as well. Any material that gets captured into the Lagrange points at this relatively large binary separation will remain trapped there over the subsequent billion years or so that it takes for the black holes to spiral together via gravitational radiation, shepherding the stars and gas along with them, and ultimately resulting in a bright accretion flare days to weeks before the final merger.

Furthermore, with advance warning from LISA, we will know roughly *where* to look and exactly *when* to look for the corresponding X-ray burst, catching the merger in the act with a smoking gun. Combining the electromagnetic and gravitational wave signals opens up a myriad of scientific opportunities, allowing us to study cosmic acceleration, galaxy formation and evolution, and peer deep into the maelstrom surrounding active galactic nuclei.

Millisecond Pulsar Eclipses: Weighing a Neutron Star

Neutron stars are compact remnants that are formed in the death of a massive star, a supernova explosion. These stars are only about 15 miles across yet contain up to twice the mass of the Sun. This makes them by far the densest objects we know of in the universe. Scientists would very much like to get their hands on that dense matter in the core of neutron stars because it would enable them to test physical theories of matter under the most extreme gravity conditions. But that's not likely to happen into the foreseeable future, if ever, since earthly laboratories simply cannot produce the same conditions. One way to overcome this problem is to look to the skies for extreme objects like neutron stars. Measurements of two basic properties of a single neutron star—its mass and radius—reveal a lot about the structure of the dense matter inside the star and constrains the so-called equation of state of nuclear matter.

It's not easy to measure neutron stars when the target is half a galaxy away, but nature has provided some circumstances that make it possible, though challenging. Neutron stars in close binary systems can occasionally capture some matter from their binary companion star. When this happens—a process known as accretion—they become bright X-ray sources that can be studied with X-ray observatories in space. One such observatory is the Rossi X-ray Timing Explorer (RXTE), which was launched in 1995 as a partnership of NASA's Goddard Space Flight Center, the Massachusetts Institute of Technology, and the University of California at San Diego. RXTE mission and science operations are performed at NASA's GSFC. At the end of 2010, RXTE celebrated its fifteenth anniversary on orbit and continues to provide new discoveries.

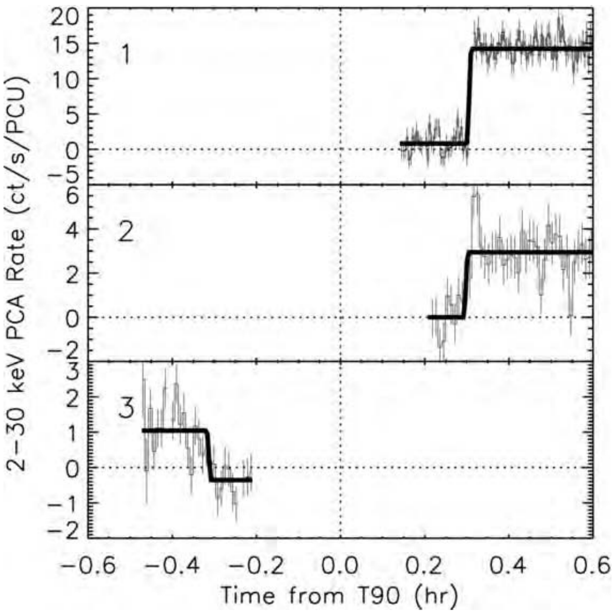


Swift J1749.4–2807 is the first accreting millisecond pulsar to undergo eclipses. The pulsar and its companion star are separated by 1.22 million miles, or about five times the distance between Earth and the Moon. Irradiated by the pulsar's intense X-rays, the star's outer layers puff up to make it about 20 percent larger than a star of its mass and age should be. This artist's rendering includes additional data about the system. Credit: NASA/GSFC

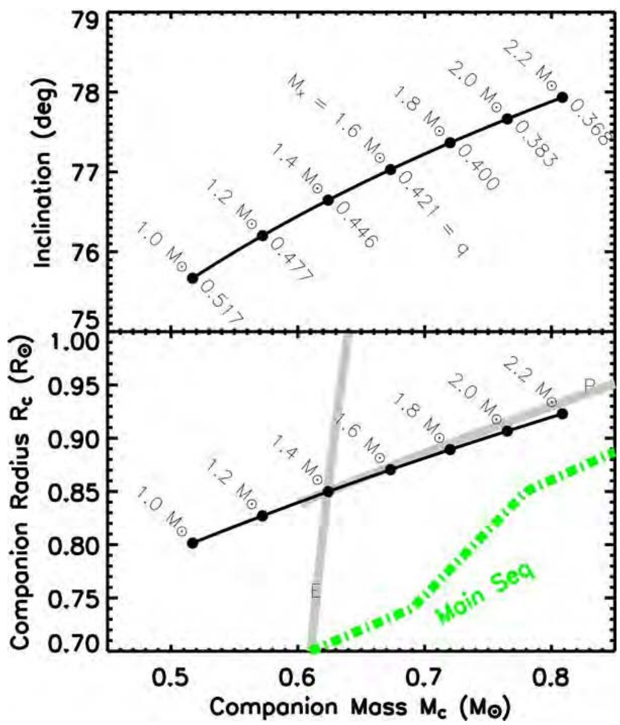
RXTE has found that about a dozen accreting neutron stars are fast-spinning pulsars (called Accreting Millisecond Pulsars, AMPs). X-ray pulses tracked by RXTE measure the rotation of the neutron star, some of which are spinning faster than the blades of a high-speed kitchen blender.

Drs. Craig Markwardt and Tod Strohmayer, X-ray Astrophysics Branch, have been using RXTE observations to study AMPs in an effort to try and understand super-dense neutron star interiors. A recently discovered AMP, known as Swift J1749.4–2807 (hereafter J1749), was discovered as an X-ray source in June 2006, when a brief accretion outburst brought it to the attention of NASA's Swift satellite. During a new outburst in April 2010, RXTE found that the previously discovered source is in fact a 518-Hz spinning pulsar. Careful timing of its X-ray pulses with RXTE revealed that the neutron star is in an 8.82-hour circular orbit with a low mass companion star that possesses about two-thirds the mass of our own sun. Just as a radar gun uses the Doppler effect to measure the speed of a baseball pitch, RXTE's tracking of the X-ray pulses from the spinning neutron star lets astronomers measure the speed of the star in its orbit. This information is enough to measure the size of the neutron star's orbit and its velocity, but it is not quite enough to accurately measure the neutron star's mass.

However, RXTE also found another remarkable property of this AMP: J1749's neutron star is eclipsed every orbit by its companion star. During the week-long April outburst of J1749, Markwardt and Strohmayer found three periods when its X-ray emission briefly disappeared. Each eclipse, which lasts 36 minutes, occurs whenever the neutron star passes behind its binary companion star. This is the first time X-ray eclipses have been seen from a fast-spinning, accreting neutron star. The duration of the eclipse gives important additional information about the size of the companion star and the angle at which the orbital plane is tilted with respect to the observer's line of sight. When this information is combined with the X-ray-pulse timing, it provides an intimate portrait of the binary system and its stellar members but doesn't quite allow for a precision neutron star mass measurement—yet.



X-ray light-curve segments of Swift J1749.4–2807, showing eclipse features. The RXTE observations captured three eclipse transitions, known as ingresses and egresses. Due to RXTE observing coverage, it was not possible to observe a single complete eclipse. Each panel is centered on the nearest epoch of T90 based on pulse-timing data, which is the expected epoch of mid-eclipse. The best-fit individual eclipse models are also shown (thick black line).



Joint eclipse and pulse-timing solution for J1749, assuming a Roche-lobe-filling companion star, for both the binary inclination (top) and companion radius (bottom). The solid black lines show the allowed solutions for the measured parameters of Swift J1749.4–2807 for a range of neutron star masses, M_x, and binary mass ratios, $q = M_c/M_x$, as indicated. The curve for main-sequence stars from Zombeck (1982) is also shown (green). The bottom panel shows an example of how the constraints from pulse timing and the Roche-lobe constraint (P) and eclipse duration (E) intersect at a single point for a 1.4 M_{sun} neutron star. The actual uncertainties are thinner than the plotted lines.

One additional measurement is required to uniquely solve for the masses of both stars in the binary: the mass or velocity of the companion star. If it can be independently determined, then the combination of pulsar timing, eclipse data and primary mass/velocity would give precise mass measurements for each star in the binary. One way to do this is to search for optical or infrared absorption lines from the companion star. Doppler shifts in the lines produced by its orbital motion would constrain the companion star's velocity. At present, such observations have not been attempted because J1749 disappeared from view before its exact location in the sky could be determined accurately enough for the largest ground-based telescopes to find.

However, a pioneering X-ray measurement well within the capability of RXTE may make a hunt for the star irrelevant. One consequence of relativity is that a signal—such as a radio wave or an X-ray pulse—experiences a slight timing delay when it passes very close to a massive object. First proposed by Irwin Shapiro at the Massachusetts Institute of Technology (MIT) in Cambridge, Mass., in 1964 as a new test for predictions of Einstein's relativity, the delay has been demonstrated repeatedly using radio signals bounced off of Mercury and Venus and experiments involving spacecraft communications. Thus, high-precision measurements of J1749's X-ray pulses just before and after an eclipse could reveal a Shapiro delay. For J1749, the predicted delay is 21 microseconds, or 10,000 times faster than the blink of an eye. But RXTE's superior timing resolution allows it to record changes 7 times more rapid. With only three eclipses observed during the 2010 outburst, RXTE hasn't yet captured enough data to reveal a large delay. However, the measurements set a limit on how massive the normal star can be. Markwardt and Strohmayer's study shows that if the star's mass was greater than 2.2 times the Sun's, RXTE would have detected the Shapiro delay.

Supernova Shock Interactions

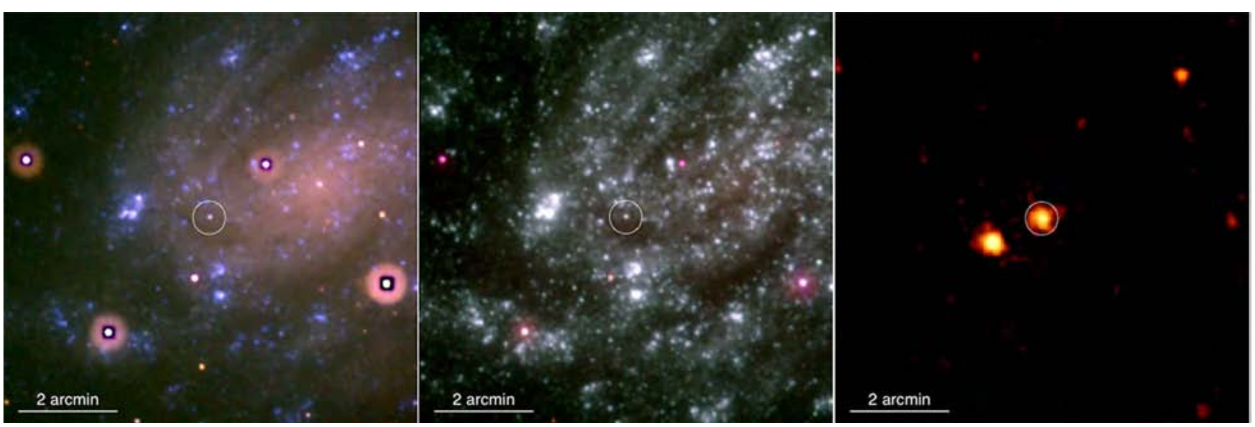
Core-collapse supernovae are the final stages in the evolution of stars with zero-age main sequence masses greater than 8 solar masses. They are among the most energetic phenomena in the universe, releasing more than 10^{51} erg in a few seconds. The explosion of a core collapse supernova in a dense environment produces a fast shock wave in the circumstellar material (CSM) and a reverse shock wave into the outer supernova ejecta. Two characteristic regions of X-ray emission are formed by the interaction: the forward shock wave in the CSM at 10,000 km s^{-1} produces gas with a temperature ~ 10^9 K, and the reverse shock wave in the supernova ejecta, traveling at a speed 1,000 km s^{-1} less than the forward shock, produces gas with 10^7 K. The reverse shock is formed where the freely expanding supernova ejecta catches up with the CSM shocked by the blast wave. Gas heated to such high temperatures produces radiation predominantly in the X-ray range. X-ray emission from this interaction is expected for all core collapse (Type Ib/c and II)supernovae with substantial CSM established by the massive progenitors.

Over the past three decades, searches for X-ray emitting supernovae have been successful for only a relatively small number of events in the near aftermath (days to months) of the explosion. While the primary goal of the Swift mission is to study GRBs, it has proven to be an invaluable tool to the study of transient phenomena. During the last five years, Swift has detected and monitored 20 new X-ray supernovae, doubling the number known (now 46). The large sample of X-ray supernovae allows, for the first time, a comparative study of the circumstellar environments and wind properties of the progenitors.

The detection of SN 2006bp with Swift in X-rays for up to 12 days after the explosion indicated that the outgoing shock and ejecta interact strongly with the CSM. A study led by Luc Dessart and his colleagues however, showed that the interaction had no measurable effect on the UV and the optical flux evolution.

While the vast majority of all supernovae fade rapidly in X-rays over the days and weeks following the explosion, Swift detected a notable exceptions: The peculiar Type Ib SN 2006jc showed a unique rise of the X-ray emission by a factor of ~5 over a period of four months, followed by a rapid decline. Stefan Immler and his colleagues interpreted the unique X-ray and UV properties as a result of the supernova shock interacting with a shell of material that was deposited by an outburst of the supernova progenitor two years prior to the explosion. The results are consistent with the explosion of a Wolf-Rayet star that underwent an episodic mass ejection qualitatively similar to those of luminous blue variable stars. This led to the formation of a dense (~10^7 cm^{-3}) shell at a distance of ~10^{16} cm from the site of the explosion, which expanded with the Wolf-Rayet wind at a velocity of (1300 ± 300) km s^{-1}.

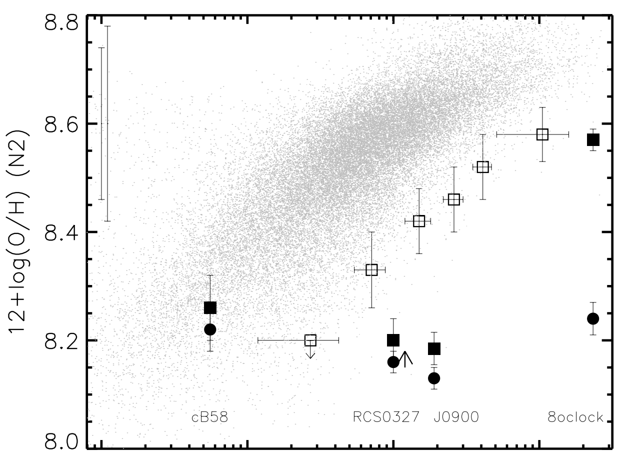
A dramatic upturn in the *u* and *uvw*1 (λ_c = 2600 Å) light curves occurred for SN 2008ax on day 4 after an initial rapid decline, which is attributed to adiabatic cooling after the initial shock breakout by Pete Roming and his colleagues. This rapid decline and upturn is reminiscent of the Type IIb SN 1993J on day 6 after the explosion. A fading X-ray source is also located at the position of SN 2008ax, implying an interaction of the SN shock with the surrounding circumstellar



The image shows the field of Supernova 2010da in the nearby galaxy NGC 300 as observed by Swift's Ultraviolet/Optical Telescope in the optical (left), UV (middle), and with the X-Ray Telescope in X-rays (right).

material and a mass-loss rate of the progenitor of a few 10^{-6} M_{sun} yr^{-1}. Combining the Swift UV, optical, and X-ray data with data taken at radio wavelengths and comparison to models of helium exploding stars implies that the progenitor of SN 2008ax was an unmixed star in an interacting binary system with an ejecta mass of 2.9 M_{sun}, and a nickel mass of 0.06 M_{sun}.

While X-ray emission is expected for core collapse supernovae situated in a dense, wind-blown environment, no X-ray emission is expected from Type Ia supernovae if they are in a double-degenerate binary system. However, if supernovae Ia are in single degenerate systems where the white dwarf has a stellar binary companion, X-rays would be produced if the supernova's outgoing shock interacted with the mass lost by the companion star. To probe these scenarios, Brock Russell and Stefan Immler used all available Swift X-ray data from a sample of 48 nearby Type Ia supernovae and applied stacking analysis to obtain an ultra-deep exposure time of 2.6 Ms. No X-ray emission was found at the position of the stacked supernovae, placing low upper limits on the mass lost in stellar winds of possible companion stars (~10^{-7} M_{sun} yr^{-1}), challenging single-degenerate models for the origins of Type Ia supernovae.



The relationship between stellar mass and metalicity at z=0 and z=2. SDSS galaxies define the z=0 relation (grey cloud). The z=2 relation is shown by stacked spectra of the unlensed z=2 LBGs from Erb et al. (2006) (hollow squares), as well as four lensed galaxies at z 2(filled points): J0900+2234 from Bian et al. (2010); cB58 from Teplitz et al. (2000) and Siana et al. (2008); the 8 o'clock arc from Finkelstein et al. (2009); and RCS0327 (Rigby et al. 2011). Lensed galaxies are allowing Rigby and collaborators to explore the shape and the evolution of the mass-metallicity relation.

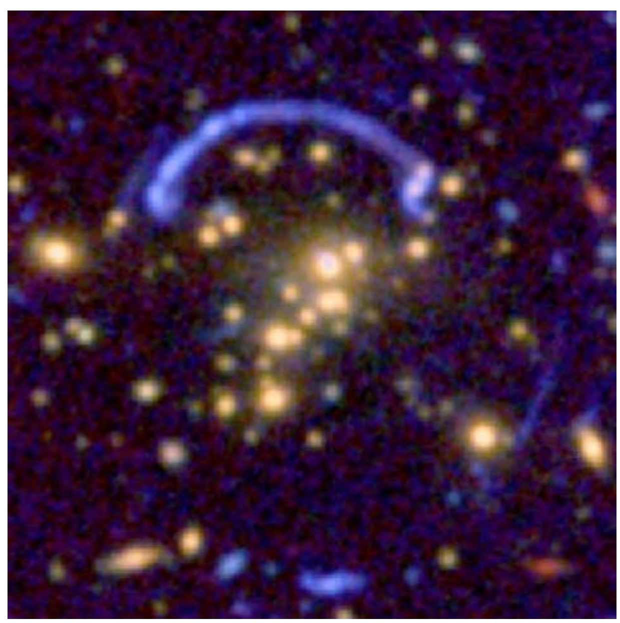
The Inner Workings of Star-forming Galaxies at the Epoch of Star Formation

In the past two decades, astronomers have found the galaxies that formed most of the universe's stars, and have determined that most star formation occurred 2 to 6 billion years after the Big Bang (redshifts of 1 to 3).

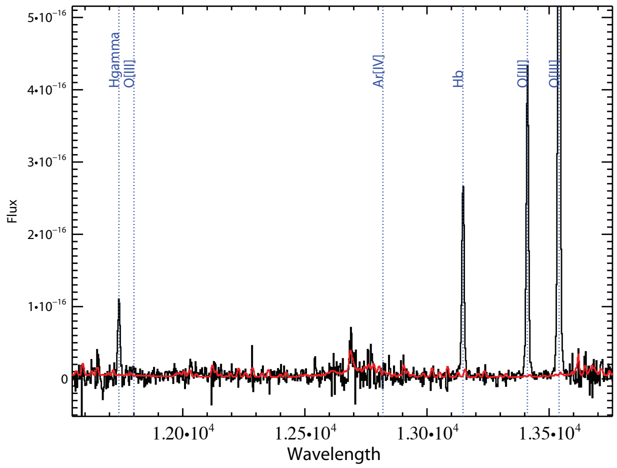
Unfortunately, these galaxies are too faint to study in detail with current telescopes. As a result, we have many unanswered questions about how these galaxies formed their stars, and how they compare to galaxies still forming stars today. Answering these questions is one of the goals of the James Webb Space Telescope.

Jane Rigby (Observational Cosmology Laboratory) and collaborators at the University of Chicago are overcoming the limits of current telescopes by using gravitational lensing. Massive clusters of galaxies act as natural telescopes that bend and magnify the light of background galaxies. In rare cases, gravitational lensing can make galaxies appear 20 to 100 times brighter than they actually are. This is approximately the jump in sensitivity between current telescopes and next generation facilities, and thus enables extremely-large-telescope science today, albeit for small samples.

Using this trick of nature, Rigby and collaborators are studying the inner workings of a small number of



RCS0327, a spectacular lensed galaxy at z=1.70, as imaged from Wuyts et al. 2010. This is the brightest lensed galaxy yet discovered. Multiband Hubble images are scheduled for March 2011.



Nirspec spectrum of RCS0327, obtained with NASA Keck time, from Rigby et al. 2011. The nebular emission lines are detected at extremely high signal-to-noise ratio, allowing precise measurements of the physical conditions inside this star-forming galaxy.

galaxies, which are representative of the population of galaxies that formed the universe's stars.

In the past year, the team has focused on the most spectacular example known, a galaxy named RCS 0327–1326. Discovered by the Chicago group (Wuyts et al. 2010, ApJ, 724, 1182), this galaxy has been magnified by a factor of 17, and appears so bright that it can be studied more thoroughly than any other galaxy at its epoch.

The team has mapped RCS0327 with the Spitzer Space Telescope (led by U. Chicago graduate student Eva Wuyts) and the Chandra X-ray Observatory (led by GSFC's Rigby). In 2011 they will map it with the Hubble and Herschel space telescopes. These multi-wavelength observations are mapping out the new star formation, older stellar populations, and extinction, and will determine whether an active galactic nucleus is present.

Rigby is leading a spectroscopic survey of this galaxy, using the Magellan telescope in Chile and NASA time on the Keck telescope in Hawaii (Rigby et al. submitted to ApJ.) These spectra reveal the physical properties inside this galaxy: the gas density, intensity and shape of the radiation field, abundance of the elements O, N, Ne, and Ar, and the number of massive stars. They also show that the galaxy is driving out its own gas in a massive wind, which might prevent future star formation.

In parallel with this detailed dissection of the brightest few lensed galaxies, the team is surveying 100 lensed galaxies with Spitzer imaging and Magellan and Keck spectra. The goal is to measure the buildup of oxygen and nitrogen in star-forming galaxies at the epoch when most of the stars formed.

Research and Development

Suborbital

Super Trans-Iron Galactic Element Recorder (Super-TIGER)

Super-TIGER is a new large-area balloon-borne instrument under development by Washington University in St. Louis (PI, W. Robert Binns), GSFC, Caltech, and JPL. The GSFC team includes John Mitchell, Eric Christian, Georgia De Nolfo, Thomas Hams, Jason Link, and Makoto Sasaki.

Super-TIGER will measure the individual abundances of elements over the range $30 \leq Z \leq 42$ with high statistical accuracy to test and clarify the emerging model of cosmic-ray origin in OB associations and models for atomic processes by which nuclei are selected for acceleration. Exploratory measurements with lower statistics will extend to $Z = 60$. Super-TIGER will also measure, with excellent statistical precision, the energy spectra of the more abundant elements $14 \leq Z \leq 28$ at energies $0.8 \leq E \leq 10$ GeV/nucleon. These measurements will provide a sensitive test of the hypothesis that microquasars or other phenomena could superpose features on the otherwise smooth energy spectra.

Super-TIGER is based on experience with the smaller TIGER instrument that was flown from Antarctica in 2001 and 2003 for a total of 50 days and produced the first measurements of individual element abundances for ^{31}Ga, ^{32}Ge, and ^{34}Se. Super-TIGER measures the charge and energy of incident nuclei using three layers of plastic scintillator and two Cherenkov detectors, one with an acrylic radiator and one with a silica aerogel radiator. A scintillating optical fiber hodoscope gives particle trajectories to enable corrections for path length through the detectors, detector response maps and interactions in the atmosphere and in the instrument.

Super-TIGER uses two independent detector modules, each with a 1.15 m × 2.3 m active area, giving a total detection area of 5.3 m^2. Each module is only 60 cm thick to maximize its geometric acceptance. The detector layout and minimal column density give an effective geometry factor of 2.5 m^{2}sr at $Z = 34$ — seven times larger than TIGER. Super-TIGER can accomplish its goals in two typical long-duration Antarctic flights, with the first planned for 2012.

The Super-TIGER instrument in construction for a 2012 Antarctic long-duration balloon flight. Two independent detector modules are used to optimize performance.

GSFC is responsible for both the acrylic and aerogel Cherenkov detectors, the scintillators and the mechanical structure of the instrument and payload. In addition, instrument and payload integration will be carried out at GSFC. Detector and payload systems are currently in construction and instrument integration is scheduled to begin in November 2011.

Super-TIGER is a forerunner of the ENTICE (Energetic Trans-Iron Composition Experiment) instrument proposed for the OASIS (Orbiting Astrophysical Spectrometer in Space) mission. In a three-year mission, ENTICE would provide the first statistically significant elemental-abundance measurements in the actinide range.

Cosmic Ray Energetics and Mass (CREAM)

The balloon-borne CREAM instrument was developed for direct measurements of cosmic-ray spectra $1 \leq Z \leq 26$ at total energies greater than 10^{11} eV to test models of cosmic-ray acceleration. In addition, CREAM measurements of the energy-dependent abundance ratios of secondary cosmic-ray species to their primary progenitors test models of cosmic-ray transport and storage in the Galaxy. The CREAM collaboration includes the University of Maryland (PI, Eun-Suk Seo), GSFC, Pennsylvania State University, Northern Kentucky University, and Ohio State University as well as collaborators in Korea, France, and Mexico. ASD team members are John Mitchell and Jason Link.

CREAM has made a series of long-duration balloon flights to accumulate the large exposure needed to measure the energy spectra of the most common

The CREAM instrument just prior to launch from Williams Field, McMurdo Station, Antarctica

elements up to about 10^{15} eV. At these energies, most measurements have been based on the detection by ground-based instruments of the showers of particles produced by interactions of primary cosmic rays in the atmosphere. These indirect measurements can only infer the identity of the incident particle. Direct measurements by CREAM provide invaluable information on cosmic-ray composition, as well as the calibration data required to interpret airshower results. CREAM has flown six times over Antarctica, accumulating about 161 days of exposure. The flight of CREAM-VII is planned for the 2011–2012 austral summer.

The combined CREAM and airshower data test models of Fermi shock acceleration of cosmic rays in supernova remnants. Standard models for this mechanism predict single-power-law spectra until a rigidity-dependent acceleration limit is reached. Above this "knee" the all-particle spectrum steepens accompanying a progressive composition change with increasing energy from dominance by light elements to dominance by heavier elements. CREAM has recently reported spectra that depart from single power laws, hardening above 200 GeV/nucleon, with the proton spectrum slightly steeper than those of helium and heavier nuclei. Among proposed explanations for these results are the effects of a nearby supernova remnant or distributed reacceleration within an OB association.

CREAM measures the charge of incident nuclei using a plastic scintillator timing detector and a silicon pixel detector. Depending on the energy and species of the incident particle, its energy is measured by a silica-aerogel Cherenkov camera (CREAM-III, IV, V, VI), a transition radiation detector (CREAM-I), and a tungsten-scintillating optical-fiber calorimeter (all versions). The geometric acceptance of the TRD is ~ 1.3 m^2sr and the effective geometric acceptance (including interactions) for the calorimeter is about ~0.3 m^2sr for protons and greater for higher Z nuclei. A new TRD has been developed for CREAM-VII by CERN (Switzerland) and JINR (Russia) to enable improved measurements of secondary-to-primary ratios.

GSFC responsibilities are an acrylic Cherenkov detector for rapid particle identification to trigger the instrument on nuclei heavier than He and a scintillating optical-fiber penetration detector that aids triggering on high-energy events and gives a reference time for the timing scintillators. GSFC supports integration and test of CREAM as well as launch and flight operations.

X-ray Quantum Calorimeter (XQC) and Micro-X

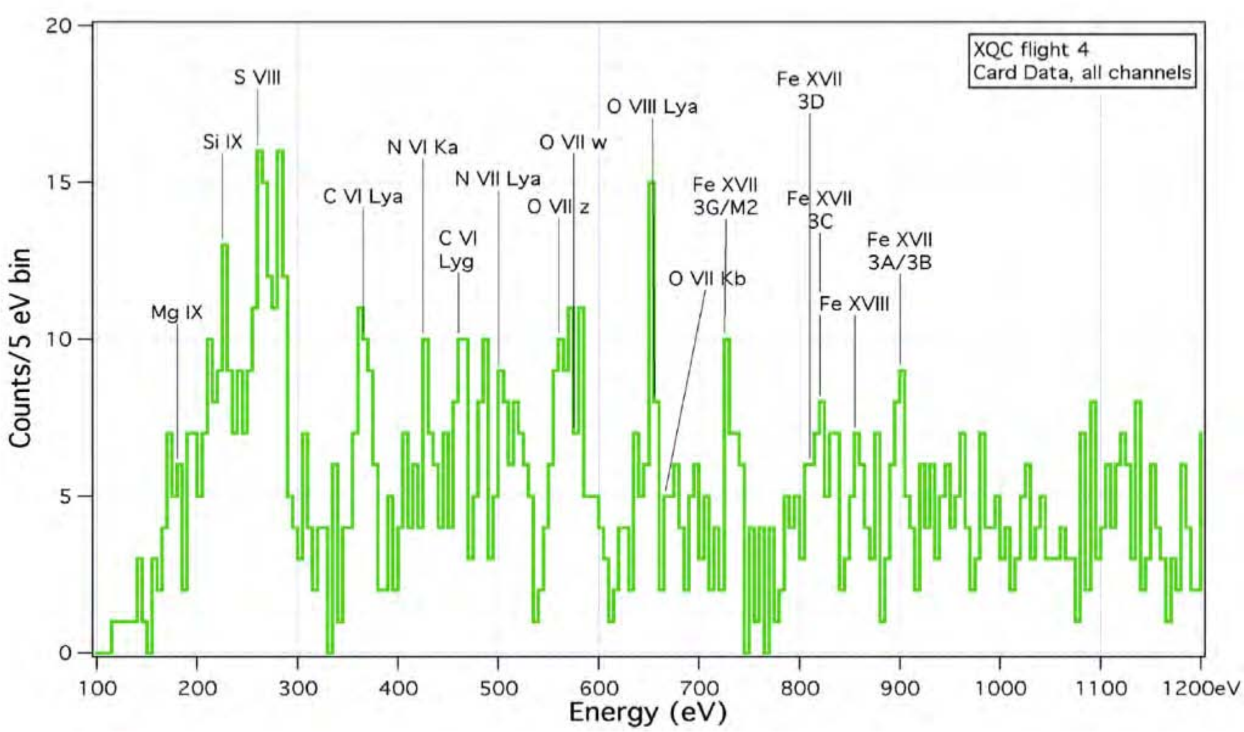
The X-ray Quantum Calorimeter (XQC) is a broadband, non-dispersive X-ray spectrometer built to study the soft X-ray background in the band from 0.05 to 2 keV. The ASD research team members include Porter, Kelley, Kilbourne, and Eckart. Collaborating institutions include the University of Wisconsin (Madison), the University of Miami, and Yale University.

The spectrometer was built to differentiate the spectral components that are thought to make up the ubiquitous soft X-ray background, including emission from the Local Bubble, the Galactic halo, and solar-wind charge exchange in the exo-atmosphere and the heliosphere. The superposition of these temporally and spatially variable sources can create a complicated spectral picture that requires high-resolution spectroscopy to unwind. Detailed spatial maps first were made with sounding rockets, then with ROSAT, and the first high-resolution spectra in the 0.25 keV band were made with the DXS shuttle-attached payload that used a scanning dispersive spectrometer.

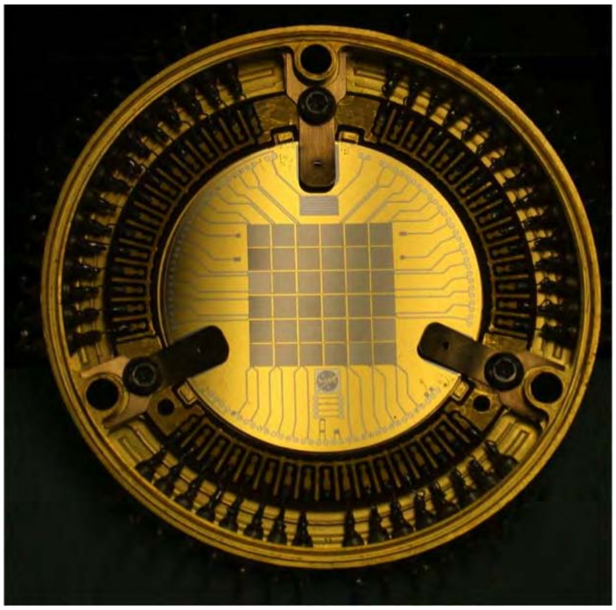
The XQC, however, is the first broadband non-dispersive, high-resolution spectrometer to probe the entire X-ray-emitting range, from M-shell Fe emission at 70 eV up to 2 keV where the diffuse emission becomes dominated by unresolved extragalactic sources. In addition, the XQC payload is the first—and currently, the only—X-ray calorimeter array that has flown in space.

The XQC spectrometer is based on a 36 pixel X-ray calorimeter array that was designed and produced at GSFC. Each pixel in the calorimeter array is relatively large at 2mm × 2mm, and has an energy resolution at O VII Ka of better than 8 eV FWHM. The detector array is operated at 50 mK using a small adiabatic demagnetization refrigerator built at the University of Wisconsin. The payload does not use an X-ray optic since this would significantly reduce the grasp of the experiment, but is instead collimated to a one-steradian field of view.

The XQC has flown four times since 1995, with the most recent flight in March 2008. The fourth



Preliminary spectrum of the soft X-ray background centered at galactic coordinates 30°, +60° as observed with the XQC during its fourth flight in March 2008. The spectrum shows line emission from several highly charged ions and is likely a superposition of several emission mechanisms.



The XQC payload uses a 6 × 6 pixel X-ray calorimeter array develop and produced at GSFC. Each pixel in the array is 2 mm × 2 mm, and utilizes a 0.8-μm-thick HgTe X-ray absorber. The detector array has an energy resolution better than 8 eV FWHM at 600 eV and has a nominal operating band from 0.05 to 2 keV.

flight used a detector array with four times the collecting area of previous flights and is based on technology developed for the Astro-E2 program. The data from the fourth flight is currently being processed, but preliminary results show significant contributions from C IV, O VII, OVIII, Fe XVII, and Fe XVIII. Previous flight have placed constraints on certain types of dark matter, and have detected and placed limits on Local Bubble emission from M-shell transitions in Fe IX, X, and XI. Flight five of the XQC is planned for mid-2011 and will use a new, refined version of the large-area detector design for flight 4. The XQC detectors for flight 5 were fabricated in late 2009, and have been installed in the flight instrument. We are currently waiting on sounding rocket infrastructure from NASA's sounding rocket program.

The Micro-X payload is designed to be the first X-ray calorimeter payload using focusing X-ray optics. It uses significant design heritage from the XQC program, including a very similar adiabatic demagnetization refrigerator. However, the detector and readout technology are derived from the IXO program. The ASD research team members include Porter, Kelley, Kilbourne, Bandler, Adams, Eckart, Smith, Serlemitsos, and Soong. Collaborating institutions include the University of Wisconsin (Madison), MIT, University of Miami, University of Florida, and the National Institute of Standards and Technology. The Micro-X payload will use a 121 pixel (11 × 11) X-ray calorimeter array with superconducting transition edge (TES) thermistors operating at 50 mK. It is designed to have an energy resolution of 2 eV (FWHM) across the energy band from 0.05 to 2 keV. The Micro-X payload will use a focusing optic designed and produced at GSFC for the SXS sounding rocket that flew in 1989 and is the predecessor of the optics used for BBXRT, ASCA, Astro-E2, and Astro-H.

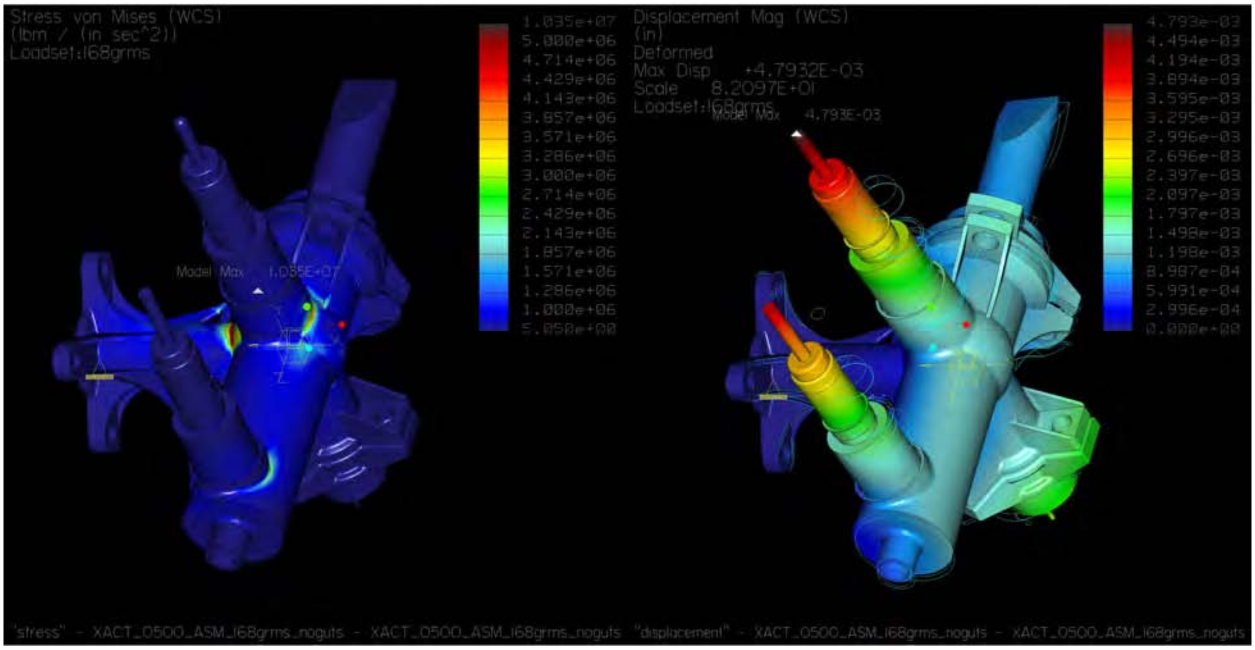
The Micro-X payload is scheduled to fly in late 2011 to observe the bright eastern knot of the Puppis-A supernova remnant. The detector array is designed and produced by GSFC and will be read out using a cryogenic SQUID multiplexer and room-temperature electronics jointly developed by GSFC and NIST. GSFC will also provide the refurbished SXS X-ray optic with 200 cm^2 collecting area at 1 keV and a 2.5 arcmin PSF.

Micro-X will provide some of the first detailed high-resolution spectra of a supernova remnant, with about 40,000 counts expected during the flight. The payload will be the first opportunity to utilize high-spectral-resolution, broadband, spatial-spectral imaging, and will provide a glimpse of what we can expect from Astro-H and then IXO in the future.

X-ray Advanced Concepts Testbed (XACT)

XACT is a new suborbital X-ray payload being developed at GSFC to test and advance Technology Readiness Levels (TRL) of several technologies that could

First integration test of the XACT optics with the spider assembly.



Stress analysis of 3-D printed modulated X-ray source for XACT.

enable future missions (Gendreau, PI). The scientific objective of XACT is to measure the X-ray polarization properties of the Crab Nebula and pulsar and of the accreting binary Her X-1. Polarimetry is a powerful tool for astrophysical investigation that has yet to be exploited in the X-ray band, where it could provide unique insights into neutron stars, black holes, and other extreme-physics environments.

With powerful new enabling technologies, XACT will demonstrate X-ray polarimetry as a practical and flight-ready astronomical technique. The technologies XACT will bring to flight readiness will also provide important new capabilities for NASA missions in space-based X-ray spectroscopy, timing, and photometry. XACT combines new ultra-lightweight optics, advanced photoelectric X-ray polarimeters, and novel calibration sources in a standard sounding-rocket payload.

The XACT optics—lightweight concentrators optimized for unresolved sources—will provide the largest focused X-ray-collecting area ever achieved on a sounding rocket. Currently under development at GSFC, they will have the largest focused collecting-area-to-mass ratio ever flown, enabling future space-based missions that require truly enormous throughput and low background. Scientists Lalit Jalota and Yang Soong are leading this effort with assistance from technicians David Ficau, Grant Olsen, and Nick Spartana. The first full shells have been replicated, and the first spider assembly to hold the shells has been made.

The XACT polarimeters are the latest innovation in photoelectron tracking devices that combine a large polarization response with high quantum efficiency to achieve unprecedented sensitivity. ASD scientists recently originated this polarimetry technique, based on the negative-ion Time Projection Chamber (TPC), and are currently developing it for astrophysical and heliospheric missions in the 1–100 keV band. The TPC polarimeter is the basis for the SMEX GEMS mission. XACT will leverage these efforts to deliver the polarimeters at a low incremental cost. Scientists Kevin Black, Keith Jahoda, and Joe Hill lead this effort.

The final drawings are done of the optical bench assembly that holds the optics relative to the polarimeters. The major structures for this bench have been ordered. Integration of the optical bench will be complete before April 2011.

XACT will demonstrate in-flight calibration using a modulated electronic X-ray source that can be pulsed for arbitrary and commandable intervals. Such a source can be used to provide calibration information on demand. This minimizes the associated background and results both in higher sensitivity and observatory-scheduling freedom for future missions. Mechanical Engineer Steve Kenyon has been leading the effort to miniaturize the source and has successfully made sources weighing 150 grams—a factor of 3 improvement from the beginning of the year. We are now making the sources even lighter with 3-D printing technology. We have begun the fabrication of the first two 3-D printed X-ray sources in steel. The second design will be used for the XACT flight and will serve as an ETU for a similar source on the GEMS SMEX. The modulated X-ray source has been successfully used to calibrate drift velocities on several laboratory polarimeters.

The XACT program has also included students from several schools. Three high school students have participated in the design of the X-ray source. Eight undergraduate students from Olin College have worked on in flight alignment monitoring system designs. One undergraduate from the U.S. Naval Academy has further refined this alignment system. One undergraduate from the University of Kentucky has helped with automation of the X-ray mirror measuring. A graduate student (Erin Balsamo) has assisted in the design of the collimator that will be used to align the instrument.

The XACT goals are accomplished with a simple flight plan that is well within the launch and recovery envelopes of a standard Black Brant IX at the White Sands Missile Range. The first launch will be in December 2011 to observe the Crab. This will be followed by a second launch in June 2012 to look at Her X1.

Primordial Inflation Polarization Explorer

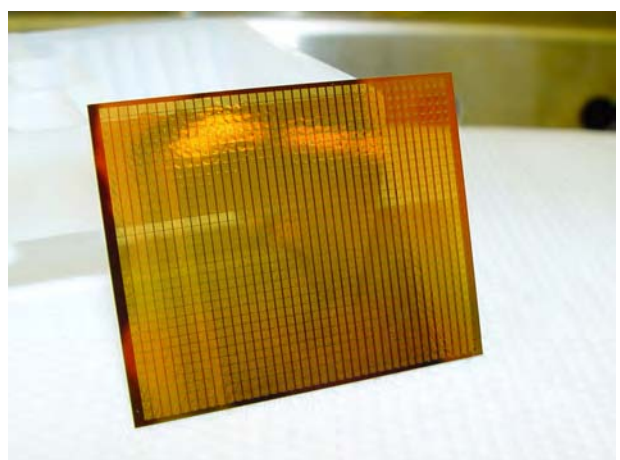
The Primordial Inflation Polarization Explorer (PIPER) is a balloon-borne mission to measure the polarization of the cosmic microwave background in search of the signature of primordial gravity waves excited by an inflationary epoch in the early universe. Alan Kogut is the PI, and ASD team members include Benford, Chuss, Fixsen, Jethava, Johnson, Mirel, Moseley, Sharp, Staguhn, and Wollack.

PIPER addresses fundamental questions at the intersection of physics and cosmology. Cosmology posits a period called inflation, shortly after the Big Bang, when the expansion of space-time accelerated dramatically to “inflate” the universe from subatomic to macroscopic scales. Inflation neatly explains the initial conditions of Big Bang cosmology (a spatially flat, homogeneous universe with scale-invariant density perturbations), but it relies on the extrapolation of physics to energies a trillion times above those accessible to direct experimentation in particle accelerators. PIPER will test inflation by measuring the polarization pattern in the cosmic microwave background caused by a background of gravity waves created during an inflationary epoch. Such a signal is expected to exist, with observable amplitude and a unique spatial signature. Detection of the gravity-wave signature of inflation would have profound consequences for both cosmology and high-energy physics. It would establish inflation as a physical reality, determine the relevant energy scale, and probe physics at energies near Grand Unification to provide direct observational input for a “final theory” of quantum mechanics and gravity.

PIPER achieves unprecedented sensitivity by combining several technologies pioneered by Goddard researchers.

• Large-format bolometric detectors. PIPER will fly 5,120 transition-edge superconducting bolometers in a Backshort-Under-Grid (BUG) architecture. By moving all wiring *beneath* the array, the BUG architecture allows efficient two-dimensional tiling of the focal plane without any reflective elements that would reduce the optical efficiency. PIPER has produced its first 32 × 40 bolometer arrays for characterization.

• A Variable-Delay Polarization Modulator (VPM) injects a time-dependent phase delay between orthogonal linear polarizations to cleanly separate polarized from unpolarized radiation. The fast (3 Hz)



The PIPER prototype 32 x 40 array of transition-edge superconductor bolometers uses the Backshort-Under-Grid (BUG) architecture to tile the front surface with the absorbing elements. Wiring is on the back side to minimize unwanted reflections. PIPER will fly four such arrays for a total of 5,120 detectors.

Loading the recovered BESS-Polar II magnet into the Basler aircraft at the recovery site.

modulation allows full characterization of the incident radiation into Stokes I, Q, U, and V parameters on time scales fast compared to instrument drifts or beam motion on the sky. VPM development for PIPER complements technology development for a future large mission (the Inflation Probe).

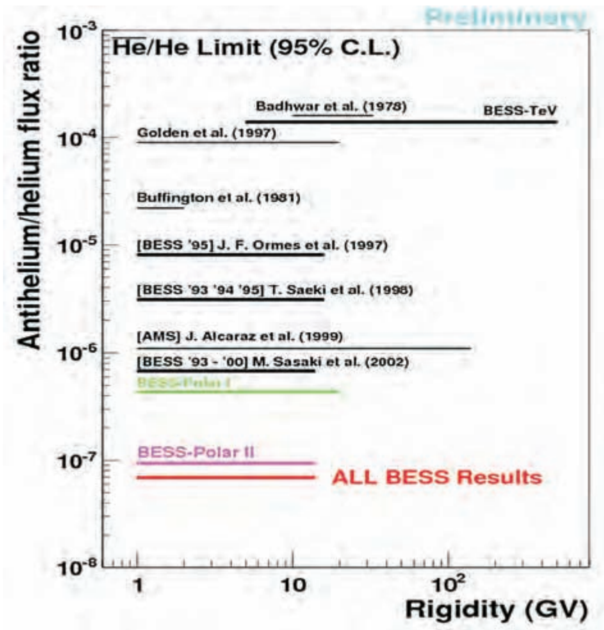
• Open-aperture cold optics. PIPER's twin telescopes fit within the old ARCADE dewar and will operate at 1.5 K to provide background-limited sensitivity. Maintaining all optical elements at 1.5 K or colder improves sensitivity by a factor of 10 compared to ambient optics, allowing PIPER to use conventional (overnight) balloon flights instead of more challenging Antarctic operations,

• PIPER will map the sky in both linear and circular polarization, at wavelengths 1500, 1100, 850, and 500 μm (frequencies 200, 270, 350, and 600 GHz). It will detect the signature of inflationary gravity waves to a factor of three fainter than the lowest value predicted by inflationary models. The unbiased survey of submillimeter polarization will also provide an important probe of the interstellar dust cirrus and the large-scale structure of the Galactic magnetic field, and will be the first sky survey in circular polarization at these wavelengths. PIPER has begun integration and test activities and is scheduled for flight in late 2012 or early 2013.

Balloon-borne Experiment with a Superconducting Spectrometer (BESS)

BESS is a highly successful U.S.-Japan program that uses elementary particle measurements to study the early universe by providing fundamental data on the spectra of light cosmic-ray elements and isotopes. BESS measures the energy spectra of cosmic-ray antiprotons to investigate signatures of possible exotic sources, and searches for heavier antinuclei that might reach Earth from antimatter domains formed during symmetry-breaking processes in the early universe.

BESS is led jointly by GSFC (PI, John Mitchell) and KEK, the Japanese High Energy Accelerator Research Organization (PI, Akira Yamamoto). The ASD team includes Thomas Hams and Makoto Sasaki. Collaborating institutions in the U.S. are the University of Denver and the University of Maryland, and in Japan, the University of Tokyo, Kobe University, and ISAS/JAXA.



The BESS antihelium/helium ratio 95-percent confidence limit has improved by over two orders of magnitude.

The BESS collaboration carried out nine conventional northern-latitude flights between 1993 and 2002, recording 2,237 mass-resolved cosmic-ray antiprotons and confirming that the majority are secondary products of the interactions of primary cosmic-ray nuclei with interstellar gas. Flights near solar minimum in 1995 and 1997, however, observed low-energy antiproton flux slightly in excess of purely secondary expectations, suggesting a possible contribution from an exotic primary source, such as the evaporation of small primordial black holes (PBH) or the annihilation of candidate dark matter particles.

BESS-Polar was developed to extend measurements to lower energies and to greatly increase sensitivity using long-duration balloon flights over Antarctica. The BESS-Polar magnetic-rigidity spectrometer uses a unique solenoidal superconducting magnet with a thin coil and cryostat and a precision trajectory-tracking system. A plastic scintillator time-of-flight system, with two layers at the top and bottom of the instrument and one layer inside the magnet bore, below the tracker, measures the charge and velocity of incident particles. A silica aerogel Cherenkov detector rejects light background particles. With geometric acceptances of ~ 0.3 m^2sr, BESS and BESS-Polar are the largest balloon-borne magnet instruments.

GSFC is responsible for the outer scintillators, the instrument electronics, and the Cherenkov detector PMTs. BESS-Polar integration and testing took place at Goddard, which also co-led launch and flight operations. GSFC has principal responsibility for instrument calibration and performance analysis.

BESS-Polar I flew for 8.5 days in 2004—at a transient period prior to solar minimum—and reported 1,512 antiprotons. BESS-Polar II recorded data with the magnet energized for 24.5 days in 2007–2008, flying near solar minimum, when the sensitivity of the antiproton measurements to a low-energy primary component is greatest, and has detected ~8,000 antiprotons. Depending on the antiproton energy, this is 10–20 times the combined BESS 1995/97 statistics. The instrument performed very well, and initial analysis of 13.5 terabytes of data obtained on 4.7 billion cosmic-ray events has been completed. GSFC led the instrument calibration of BESS-Polar II and preparation of the physics data files. The preliminary BESS-Polar II antiproton spectrum has been reported at conferences and the final antiproton results are being prepared for publication.

No antinucleus heavier than an antiproton has been detected in any BESS flight through BESS-Polar II. These data have provided the most stringent test of the presence of heavier antinuclei in the current universe. Analysis of BESS-Polar II data at GSFC in the rigidity range from 1–14 GV, gives a 95-percent confidence upper limit of 9.4×10^{-8} for antihelium/helium. Combining all results from 1993 through 2007, the upper limit on antihelium/helium is 6.9 x 10^{-8}, more than two orders of magnitude lower than the first BESS limit.

BESS has also carried out the only search to date for antideuterons, which may be produced in local processes, including the evaporation of PBH and super-symmetric particle annihilation. It has reported an upper flux limit of 3×10^{-4} (m^2 s sr GeV/nucleon)$^{-1}$. The sensitivity of this search will be greatly increased with data from the two BESS-Polar flights.

BESS-Polar II could not be recovered in 2008 because its flight was terminated late in the season and in a remote location approximately 1,000 miles from the U.S. McMurdo Station. Mitchell led its successful recovery in 2009/10 by a team that included Hams and KEK scientists Koji Yoshimura and Yasuhiro Makida. During a 13-day deep-field camp, the team carefully disassembled the instrument for air transport, including partial disassembly of the superconducting magnet. The instrument was subsequently returned to

GSFC for evaluation, and all detector systems were determined to be operational. The magnet was sent to Japan for refurbishment by Toshiba and has been successfully reassembled. Following cryogenic testing, the magnet will be sent to GSFC for instrument integration.

Gamma-Ray Burst Polarimeter

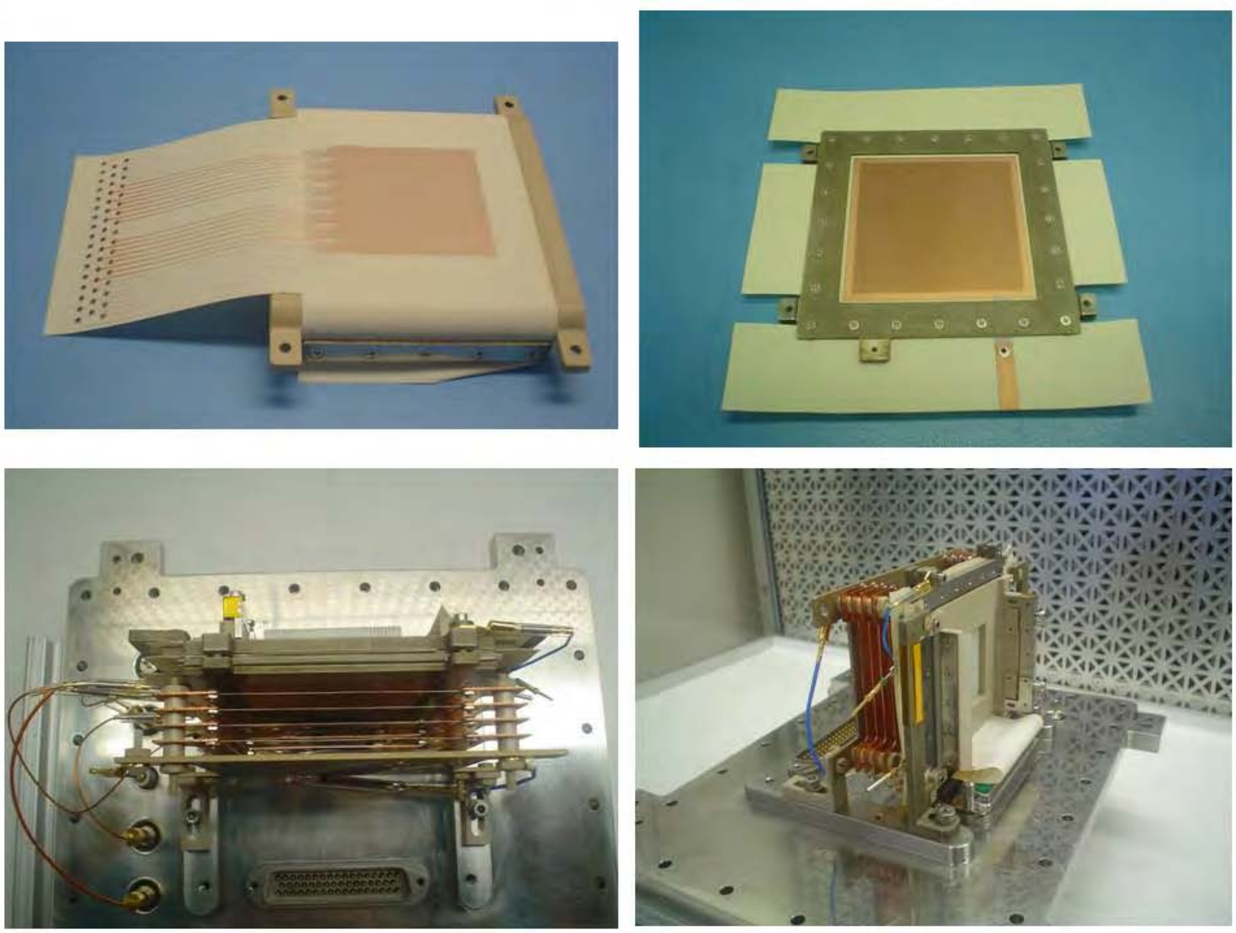
The Gamma-Ray Burst Polarimeter (GRBP) is an instrument originally designed for a small U.S. Naval Academy (USNA) satellite called MidSTAR-2 (Joe Hill, PI, and K. Jahoda, co-I). USNA funding for MidSTAR-2 has diminished, but the design and fabrication of GRBP continued through 2010, focused for a mission of opportunity (MoO) on another small satellite or for a sounding rocket.

Similar to GEMS, the GRBP utilizes Time-Projection Chamber (TPC) technology to make polarization measurements of X-rays in the 2–10 keV energy band. A TPC provides a complete 3-D picture of the ionization deposited in a gas volume, which makes it extremely useful in tracking charged particles in a high-track-density environment, and for identifying particles through their ionization energy loss. GRBP employs a negative-ion gas to reach a higher sensitivity and wider field-of-view instrument with lower power.

GRBP is designed to satisfy three requirements:

- To demonstrate a new technology (negative-ion TPC) in a space environment for the first time;
- To measure the polarization of the Crab Nebula, the only source for which the polarization has been conclusively measured in the X-ray band;
- To measure the polarization of 5 to 10 gamma-ray bursts (GRBs) in a two-year mission.

Polarization measurements of even a handful of GRBs will allow us to discriminate between different theories about the mechanisms behind these hugely powerful and enigmatic events. A demonstration of



Top (left) view and isometric (right) views of the GRBP detector unit.

Modulation as a function of energy with a gas mixture is CO_2+Nitro (197.5:15 Torr) and the field strength was 1086 V/cm. The modulation decreases above 6.4 keV, likely due to incorrect track reconstruction due to the length of higher energy tracks.

the GRBP instrument will increase the technology readiness level for future missions.

The design of the flight detectors and polarimeter enclosure are complete. They will not be fabricated until a launch platform is identified and the interface finalized. This year a single flight-like detector unit and enclosure have been assembled (see attached figure), optimized and the unit is now being characterized as part of a University of Iowa students PhD thesis.

The GRBP detector unit was tested in the lab with a 4.5 keV polarized X-rays, and then over a five-day period at the Brookhaven National Laboratory's (BNL) National Synchrotron Light Source (NSLS). The NSLS beamline X-19A has a well-collimated, highly polarized beam with an energy range of 2.1–17 keV, a maximum rate of $1x10^{11}$ counts/sec.

Polarisation phase measurements were made for different beam positions in the detector active area using a gas mixture of CO_2+Nitro (197.5:15) Torr. We demonstrated that the drift field strength matches clocking of the strip readout by demonstrating that there is no change in the measure phase of the polarization with detector position. The detector modulation factor has been measured over the 3.5 keV–8 keV energy range and the results are shown in the attached figure. The modulation is ~37 percent and flat from 3.5 to 6.4 keV. The modulation *decreases* at 7 and 8 keV. This is likely related to the moments based reconstruction of the photoelectron direction having reduced accuracy for long tracks and will be investigated.

The GRBP drift velocity was measured with a modulated X-ray source. The test demonstrated that the uniformity of the field-cage design and that the drift velocity remains uniform over time indicating a low level of self-contamination.

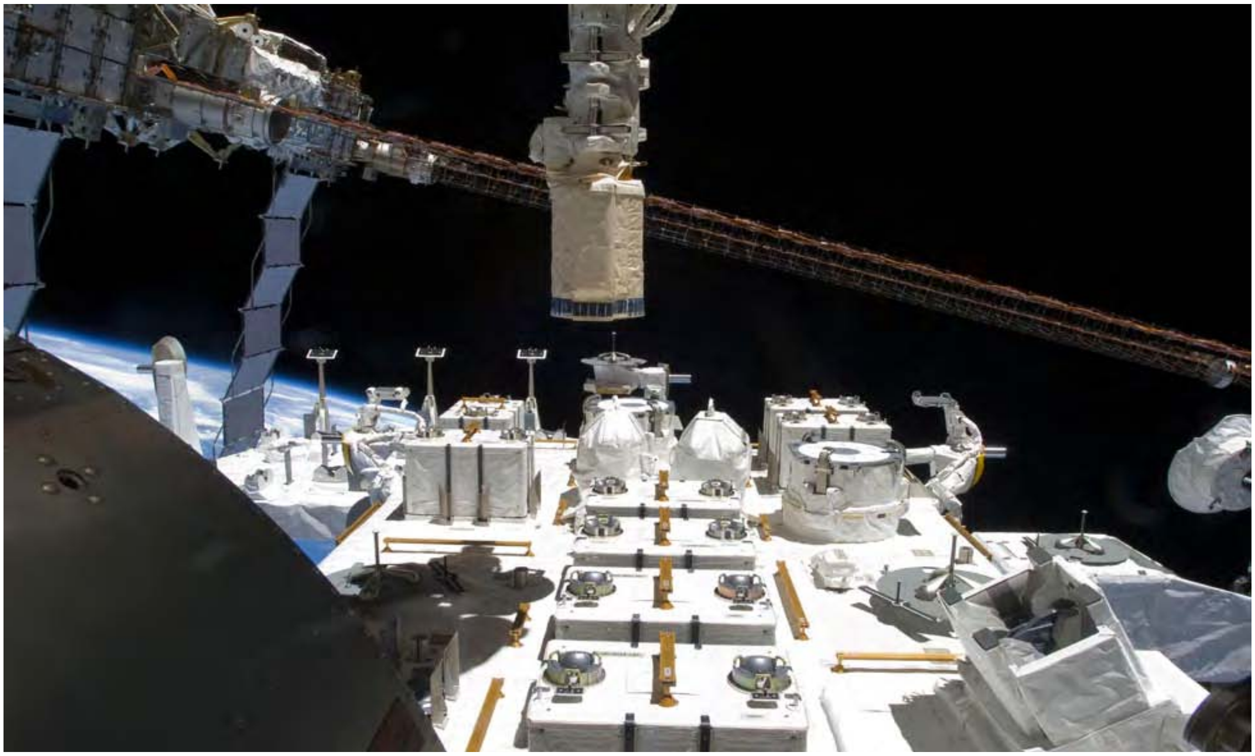
In addition to the detector testing, an end-to-end test of the SIDECAR readout electronics with the GRBP detector unit was successfully completed, and generated photoelectron tracks analogous to the GSE readout. The Electronics box that provides the low voltages, high voltages, and house-keeping telemetry is complete and ready for the definition of the flight interface to be implemented in the FPGA card.

The team is investigating alternative launch opportunities. The most likely scenario that is compatible with the instrument delivery schedule is that GRBP will be tested on a sounding rocket. This will accomplish the first two goals and prove the design such that a satellite version could be built to measure the polarization of GRBs.

Calorimetric Electron Telescope (CALET)

CALET is a new mission selected by JAXA for a launch in 2013 to the Japanese Experiment Module-Exposed Facility (JEM-EF) on the International Space Station. CALET will measure the high-energy spectra of electrons, nuclei, and gamma-rays to address outstanding questions including signatures of dark matter, the sources of high-energy particles and photons, and the details of particle acceleration and transport in the galaxy. The CALET project (PI Shoji Torii, Waseda University) includes researchers from Japan, the U.S., Italy, and China. The U.S. CALET team of Louisiana State University, GSFC, Washington University in St. Louis, and the University of Denver will participate in CALET development, testing, instrument modeling, flight operations, flight data processing, and science analysis. The ASD team of John Mitchell, Thomas Hams, John Krizmanic, Alexander Moiseev, and Makoto Sasaki are responsible for the instrument simulation and performance model, technical support for instrument development, and leadership of U.S. support for accelerator testing and calibration.

CALET is a calorimeter-based instrument with superior energy resolution and excellent separation between hadrons and electrons and between charged particles and gamma rays. The main telescope has a field-of-view of ~45° from the zenith and a geometric

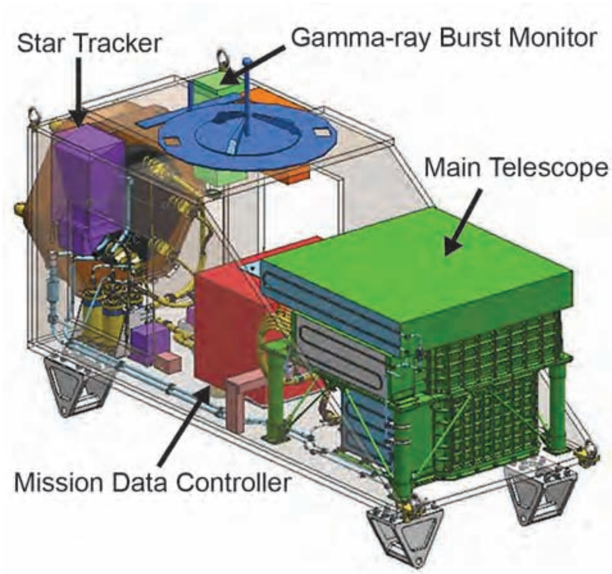


The Japanese Experiment Module - Exposed Facility as it looks from inside the module on the International Space Station.

acceptance of 0.12 m^2-sr. The calorimeter is divided into an imaging calorimeter (IMC) section that provides tracking and accurately determines the starting point of showers, and a total absorption calorimeter (TASC) section that measures total particle energy. The IMC contains ~3 radiation lengths (X_o) of tungsten interspersed between eight x-y layers of scintillating optical fibers read out by multi-anode photomultipliers. Most electrons and photons will initiate showers in the IMC, which measures the starting point of the shower and its development until it enters the TASC. The TASC is a stack of lead tungstate (PWO) crystals arranged in x-y layers to track the axis of the shower. Each log is read out by two photodiodes plus an avalanche photodiode. The TASC has a total thickness of 27 X_o and collects the total energy in the shower with a leakage of only a few percent for electrons. A charge detector subsystem at the top of the telescope measures the charge of incident particles and functions as an anti-coincidence detector for gamma-ray measurements.

CALET is focused on investigating the high-energy total electron spectrum into the trans-TeV energy range. These measurements have the potential to identify, for the first time, the signature of high-energy particles accelerated in a local astrophysical engine and subsequently released into the Galaxy. Electrons lose energy rapidly by synchrotron and inverse Compton processes. The distant-source spectrum is expected to be relatively featureless, falling approximately as E^{-3} and softening rapidly above 1 TeV. Electrons with TeV energy must have been accelerated within about 10^5 years and can have diffused at most a few hundred pc. The electron lifetime and the diffusion distance decrease rapidly with energy. Detection of electrons with energy significantly above 1 TeV would indicate the presence of a nearby source and the arrival directions of these electrons should also show detectable anisotropy. Individual sources might also produce features in the spectrum at lower energies. CALET will resolve discrepancies among recent results from balloon experiments (BETS, ATIC, PPB-BETS), space experiments (Fermi, PAMELA) and ground-based air Cherenkov telescope observations (HESS).

High-energy electrons and positrons may also be produced by dark-matter annihilation. CALET will search for signatures of dark-matter annihilation producing features in the electron or gamma-ray spectra.



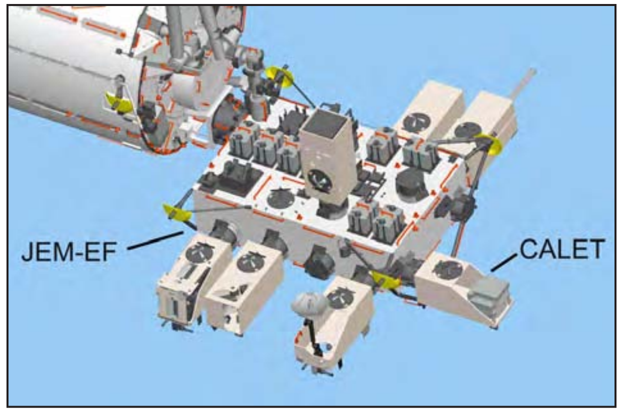
The Calorimetric Electron Telescope (CALET) mission for the JEM-EF.

Together with measurements at the Large Hadron Collider, details of the spectra of high-energy cosmic-ray electrons and positrons may hold the key to revealing the nature of dark matter.

The spectra of primary cosmic-ray nuclei, and the important secondary elements such as Boron, hold the key to understanding galactic particle transport at very high energy. CALET will measure the B/C ratio with precision to about a decade in energy beyond current results, and thereby test many of the models currently proposed. CALET will also extend the measurements of the spectra of cosmic ray nuclei from hydrogen to iron, with high resolution, into the region of the spectral "knee" to investigate possible structure and energy-dependent composition changes.

CALET will perform a gamma-ray all-sky survey, complementing Fermi and HESS observations, to detect intense high-energy sources, study the diffuse component, and search for new regions of emission. CALET includes a low energy (7 keV – 20 MeV) gamma-ray burst monitor. GRB measurements are also extended to high energy using the main telescope.

The electron, nucleus, and gamma-ray measurements of CALET would be extended to higher energy and greater precision by the HEPCaT (High-Energy Particle Calorimeter Telescope) instrument studied by a team led by John Mitchell and proposed as part of the OASIS (Orbiting Astrophysical Spectrometer in Space) mission. HEPCaT would measure cosmic-ray electrons to energies well above 10 TeV and nuclei to energies of 10^{15} eV.

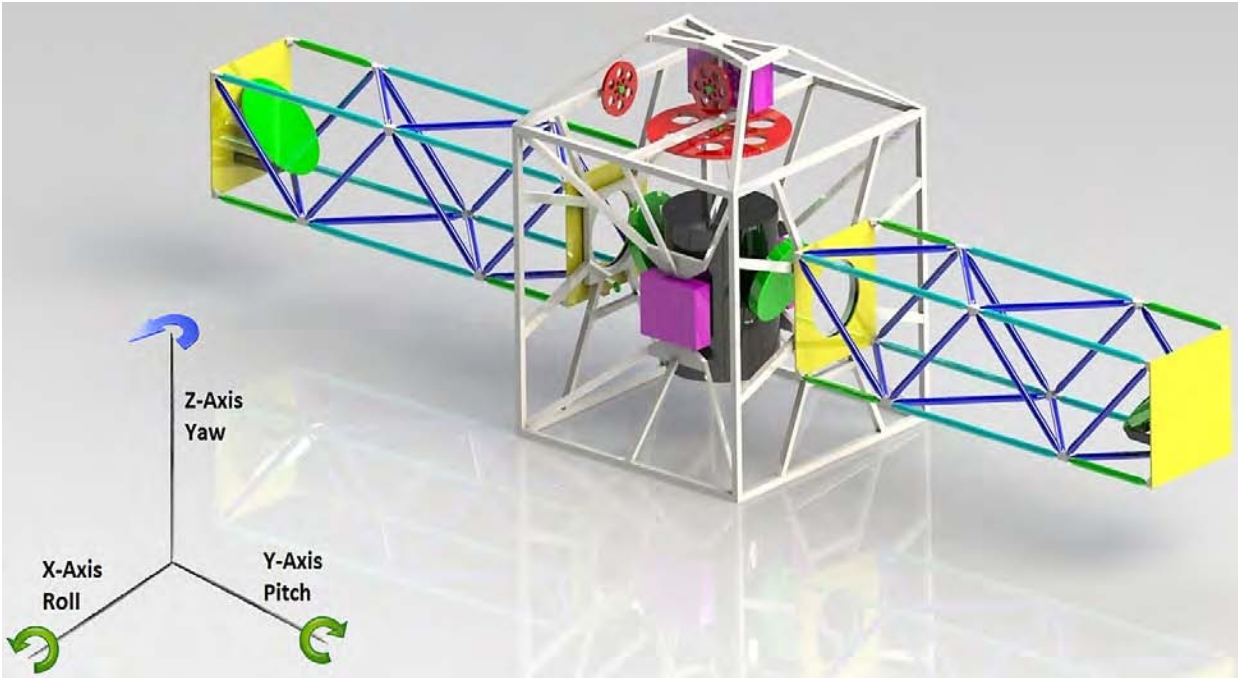


The Calorimetric Electron Telescope (CALET) mission configuration for the JEM-EF.

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII)

Astronomical studies at infrared wavelengths have revolutionized our understanding of galaxies, stars, and planets, as well as their origins. But further progress on major questions is stymied by the inescapable fact that the spatial resolution of single-aperture telescopes degrades at long wavelengths. Exciting physical processes lurk below our current far-infrared (FIR) resolution, including clustered star formation, powerful interactions between normal matter and monstrous black holes at the cores of galaxies, and the formation of planetary systems. Interferometry is a path to high angular resolution in the FIR, making it a potent tool for scientific discovery.

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) is an 8-meter boom interferometer to operate in the FIR (30–90 μm) on a high-altitude balloon that was selected for funding under the ROSES/APRA program in 2010. The long baseline will provide unprecedented angular resolution (~0.5") in this band. These wavelengths are inaccessible from the ground; the high atmospheric transmission at balloon altitudes, in combination with BETTII's unique double-Fourier instrument will allow spectral resolution of up to $R \equiv \lambda/\Delta\lambda \sim 200$. By combining these capabilities, BETTII will provide spatially-resolved spectroscopy on astrophysically important sources. BETTII's first flight will isolate the far-infrared emission from forming stars in cluster en-



BETTII's 8-meter boom will provide angular resolution of ~0.5" at 40 mm. Carbon-fiber construction leads to a stiff boom structure, while keeping the overall payload weight low.

vironments, allowing us to tightly constrain models of cluster formation.

The scientific goals of BETTII drive key technical requirements for the design. BETTII is a Michelson interferometer, combining the light from two separated collector mirrors (siderostats) at a 50/50 beamsplitter in the pupil plane. A scanning optical delay line is used to vary the optical path difference between the two arms of the interferometer; the interferometric fringe pattern is recorded on the detector. Relative astrometric information is derived from the optical path difference between the fringe packets corresponding to discrete sources. The angular size of a source can be derived from the ratio of the fringe amplitude to the amplitude from an unresolved calibration source. The fringe envelope contains spectral information. Thus, an interferometer like BETTII, when used to observe a source with a large number of interferometric baselines, yields integral field spectroscopic data, or a spatial-spectral data cube.

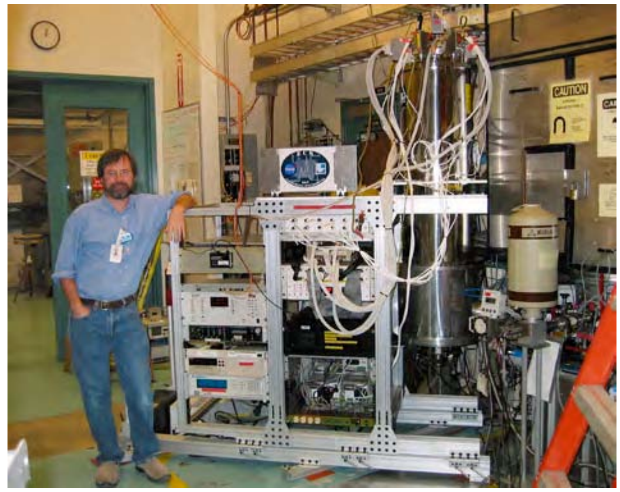
A successful flight of BETTII will pave the way for future space interferometry by demonstrating key technologies, including wide-field phase referencing for image reconstruction and the technique of double-Fourier interferometry. A traditional Michelson interferometer uses a single detector and has a field of view determined by the size of the individual light collecting apertures. By using a detector array, one observes interferograms corresponding to multiple contiguous primary beams simultaneously on different pixels. This technique—wide-field double-Fourier interferometry—has been demonstrated on a laboratory testbed, but never in a flight-like environment.

The first flight of BETTII is planned for Spring 2015. Data acquired with BETTII will be complementary to observations with space observatories such as Herschel and the James Webb Space Telescope, exploring the FIR wavelength range with unprecedented high angular resolution. These data will be powerful tools for understanding star formation in clusters. Further, BETTII will validate technologies and retire risks for future space interferometers, such as the Space Infrared Interferometric Telescope.

The BETTII project is a collaboration between NASA's Goddard Space Flight Center and the University of Maryland, with assistance from the Far-Infrared Telescope Experiment team in Japan. The BETTII team includes ASD scientists Stephen Rinehart, Rich Barry, Dominic Benford, Dale Fixsen, Bill Danchi, Johannes Staguhn, Robert Silverberg (Emeritus), as well as David Leisawitz (Science Proposal Support Office), Christine Jhabvala (Instrument Systems & Technology Division) and Lee Mundy (UMCP).

Technology Development

Laboratory Astrophysics Using an X-ray Microcalorimeter with an Electron Beam Ion Trap



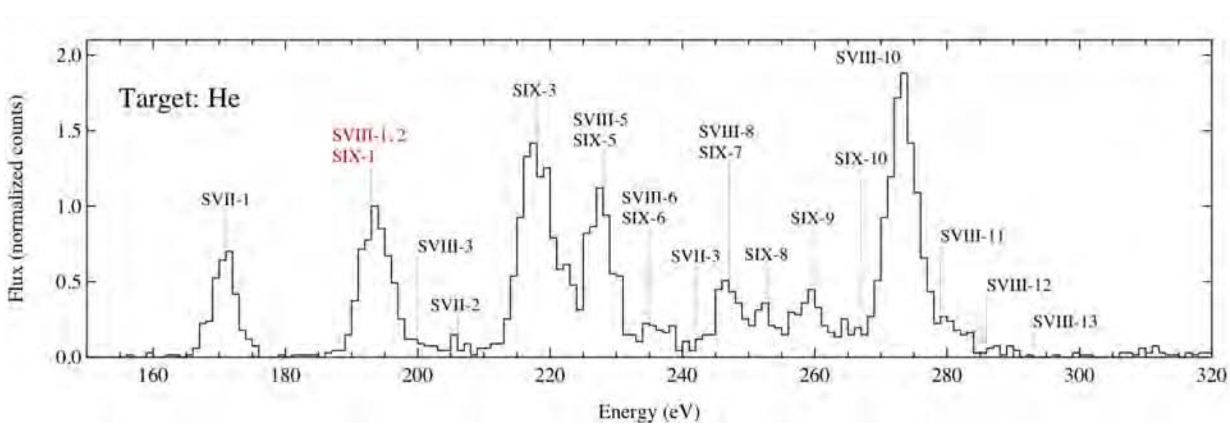
The GSFC developed EBIT Calorimeter Spectrometer (ECS) attached to the EBIT plasma instrument at the Lawrence Livermore National Laboratory.

Our laboratory astrophysics program is designed to simulate astrophysical plasmas in the laboratory in order to benchmark and provide guidance to the atomic codes that form the basis of the spectral synthesis models used in X-ray astrophysics. These models are used to relate spectra observed from an astrophysical object to conditions in the source, including temperature, ionization-equilibrium, composition, density, turbulence and bulk motion. This work is fundamentally important as high-resolution spectroscopy becomes the dominant tool in exploring the physics of X-ray-emitting objects.

This has already started with the observation of bright point sources with the high-resolution dispersive spectrometers on Chandra and XMM/Newton. It will become critically important with the upcoming Astro-H and International X-ray Observatory, which will produce a detailed, high-spectral-resolution image with every observation. Our program is designed to validate and correct the accuracy of the spectral synthesis models in controlled ground-based experiments, giving us confidence that we have correctly ascribed observed spectral features to known conditions in the astrophysical source.

The basis of our program is a high-resolution, non-dispersive, X-ray calorimeter spectrometer, a suite of very-high-resolution dispersive spectrometers, and the Electron Beam Ion Trap (EBIT) plasma generator at the Lawrence Livermore National Laboratory (LLNL). ASD scientists include Porter, Kelley, Kilbourne, Adams, Smith, Koutroumpa, and Leutenegger. Other collaborating institutions include Stanford University and the National Institute of Standards and Technology. The LLNL EBIT can produce nearly any plasma conditions, from low-charge states in light elements to bare uranium with electron beam energies of up to 200 keV. Nearly any charge state of any astrophysically interesting element can be produced, either as a pure charge state or in a Maxwellian distribution at known temperature.

Non-equilibrium ionization conditions can also be produced with almost any astrophysically interesting ionization parameter. Typical measurements in our program include spectral-line identification, absolute cross sections, recombination, charge-exchange recombination, and cross sections in thermal and non-



X-ray emission due to Charge Exchange recombination from L-shell S produced in the EBIT instrument and measured by the ECS spectrometer.

thermal distributions. Measurements are related back to theory, the results of atomic calculations, and to the standard X-ray spectral synthesis models used in X-ray astrophysics.

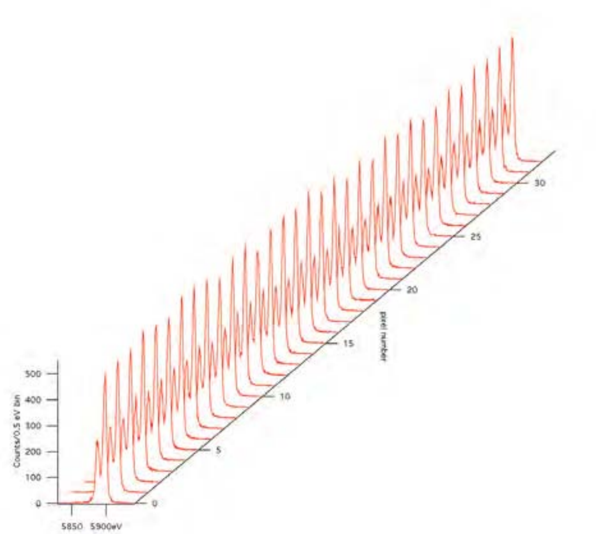
A key instrument in these measurements is a broadband, high-resolution X-ray calorimeter instrument provided by GSFC beginning in 2000 and now on its third revision. This system has been operated almost continuously for the past 9.5 years. It has produced well over two dozen peer-reviewed articles, and it has made critical measurements of absolute cross sections in L-shell Fe and Ni, as well as charge-exchange measurements in S, C, O, and Fe. Many investigations are on going. The emphasis in 2010 has been a detailed look at L-shell charge exchange, mostly with sulfur and iron, as a function of ionization state, a key component of magnetospheric charge exchange for which there exists no predictive theory. Magnetospheric and heliospheric charge exchange are key components of spatially, spectrally, and temporally variable foreground emission which complicate observations of, for example, the soft X-ray background, warm-hot intergalactic medium, and clusters of galaxies. Charge exchange emission is also very diagnostic and if observed in a celestial source can provide key information on the composition, ionization state, and relative velocity of both the donor and acceptor species. Our laboratory investigation is unique in the world at providing the first controlled high-resolution spectra of charge exchange in astrophysical elements and is geared to provide information to guide the development of a predictive atomic theory, especially for the key L-shell emission which dominates local charge exchange.

GSFC first installed an X-ray calorimeter instrument at the LLNL EBIT facility in the summer of 2000, based on the engineering-model detector system for the Astro-E observatory. The system was significantly upgraded using technology developed for Astro-E2 in 2003. A dedicated facility-class instrument designed from the ground up for laboratory astrophysics was installed in 2007. The current instrument, dubbed the EBIT Calorimeter Spectrometer (ECS), utilizes a 32-channel X-ray calorimeter array from the Astro-E2 program installed in a long-lifetime, automated laboratory cryostat that enables continuous experiments for up to 70 hours with a two-hour recharge. The detector array is populated with 16 mid-band (0.05–12 keV) X-ray absorbers with 4.5 eV FWHM resolution at 6 keV, and 16 high-band (0.1–100 keV) X-ray absorbers with 30 eV FWHM at 60 keV.

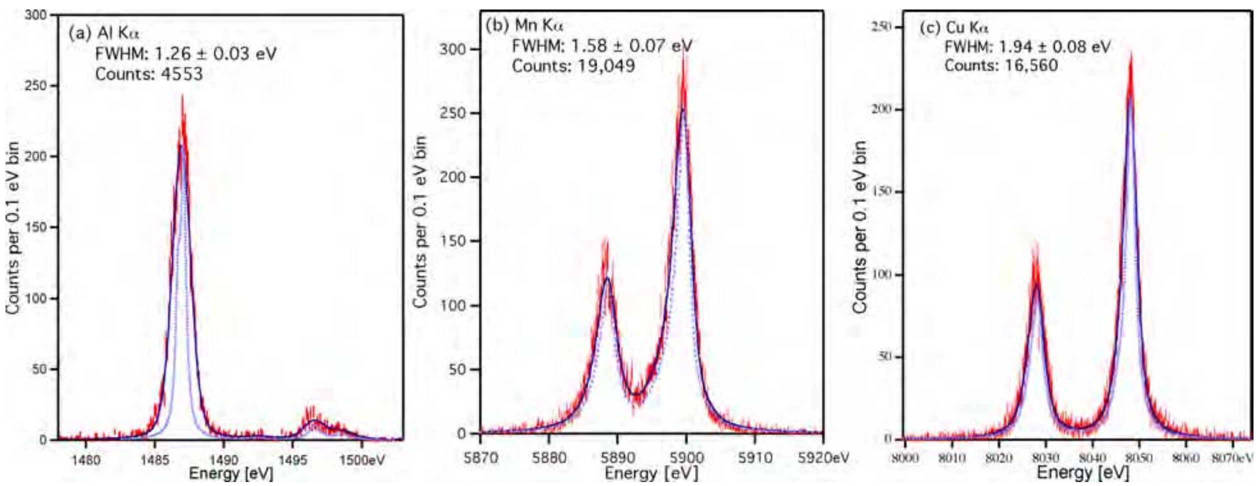
We are currently designing and constructing the fourth-generation instrument that will be based on detector technology from the IXO development program. It will be installed in a completely automated cryogen-free cryostat. The fourth-generation instrument is dubbed the Transition-Edge Microcalorimeter Spectrometer (TEMS) and will be composed of a checkerboard hybrid of 128 low-band (0.05-1 keV) pixels with 0.8 eV resolution at 1 keV, and 128 mid-band (0.05-10 keV) pixels with 2.0 eV resolution at 6 keV. In addition, there will be a 64 channel high-band array (0.1–200 keV) with 30 eV resolution at 60 keV. The TEMS instrument will become the workhorse instrument in our laboratory astrophysics program to make sure that our measurements and understanding of atomic processes are ready to interpret the spectra we will obtain with the Astro-H and IXO observatories. TEMS will be installed at the EBIT facility in 2012.

X-ray Calorimeter Development

An X-ray calorimeter determines the energy of an incident X-ray photon by measuring a small change in temperature. Three types of X-ray calorimeters presently dominate the field, each characterized by the thermometer technology. The first two types use temperature-sensitive resistors: semiconductors in the



Mn Ka spectra measured with the SXS/Astro-H engineering model detector system. The resolution across the pixels ranges from 3.6 – 4.6 eV.



Energy resolution of a small TES calorimeter measured at three different energies using X-ray fluorescence. The pixel dimensions are 57 μm x 57 μm x 4.5 μm, with an underlying 35 μm TES. In each spectrum, the light blue dotted line shows the intrinsic line shape of the K transition. The red lines represent the data, and the darker blue line is the intrinsic line shape convolved with the best fit instrumental broadening (assumed to be Gaussian).

metal-insulator transition and superconductors operated in the superconducting-normal transition. The third type uses a magnetic thermometer. These can be considered the three generations of X-ray calorimeters, although further development of each is proceeding.

The Soft X-ray Spectrometer (SXS) on Astro-H, expected to launch in 2014, will use an array of silicon thermistors with HgTe X-ray absorbers that will operate at 50 mK. Both the semiconductor and superconductor calorimeters have been implemented in small arrays. Kilopixel arrays of the superconducting calorimeters are being produced, and it is anticipated that much larger arrays will require the non-dissipative advantage of magnetic thermometers. Goddard Space Flight Center is the only institution playing a leading role in the development of each of the three dominant X-ray calorimeter technologies. The scientists of the ASD microcalorimeter team include Joe Adams, Simon Bandler, Meng Chiao, Fred Finkbeiner, Richard Kelley, Caroline Kilbourne, Scott Porter, and Steve Smith, postdocs Catherine Bailey and Megan Eckart, and co-op student Jack Sadleir. Progress is made possible through a strong collaboration with Goddard's Detector Systems Branch.

The main developments in the silicon-thermistor calorimeters since XRS/Suzaku have been in their X-ray absorbers and heat sinking. GSFC worked closely with the small business EPIR to develop HgTe absorbers with substantially lower heat capacity than the material used for XRS that yet thermalizes the energy of X-ray photons reproducibly and uniformly. The SXS thermistor array itself is based heavily on the XRS design, but includes better heat sinking to reduce the impact of cosmic-ray heating. The SXS engineering-model calorimeter array has been completed, and the resolution at 6 keV ranges from 3.6–4.6 eV across the array, with the composite performance from summing all the pixels resulting in 3.97 eV resolution. The magnitude of thermal crosstalk has been reduced by more than a factor of ten relative to XRS.

Over the past few years, Goddard has developed a microcalorimeter design that incorporates a microns-thick Au or Au/Bi absorber, designed to thermalize the absorbed energy quickly, with a superconducting transition-edge sensor (TES) made from a Mo/Au proximity-effect bilayer. In this novel design, the absorber makes direct contact with the TES only in normal-metal regions that are used to reduce noise in these sensors, which allows the use of a high-quality electroplated gold layer as the foundation for the absorber. A further constraint, that the high-conductance absorber does not electrically short out the sensor, results in an unusual T-shaped geometry for the contact. Arrays of such pixels optimized for the International X-ray Observatory (IXO) have demonstrated energy resolutions of 2–3 eV FWHM at 6 keV.

Recent Goddard TES calorimeter development has been enhanced by new understanding that many TES properties can be explained by considering these devices to be superconducting weak links, like Josephson junctions, even though the length scales in a TES are considerably more macroscopic than in a tunnel junction. In small TES devices, the effective superconducting transition temperature depends sensitively on current, one effect of which is to extend the linear operating range of such pixels. Pixels with a 0.035 mm TES and 0.057 mm absorber have demonstrated better than 2 eV resolution over a wide energy range. Such small pixels operate well without membrane isolation, allowing fabrication on a robust substrate with built-in heat sinking. These pixels are also about a factor of ten faster than the ones optimized for IXO; with the appropriate filter in the TES bias circuit, the rise and fall times will both be approximately 30 µs.

Goddard is part of an international collaboration (including Brown University, Heidelberg University, NIST/Boulder and PTB/Berlin) to develop magnetic calorimeters. The Goddard emphasis has been on designs that can be implemented in closely packed arrays. Goddard has been fabricating arrays of superconducting niobium meander inductors onto which a layer of magnetic material (Au:Er) is deposited. When a current is passed through the meander, a magnetic field is produced in the magnetic material. When an X-ray is absorbed, the heating changes the magnetic permeability, and therefore the inductance of the meander, which produces the signal. GSFC magnetic calorimeter arrays with absorbers have achieved 3.3 eV resolution at 6 keV, and there remains potential to substantially improve on this in the near future, perhaps even to under 1 eV. An outgrowth of this development is yet another type of calorimeter, the magnetic penetration thermometer (MPT), which uses the same geometry but replaces the magnetic material with a superconductor in its transition. The MPT potentially combines the best of the magnetic calorimeter and TES technologies.

X-ray Mirror Development: NuStar and IXO

Mirror technology development for the International X-ray Observatory (IXO), formerly known as Constellation-X, continues at GSFC and is led by Will Zhang. The IXO requirement is 5" angular resolution after all optics, detectors and other hardware have been assembled into the completed observatory, and Zhang and his team are well on their way toward meeting this goal.

As of this writing, the team has been able to consistently make individual mirror segments that, when properly aligned and integrated, will produce 4.5" X-ray images—close to meeting the corresponding IXO requirement on individual mirror segments of 3.3"—by using a glass-forming technique. The researchers continued a collaborative effort with Goddard's Applied Engineering and Technology Directorate (AETD). They have completed three pairs of mandrels—the forms used to shape the mirrors—that meet the IXO forming-mandrel figure requirements of 2.2". These mandrels are being used to refine techniques to fabricate mirror segments and to demonstrate that several mandrels can be utilized simultaneously to produce mirror segments meeting both quality and schedule requirements.

An aligned and bonded IXO mirror pair that has been X-ray tested.

A completed NuSTAR mirror module.

Meanwhile, they are also continuing another collaborative effort between ASD and AETD: developing the process of integrating these mirror segments into modules that, in turn, can be integrated into a flight mirror assembly. Using finite-element analysis tools, they have simulated the entire process of starting with individual mirror segments and finishing with them aligned and bonded into a module. They are engineering and implementing the process in the laboratory. As of December 2010, they have been able to align and bond a single pair of parabolic and hyperbolic mirrors to produce X-ray images at 9.7", crossing the 10" barrier. They expect to complete a mini-module with at least two pairs of mirrors by 2011. They will subject the mini-module to both X-ray performance and environmental tests to a TRL-5 for a pre-Phase-A mission.

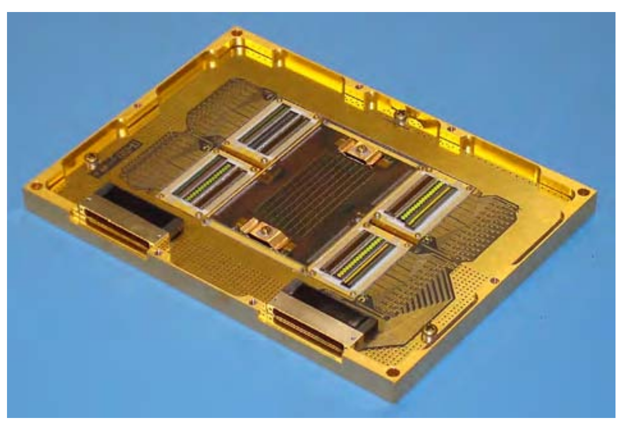
The Nuclear Spectroscopic Telescope Array (NuSTAR) is a Small Explorer under development (Harrison/Caltech, PI). ASD/GSFC is a member of the team, with the responsibility of providing glass mirror substrates using the glass-forming technology that has been developed for IXO. These substrates are shipped to the Danish Space Research Institute to be coated with multi-layers to enhance their reflectivity of high-energy (10–80 keV) X-rays. They are then shipped to Columbia University for alignment and assembly into two mirror modules.

Work began in February 2008 with facility modification and procurement of ovens and other necessary equipment. The work was completed on schedule and within budget. The entire mirror substrate production facility, located in Building 22 at Goddard, became fully operational on September 1, 2008. After a period of equipment checkout and personnel training, the production of flight substrates started in February 2009 and has been on schedule and on budget. The last batch of flight substrates will be delivered by January 31, 2011, helping the NuSTAR project to make its February 2012 launch.

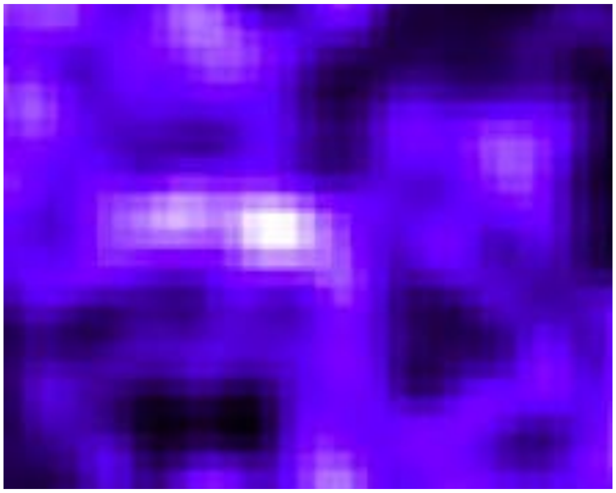
Far-Infrared Detectors

The past decade has seen dramatic advances in many areas of long-wavelength astrophysics. WMAP, following the great successes of Cosmic Background Explorer (COBE), has confirmed our general understanding of the early universe and allowed us to quantify critical parameters—its age, composition and early evolution. Spitzer has provided an extraordinary imaging and mid-infrared spectroscopic capability, which has resulted in an increasingly improving picture of the evolution of galaxies over the life of the universe. Herschel launched on May 14, 2009, and is providing our first large-scale look at the high-redshift universe in the submillimeter. WISE launched on December 14, 2009, producing an all-sky map of hundreds of millions of sources in the mid-infrared. JWST, scheduled to be launched later in this decade, will provide a window into the epoch of galaxy formation to clarify the processes that produced the present universe.

Future far-infrared and millimeter facilities will play an important role in clarifying and extending this work. More than half the power of high-luminosity galaxies is emitted in the rest-frame far-infrared, so far-infrared and submillimeter imaging and spectroscopy are required for a full understanding of the physics of



The GISMO detector array consists of 128 bolometers using superconducting transition-edge sensors read out by SQUID multiplexers. Operated at a temperature of 0.45K, this array is one of the most sensitive ever constructed for its wavelength range of 2 mm (150 GHz).



The GISMO 2-mm bolometer camera was used to help characterize COSMOS-AzTEC-3, a massive protocluster at about redshift 5.3.

these systems. The next steps in NASA's profoundly successful science program are currently being developed and the priorities for the space missions, supplemented by suborbital missions, being established.

SOFIA, having just recently completed its first science flights, will be a key facility for imaging and spectroscopic follow-up of Spitzer, Herschel, and WISE discoveries. Measurements of the polarization of the CMB promise to allow us to distinguish among models of the first instants of our universe. Further in the future, great advances in sensitivity, angular resolution and overall instrument capability will be realized by large cryogenic telescopes in space, such as SPICA, CALISTO or SAFIR, SPIRIT, and SPECS. High-performance far-infrared detector arrays are required for all this high priority work. Novel experiments in the far-infrared on balloon-borne platforms will push the boundaries of our technological capability while providing important scientific advances.

The far-IR instrument development group in ASD (Benford, Chuss, Fixsen, Kogut, Moseley, Rinehart, Staguhn, Voellmer, Wollack) has ongoing research projects to develop, implement, and field these detector arrays. Our large-format filled arrays will enable major advances in space-borne, sub-orbital and ground-based infrared, far-infrared and sub-millimeter instrumentation. Precision on-chip polarimeter detectors will enable sensitive measurement of the very slightly polarized signal from the CMB, in concert with a capable polarization modulator also developed in ASD. A balloon-borne experiment to measure the CMB polarization signal, PIPER (PI: Al Kogut), is well underway and will use both the modulator (Chuss and Voellmer) and the large-format arrays (Benford, Staguhn, Moseley, Wollack). Four of these arrays, totaling 5,120 pixels, will produce the richest polarimetric imaging of the CMB sky on its flights in 2013. Using superconducting transition-edge-sensor bolometers read out by SQUID multiplexers, the arrays flown in PIPER will provide the greatest sensitivity and pixel count of any yet fielded at submillimeter wavelengths.

This year, we began work on the world's first suborbital far-infrared interferometer experiment. The Balloon-Borne Experimental Twin Telescope Infrared Interferometer (BETTII; PI: Stephen Rinehart) will enable the highest angular resolution ever obtained at its 30–90 micron wavelengths: resolving structures at a scale as fine as 0.5 arcseconds. BETTII has a double Fourier interferometer that provides spatially-resolved spectroscopy with resolution of $\lambda/\Delta\lambda$=200 to trace important transitions in the heart of star forming regions in our galaxy and in the region close to active galactic nuclei. In addition to its cutting-edge scientific capabilities, BETTII will also demonstrate interferometry from a "near-space" platform, paving the way to space-based interferometry with even larger structures for improved sensitivity and angular resolutions. Benford, Fixsen, and Staguhn are Co-Is.

Our ground-based instruments continue to provide cutting-edge scientific results. The ZEUS spectrometer at the Caltech Submillimeter Observatory, led by Cornell using GSFC detectors (Benford, Moseley, and Staguhn), has produced the first definitive survey of far-infrared atomic line emission from high redshift galaxies. These lines trace important physical parameters of galaxies at their epoch of peak star formation. The SHARC-II camera, also at the CSO and using a 384-pixel GSFC bolometer array (Benford, Moseley, Staguhn, and Voellmer), continues to be the most productive submillimeter (350 micron) imager in the world. Our recent long wavelength (2 mm) camera based on a 128-element close-packed planar bolometer array that uses novel superconducting thermistors read out by SQUID multiplexers, named GISMO (PI: Staguhn; Benford, Moseley, Fixsen are Co-Is), has had another successful observing run in April 2010. Among its scientific results is the detection of emission from the most distant protocluster. GISMO is installed at the IRAM 30m radio telescope in Pico Veleta, Spain, where it is already available to the broader GSFC and IRAM astronomical community.

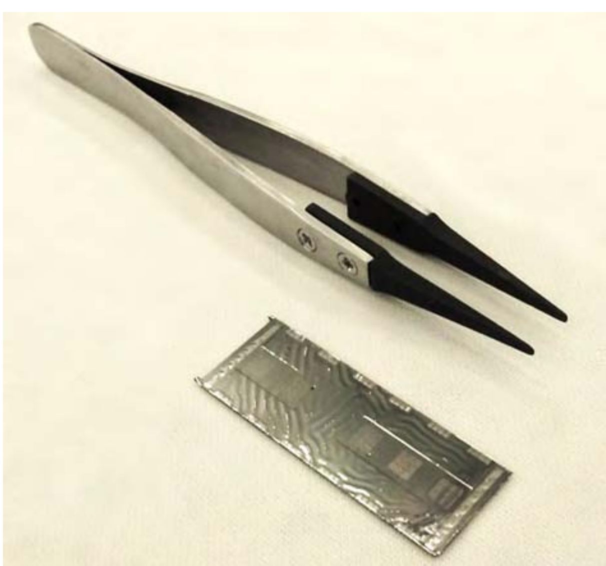
Recently, work has begun on a new generation of detector technology and instrument concepts (PIs include Benford, Moseley, Wollack). Based on superconducting resonators and kinetic inductance detection, this technology may enable entire instruments to be built on a single silicon wafer. A compact (4-inch wafer) microstrip spectrometer for the millimeter band that will provide nearly octave-wide coverage with a spectral resolution sufficient to detect multiple emission lines from galaxies is in production (PI: Moseley; Benford & Wollack are Co-Is).

MKID Detectors for Submillimeter Astronomy

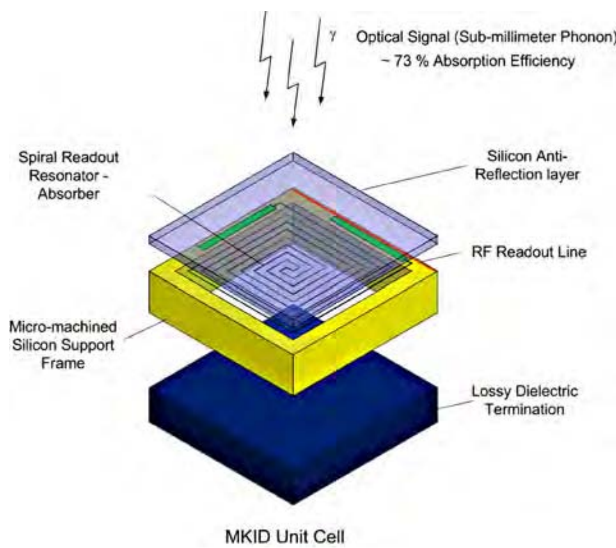
Ed Wollack and collaborators are actively pursuing the extension of Microwave Kinetic Inductance Detectors (MKIDs) technology to the 38–400 μm spectral regions via a novel detector concept. Of the high-performance detector-array technologies currently being developed, the MKIDs may have the greatest promise for scaling to very large arrays (~10^5 detectors). Such arrays can provide high quantum efficiency and can be designed to provide background-limited performance over a wide range of incident powers, making them candidates for a wide range of instruments, ranging from suborbital imagers to spaceborne spectrometers.

Such large-format detector technologies are much needed in this important spectral region. Many of the primary diagnostics of a large range of galactic processes require observations in this spectral range. The far-infrared dust emission from normal and ultra-luminous galaxies peaks in this spectral range, and its measurements are essential for understanding the energy production mechanisms and processes in the galaxies. Fine-structure lines of O III, NIII, O I, C I, and N II fall in this spectral range. These lines can provide high-quality measurements of elemental abundances and physical conditions in the emitting regions. Many excited states of molecules, such as CO, are seen in this spectral range, and provide the capability to probe physical conditions in hot molecular clouds. Low-lying transitions of hydrides in this spectral region can probe cores of cooling clouds, providing information on star-formation processes. The goal is to produce detectors that will permit the use of these powerful diagnostic tools in future missions.

Presently, MKID detectors employ a resonant tank circuit made from a superconducting transmission line. Its quality factor, Q, and central frequency are read out using a microwave reflectometer. Millimeter-wave radiation is coupled into the device from an antenna, where it breaks Cooper pairs in the superconductor. This results in a change in the kinetic inductance of the microwave circuit, causing a change in the frequency and Q of the circuit. This technique



A linear-array MKID test structure fabricated by the GSFC Device Development Laboratory.



This sketch shows the sensor topology under study. Photons with energy greater than the gap energy are absorbed in the meander. The quasiparticle excitations change the center frequency and Q of the microwave resonator.

works well at frequencies where the radiation can be coupled into the device using antennas and superconducting transmission lines. At frequencies above the superconducting gap of Nb, quality transmission lines are difficult to produce, so a different approach must be adopted. To achieve the desired sensor performance in the desired band, we modify this scheme by choosing the resonator metallization geometry and material properties consistent with its necessary roles in absorption of the incident wave and readout of the detector signal. The incoming light, with photon energy much greater than the superconducting gap, interacts with the spiral microwave transmission line.

In the approach under development, the meander is chosen to have a surface-impedance and filling factor such that it presents the optimal matching impedance to the incoming wave, about 157 Ω per square. When the optical power is absorbed, it excites quasiparticles in the superconducting spiral, modifying the kinetic inductance of the line. The transmission line is configured as a $\lambda/2$ stepped impedance resonator, designed to have a resonant frequency of ~1 GHz. The Q of the un-illuminated resonator can be controlled by appropriate selection of the coupling Q to the transmission line. The device is optimized for a particular application by choosing the unloaded Q to be equal to the Q caused by quasiparticle dissipation at maximum power. The density of quasiparticles is a measure of our signal, and is sensed by the change in frequency and Q of the readout resonator.

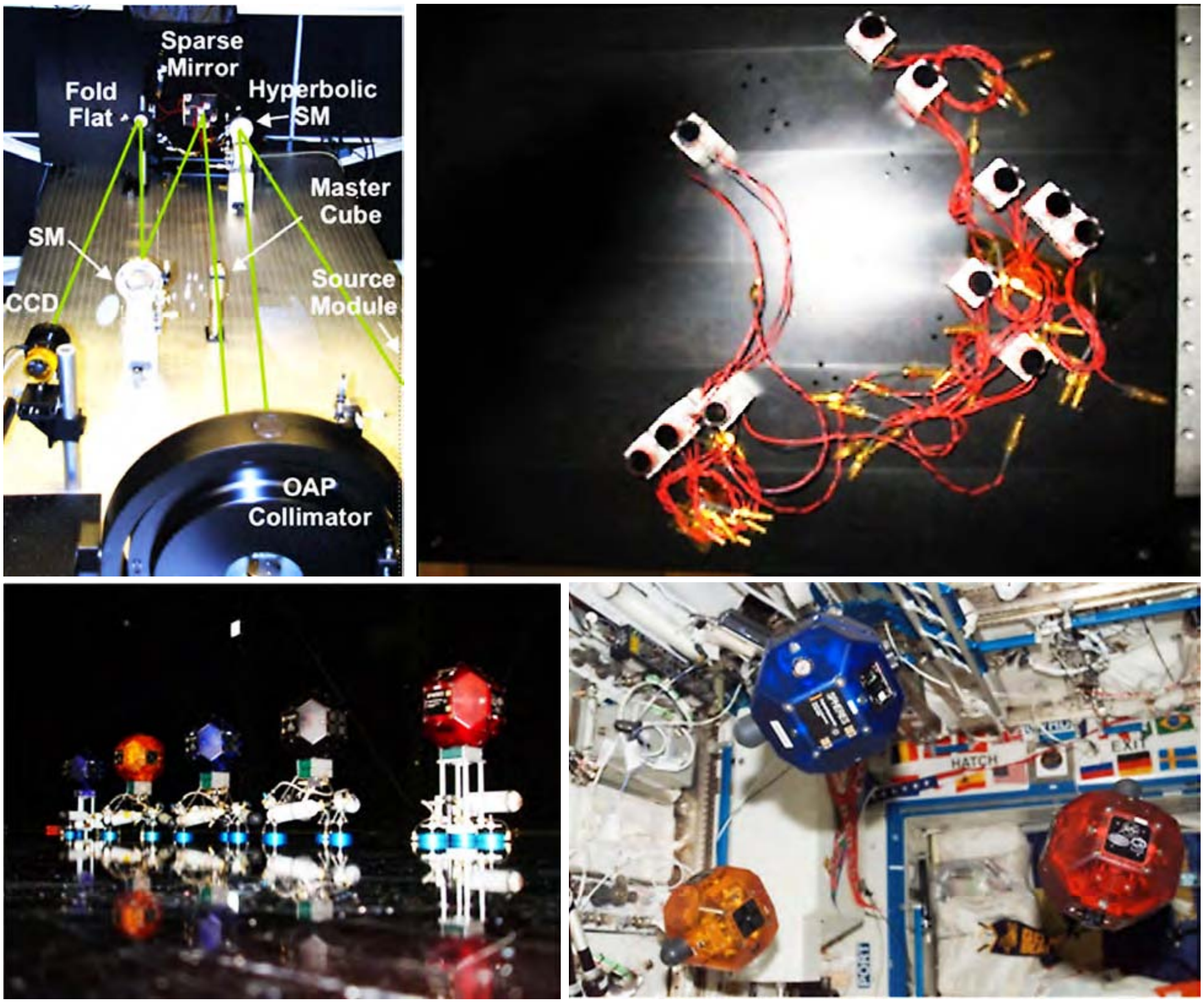
Pending successful laboratory demonstration of the devices, a test of an array will be conducted in a 350µm imager at the Caltech Submillimeter Observatory (CSO). This collaborative effort is led by Edward Wollack and includes S. Harvey Moseley (ASD), and Ari Brown, Wen-Ting Hsieh, Thomas Stevenson and Kongpop U-yen of Goddard's Engineering Directorate, and Professor Jonas Zmudizian of Caltech.

Technology Development for Space-based Imaging Interferometers

The advancement of astronomical observing facilities is always motivated by the quest for more light-gathering power (total aperture area) and for higher angular resolution (maximum diameter of the aperture). Monolithlic or segmented mirrors can only be used up to a point because engineering limitations restrict their sizes to perhaps 50 meters across. To obtain higher resolutions, it's necessary to go to sparse-aperture designs where multiple smaller mirrors are used in precisely arranged arrays to sample a larger "virtual aperture" some hundreds of meters—and possibly even a kilometer or more—in diameter. This enables the design of imaging interferometers capable of sub-milliarcsecond angular resolutions. Such observatories are feasible, but they require technology development before they are ready to fly. Some of that work is described below.

Dr. Kenneth Carpenter of the Exoplanets and Stellar Astrophysics Laboratory is coordinating the development of various technologies needed to enable large baseline, space-based imaging interferometers. These include the GSFC Fizeau Interferometer Testbed (FIT), a ground-based experiment located in a new lab in Building 34 to develop closed-loop, nanometer-level optical control of a multiple-element sparse array, and various efforts at MIT (led by Dave Miller) using the Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES), which uses hardware on ground-based flat floor facilities (2-D) and inside the International Space Station (3-D) to test centimeter-level Precision Formation Flying (PFF) and synthetic imaging algorithms; the latter MIT-led research is currently supported by a GSFC SBIR Program. The primary goals of these programs are to mature the command and control algorithms required to enable formation-flying of sparse aperture/interferometric imaging missions and to optimize maneuvers for synthetic imaging with such arrays.

Carpenter is the PI of the FIT effort and key Co-I's include R. G. Lyon and D. Mozurkewich (Seabrook Engineering). The FIT is developing and demonstrating closed-loop control, utilizing feedback from the science data, of the tip, tilt, piston, and translation of mirrors in a sparse array and of the overall system to keep beams in phase and to optimize imaging. Dave Miller (MIT) leads the experiments with SPHERES to address constellation-wide sensing and control of the formation-flying spacecraft. This program is developing and demonstrating specific algorithms for autonomous precision formation flying and efficient synthetic-imaging maneuvers of an array of spacecraft. The end goal of this research and development is the production of a single system that will provide staged-control over the full dynamic range needed to enable these missions. While the detailed design of these experiments are based on the Stellar Imager (SI) mission, the technologies being advanced will help enable



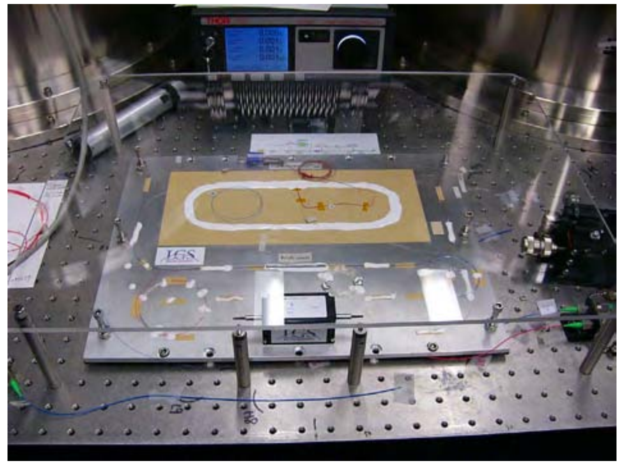
The Fizeau Interferometer Testbed at Goddard. Top left: FIT Phase 1, with baffles removed for clarity. Top right: FIT Phase 2 array plate in assembly, with 11 of 18 mirrors/actuators installed. Bottom left: MIT SPHERES on the MSFC flat floor. Bottom right: MIT SPHERES being operated inside ISS.

numerous additional missions being considered by NASA for flight, including the Space Infrared Interferometric Telescope (SPIRIT), Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), Life Finder (LF), Black Hole Imager (BHI/MAXIM), and Planet Imager (PI), as well as smaller precursor missions, such as the Fourier Kelvin Stellar Interferometer (FKSI), SI Pathfinder, selected Exoplanet Probes, and ESA's Pegase. Please see **http:/hires.gsfc.nasa.gov/si/** for additional information.

Technology Development for LISA

ASD's Gravitational Wave Astrophysics branch continued to provide demonstrations of technology readiness for the LISA mission in 2010. These efforts were lead by scientists Camp, Guzmán, Livas, Numata, Stebbins and Thorpe with help from both civil servant and contract engineers. LISA technology development activities also provided an opportunity for students from high school through graduate school to gain valuable laboratory experience. Students active in 2010 included Jenny Harding (Key HS), Elizabeth Hyde (Stone Ridge School of the Sacred Heart), Lilian Sun (River Hill HS), Jeremiah Noordhoek (MIT), Scott Smedile (VA Tech.), Darbin Reyes (Cornell), and Heather Audley (U. Hanover, Germany). Results from these activities were presented at a number of conferences including the 8th annual LISA Sympo-

The OATM actuator test bed was used to verify that the piezo-electric inchworm actuator was capable of movement over 2 cm while maintaining position stability of better than 1nm/Hz$^{1/2}$ in the LISA measurement band.



A Ytterbium fiber amplifier suitable for LISA was developed at GSFC by Numata and Camp.

sium (Stanford, CA), the 38th COSPAR Assembly (Bremen, Germany), and the 2010 APS April Meeting (Washington, DC).

Optical Assembly Tracking Mechanism (OATM) testing. LISA detects gravitational waves by monitoring the distance between each of its three spacecraft using laser interferometry. This requires that the two telescopes aboard each spacecraft be precisely pointed (approximately 8 nanoradians) toward the other two spacecraft, maximizing the exchange of light between them. The OATM enables this by allowing the spacecraft to account for the small variations (approximately one degree with a one year period) in the angle between the two LISA arms over the course of the mission. GSFC has identified an actuator known as a piezo-electric inchworm that can provide the required dynamic range and precision to drive the OATM. Thorpe, together with contract engineering support and metrology support from J. Hagopian (Optics Branch), completed development of an OATM actuator test bed and verified that the piezo-electric inchworm does indeed meet all the LISA requirements. As part of this effort, they designed, built, and characterized a thermal isolation chamber with temperature stability of better than 0.1 mK/Hz$^{1/2}$ in the LISA band, a technique that can be applied to future LISA technology development activities.

Fiber laser/amplifier development. The LISA laser must have a single-longitudinal-mode output with high intensity and frequency stability. Fiber laser/amplifier technologies have made great advances over the last decades and are overcoming limitations of traditional bulk-optics based lasers (e.g., NPRO) and amplifiers. Numata and Camp, together with technical support from the GSFC Laser and Electro-optics Branch and Lucent Government Solutions (LGS), have developed an Ytterbium fiber ring laser and an Ytterbium fiber amplifier. Space qualification testing of the fiber components was performed in 2010. It included gamma/proton radiation hardness test of fiber components and thermal vacuum cycling tests of the fiber amplifier system. No showstoppers for irradiation and thermal cycling were discovered. Detailed noise measurements of these laser systems will be performed in 2011 at GSFC.

Numata and Camp have also looked into the latest telecommunications laser technology represented by the planar-waveguide external cavity diode laser (PW-ECL) as a possible alternative to traditional NPROs and fiber lasers. PW-ECL has smaller package size, smaller parts count, and much lower cost than NPRO. In addition, the PW-ECL showed smaller intensity and frequency noise in LISA's observation band. An engineering test unit for space application will be built in 2011, in collaboration with Redfern Integrated Optics and LGS.

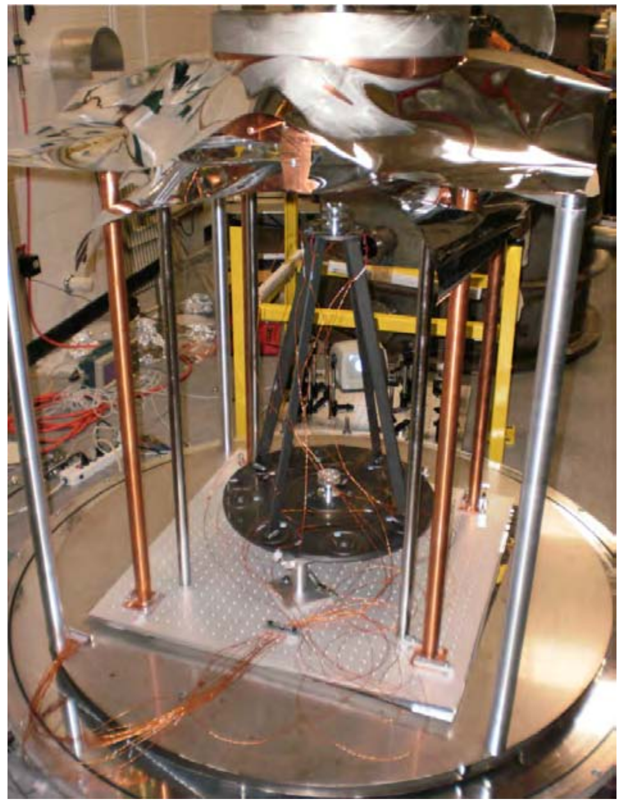
Telescope structure stability. The LISA telescope is used to increase the light-transfer efficiency between distant spacecraft. Since the telescope lies in the interferometric path, it is critical that the optical pathlength through the telescope remain stable at the picometer level.

The PW-ECL (right) has a smaller package size and fewer parts than the NPRO (left), potentially providing savings for LISA.

Livas, together with engineering support from GSFC and construction and testing support from the University of Florida, has developed a prototype metering structure of silicon carbide that will be used to evaluate the material for potential use in the LISA telescope. While not a true telescope in the sense that it does not focus light, the prototype is structurally similar to a telescope: four long legs attached to a large disk (the primary) support a smaller disk (the secondary). The six components of the telescope were manufactured individually and were then bonded together using hydroxide-catalysis bonding.

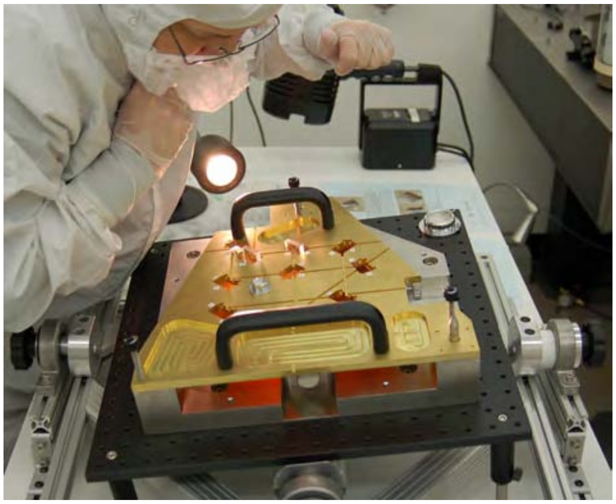
The structure is undergoing testing at the University of Florida to determine how much the structure changes dimensionally as it is cooled to the operating temperature and gradient, and then monitored to check the long-term stability with femtometer-level accuracy. Preliminary results confirm published data and show that the stability is limited by thermal effects in the environment, as expected. Next steps include adding vibration isolation and applying thermal gradients to check stability.

Optical bench construction. At the heart of the LISA interferometry system is a structure known as the optical bench that interferes beams from the various spacecraft to provide measurements of inter-spacecraft distance fluctuations at the ten picometer level. The optical pathlengths on the optical bench must be sufficiently stable so that they do not obscure the gravitational wave signal. The LISA optical bench will be built using an innovative technique known as hydroxy-catalysis bonding that has been applied in Europe to produce the optical benches for the technology demonstrator mission LISA Pathfinder. Thorpe is leading an effort funded by the GSFC IRAD program to build a small optical bench containing a frequency stabilization reference using the hydroxy-catalysis technique. Assisted by A. Preston (Laser Remote Sensing Laboratory), L. Miner and L. Kolos (Optics Branch), and K. Norman (SGT), the bench construction began in late 2010 and is expected to be complete in early 2011. Preston is also exploring the application of the hydroxide-catalysis technique to the building of retroreflectors for precision lunar and satellite laser ranging experiments.



G. Mueller's group at the University Florida has prepared a vacuum chamber for testing the dimensional stability of GSFC's prototype telescope spacer.

Laser stabilization through arm-locking. To achieve the required displacement sensitivity of roughly ten picometers, the LISA lasers must be frequency stabilized. In the laboratory this is typically accomplished by locking the laser frequency to a frequency reference such as an optical cavity or molecular absorption line. LISA provides another alternative, using



L. Miner inspects a hydroxy-catalysis bond made during construction of a prototype LISA frequency reference bench.

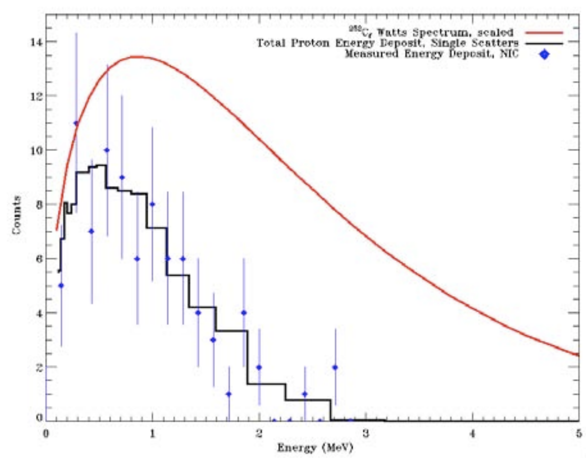
the long arms of the LISA constellation as a frequency reference. This technique, known as arm-locking has been extensively studied using analytic models of the LISA interferometry system. Thorpe, together with Livas and controls engineer P. Maghami (Attitude Control Systems Engineering Branch), have developed a time-domain simulation of arm-locking that allows the investigation of a number of effects that are not easily modeled analytically. The simulation indicates that arm-locking is indeed a viable option for LISA laser frequency stabilization and can also be used in conjunction with traditional techniques to further improve performance.

Photoreceiver development. LISA will use quadrant photoreceivers as front-end devices for the phasemeter measuring the motion of drag-free test masses in both angular orientation and separation. Guzmán, Livas and Silverberg (Observational Cosmology Laboratory Emeritus) have set up a laboratory testbed for the characterization of photoreceivers. Some of the limiting noise sources have been identified and their contribution has been either measured or derived from the measured data. A test photoreceiver with a 0.5-mm-diameter quadrant photodiode has been built with an equivalent input current noise of better than 1.8pA/√Hz below 20MHz and a 3 dB-bandwidth of 34 MHz. Following steps include spatial scanning of the photodiode surfaces, measurement of inter-quadrant cross-talk, differential wavefront sensing angle measurements, and design and testing of alternative topologies for photoreceiver electronics with lower noise and higher bandwidth performance.

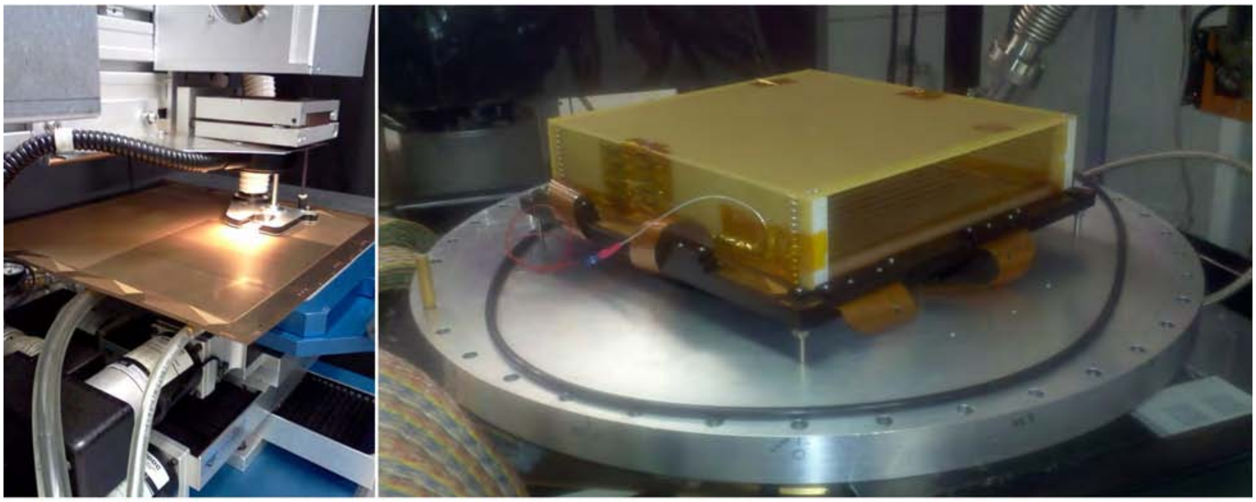
Three-Dimensional Track Imager Detector for Gamma-ray and Neutron Imaging

The development of the Three-Dimensional Track Imager (3-DTI) is motivated by the technology requirements for a future gamma-ray telescope and neutron imager that will provide optimum angular resolution over the energy range from ~5–500 MeV, and for imaging of fast neutrons, $E_n > 0.1$ MeV, from passive and active interrogation of special nuclear materials (SNM). In these applications, the direction and energy (and polarization of gammas) of the incident neutral particles is determined from the three-dimensional momenta of the charged interaction byproducts.

Drs. Stanley Hunter, with Georgia DeNolfo, Seunghee Son, Jason Link, and Michael Dion, are developing the 3-DTI for high-angular-resolution gamma-ray astronomy and neutron imaging. The 3-DTI is a large-volume time-projection chamber (TPC) with two-dimensional micro-well detector (MWD) readout. Relative time of arrival of the ionization charge provides the third spatial coordinate. Each well of the MWD (200 μm diameter on 400 μm centers) is a gas proportional counter that allows gas gain in excess of



Simulated energy spectrum, normalized counts vs. energy, (black) of protons resulting from single (n, p) interactions in CH_4+CS_2 gas mixtures, with the Watt fission spectrum (red) shown for comparison. The blue points come from preliminary analysis of 10/10 NIC prototype data for the scattered protons. Despite the data's limited statistics, the spectral agreement is very good.



Left: In-house laser micro-machining of a 30×30 cm^2 MWD. Right: The 30×30×7 cm^3 3-DTI detector configured for the Ft. Monroe field tests.

10^4. Negative ion drift is utilized to reduce the drift velocity and diffusion, which allows for the large TPC volume. Development of the 3-DTI technology for gamma-ray imaging is funded by NASA/APRA and for neutron imaging by the Office of Naval Research.

The team's accomplishments this year include:

• Son and Dion made major improvements in our UV laser micro-machining facility. These improvements have resulted in fabrication of 10 × 10 cm^2 MWDs with gas gain in excess of 10^4, a requirement for minimum ionizing electron tracking. Improvements in our micro-machining techniques have enable production of 30 × 30 cm^2 MWDs.

During the static over-water tests of the 30 cm NIC conducted at Fort Monroe, Va., the NIC was placed on a floating dock and the source was located in the bow of a boat, shown here moored to the dock.

• Son, Dion, DeNolfo, and Hunter demonstrated neutron imaging via n,p elastic scattering with the 10 × 10 × 15 cm^3 3-DTI/NIC prototype eliminating the NIC dependence on ^3He for neutron imaging. The spectrum of recoil proton energy agrees with GEANT-4 calculations done by DeNolfo confirming the energy sensitivity of the NIC.

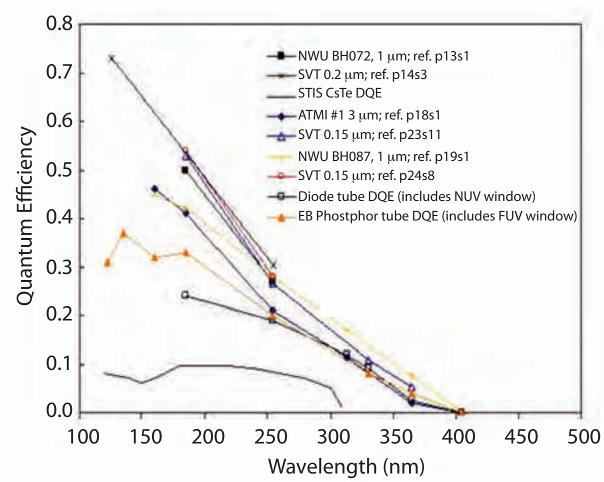
• Dion assembled a 10 cm TPC optimized for drift velocity and diffusion measurements of negative ion gas mixtures. The gas gain, drift velocity, and longitudinal diffusion were measured as a function of electric field for several CH_4 + CS_2 mixtures. The negative ion diffusion is proportional to 1/E, clearly in thermal equilibrium with the gas.

• Son and Dion completed the assembly of the 30×30×7 cm^3 3-DTI/NIC prototype and imaged neutrons from a 252Cf source. This NIC prototype was extensively tested over-water at Ft. Monroe, Va., using 252Cf and SNM sources. Son, Dion, DeNolfo, and Hunter contributed to the analysis of the field test data. These results confirm the omni-directional, multi-source, and spectral sensitivity of the NIC and advance the 3-DTI technology to TRL-6.

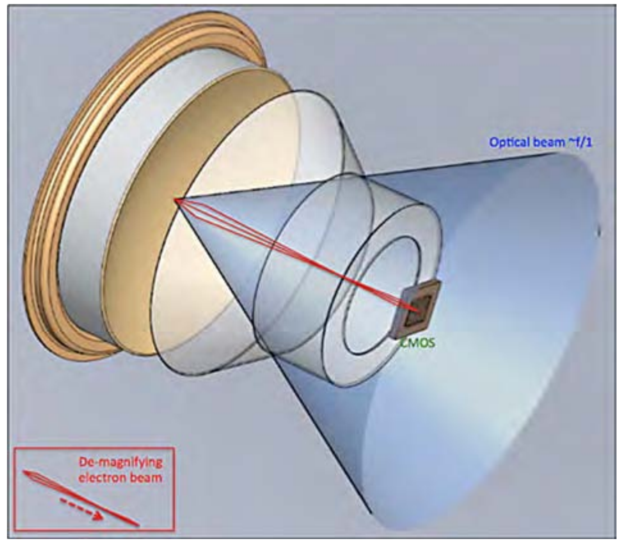
• Several papers describing the 3-DTI development were presented at international conferences.

UV and Visible Zero-Read-Noise Imaging Detector Development

A higher quantum efficiency (QE) in a detector is equivalent to improving the sensitivity of a telescope system by increasing the area of the telescope. For ex-



QE results as a function of wavelength.



Demagnifying electrostatic focused EBCMOS detector. Focusing electrodes are a ceramic/wire very dilute cage, allowing the optical beam in around the relatively small CMOS receiver.

ample, doubling the QE is equivalent to doubling the telescope mirror area, at vastly less cost. Photon-counter detectors can remove the detector's readout noise, which can be the dominant noise source for measuring the spectra of faint objects and can hide the signal.

For the UV, a new class of photocathodes are under development with higher QEs than were available in the Hubble, FUSE, and GALEX era, based on new ternary materials becoming available such as p-doped AlGaN and MgZnO, in both planar and nanowire forms. By cesiating p-doped GaN, QEs of 50–60 percent at 180 nm, a factor ~6 higher than flown on HST/STIS, and 65–68 percent at 122nm, have been obtained. A GaN photocathode has been transferred into a diode tube with the QE stable for four years, and into an EBCCD imaging tube in collaboration with Rutgers University, and larger format EBCMOS tubes are being designed.

Work continues via ROSES/APRA funding to extend the wavelength range and to obtain higher QEs and compatibility with microchannel plates (MCPs). SBIR programs funded by NASA are also developing silicon MCPs with AlGaN photocathodes. Woodgate, Kimble, Kruk, Norton, Hilton and Stock, along with GSFC engineering, university, NIST, and commercial partners, plan to build these photocathodes into EBCMOS and MCP detectors.

In the visible, photon-counting EMCCDs are being tested for use in future space spectrographs for faint objects such as exoplanet atmospheres, and are using fast controllers to reduce Clock Induced Charge to extend the useful dynamic range of the photon-counting regime. A 1k ×1k EMCCD will be used in a ground-based integral field spectrograph.

CdZnTe Detector Development for Hard X-ray Coded-Mask Detectors

It is not possible to focus gamma rays with current technology, so the wide-field Burst Alert Telescope (BAT) on Swift—in orbit for more than six years—uses a technique called coded-aperture imaging to image and localize incoming gamma rays. Gamma rays (15–150 keV) are detected at the focal plane by 32,768 pieces of CZT. This coded aperture technique is being extended to a higher energy range (5–500 keV) by Scott Barthelmy and Neil Gehrels.

This effort is developing the packaging and front-end electronics for the thicker CZT needed to go to the higher energies and to improve the energy resolution. Originally conceived for the EXIST mission, we are now focusing on smaller instruments and missions (e.g., the Hard X-ray Imager on the Brazilian Lattes-MIRAX mission).

Proto-EXIST1 was the first of a two-phase, balloon-based instrument to develop and prove the technology for the EXIST mission. Proto-EXIST1 successfully flew in October 2009 from Fort Sumner, N.M., with 6.5 hours at float altitude and a landing in western Kansas. It is lead by Josh Grindlay (CfA), with

Proto-EXIST1 payload carried by the Columbia Scientific Balloon Facility launch vehicle at Ft. Sumner, N.M. prior to launch on Oct. 9, 2009. The detector array lies within the pressure vessel at the bottom of the gondola. The coded aperture mask is on the top end of the pressure vessel. The long vertical tube is the star camera. The gondola, provided by Marshall Space Flight Center, is an azimuth-over-elevation design.

significant contributions from Goddard. The flight also tested the stacked-sheet design of the tungsten coded-aperture mask. During the flight, Cygnus X-1 was successfully imaged and a spectrum was obtained.

Goddard continues the development of the Command and Data Handling electronics in the front-end detector-array electronics (i.e., everything after the detector ASIC). The next step (still called proto-EXIST2) is replacing the front-end analog ASIC with one that has 16 times more channels, enabling more pixels to be handled in the same amount of space with much less power. The pixel pitch is dropping from 2mm to 0.6 mm. The second balloon flight, in Fall of 2011, will raise the TRL from 5 to 6 for the entire new ASIC-based detector array system.

Projects

Scientists assigned to NASA flight projects play vitally important roles during all phases of a mission's life cycle—from the development of science requirements, to concept and technology development, formulation and eventually operations. The Project Scientist works with project managers, engineers, NASA Headquarters, the mission science team (or science working group) and the wider astronomical community to assure a successful outcome. Nearly half of the scientists in ASD serve NASA either as a Project Scientist (PS) or as a Deputy Project Scientist (DPS), Mission Scientist (MS), Instrument Scientist (IS), Principal Investigator (PI), Deputy PI, and more. The top-notch science that flows from ASD missions is a testament to the knowledge, hard work and dedication that the division's technical staff brings to these roles.

Project Scientists	
ACE	Tycho von Rosenvinge
Astro-H	Robert Petre (PS)
SXS Instrument	Rich Kelley (PI)
Balloon Program	Jack Tueller (PS), John Mitchell (DPS)
Cosmic Origins	Mal Niedner (Chief Scientist)
International X-ray Observatory (IXO)	Nick White (PS), Ann Hornschemeier (DPS), Robert Petre (Deputy for Observatory)
Explorer Program	Neil Gehrels (PS)
GALEX	Susan Neff (MS)
GEMS	Tim Kallman (PS), Jean Swank (PI), Keith Jahoda (DPI), Joe Hill (IS)
Fermi	Julie McEnery (PS), Liz Hays (DPS), Neil Gehrels (DPS), Dave Thompson (DPS)
HEASARC	Alan Smale (Director), Lorella Angelini (DPS)
HST	Jennifer Wiseman (PS), Observatory PS (Open), Ken Carpenter (Operations DPS)
LISA	Robin Stebbins (PS), Jordan Camp (DPS), Jeff Livas (DPS), Stephen Merkowitz (DPS)
JWST	John Mather (PS), Jon Gardner (DPS), Mal Niedner (DPS for Technical), Matthew Greenhouse (ISIM PS), Bernard Rauscher (DPS for ISIM), Mark Clampin (Observatory PS), Charles Bowers (DPS for Observatory), George Sonneborn (Operations PS), Jane Rigby (DPS for Operations), Randy Kimble (DPS for I&T)
JWST microshutters	Harvey Moseley (PI)
NASA Engineering Safety Center	Ed Wollack
Physics of the Cosmos	Jean Allen (Chief Scientist)
WFIRST	Neil Gehrels (PS), Jeff Kruk (IS)
RXTE	Tod Strohmayer (PS)
Sounding Rockets	Scott Porter (DPS)
Suzaku	Rob Petre (PS), Lorella Angelini (DPS)
Swift	Neil Gehrels (PI), Scott Barthelmy (DPI)
WISE	Dave Leisawitz (MS), Dominic Benford (DMS)
WMAP	Gary Hinshaw (PS)
XMM	Steve Snowden (PS)

In Operation

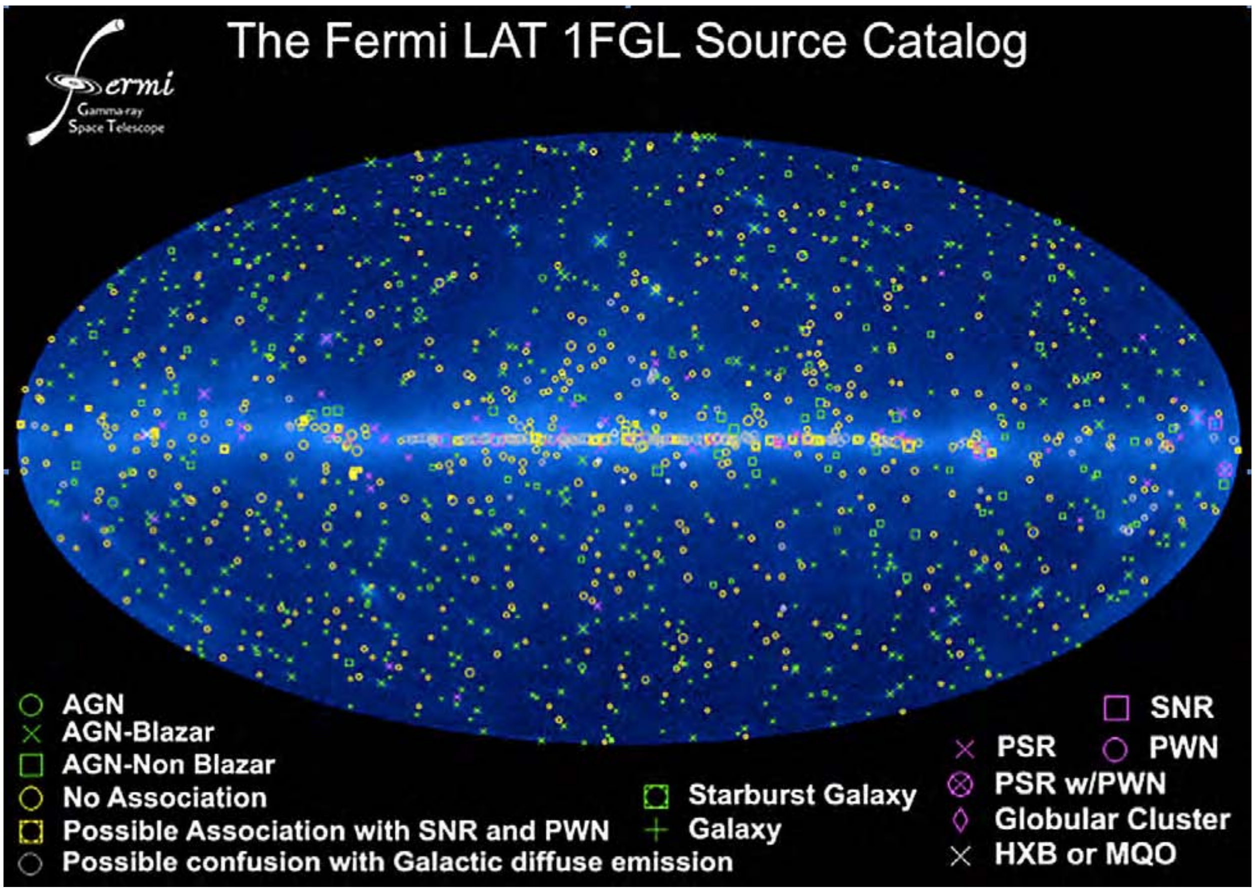
Fermi Gamma-ray Space Telescope

Science

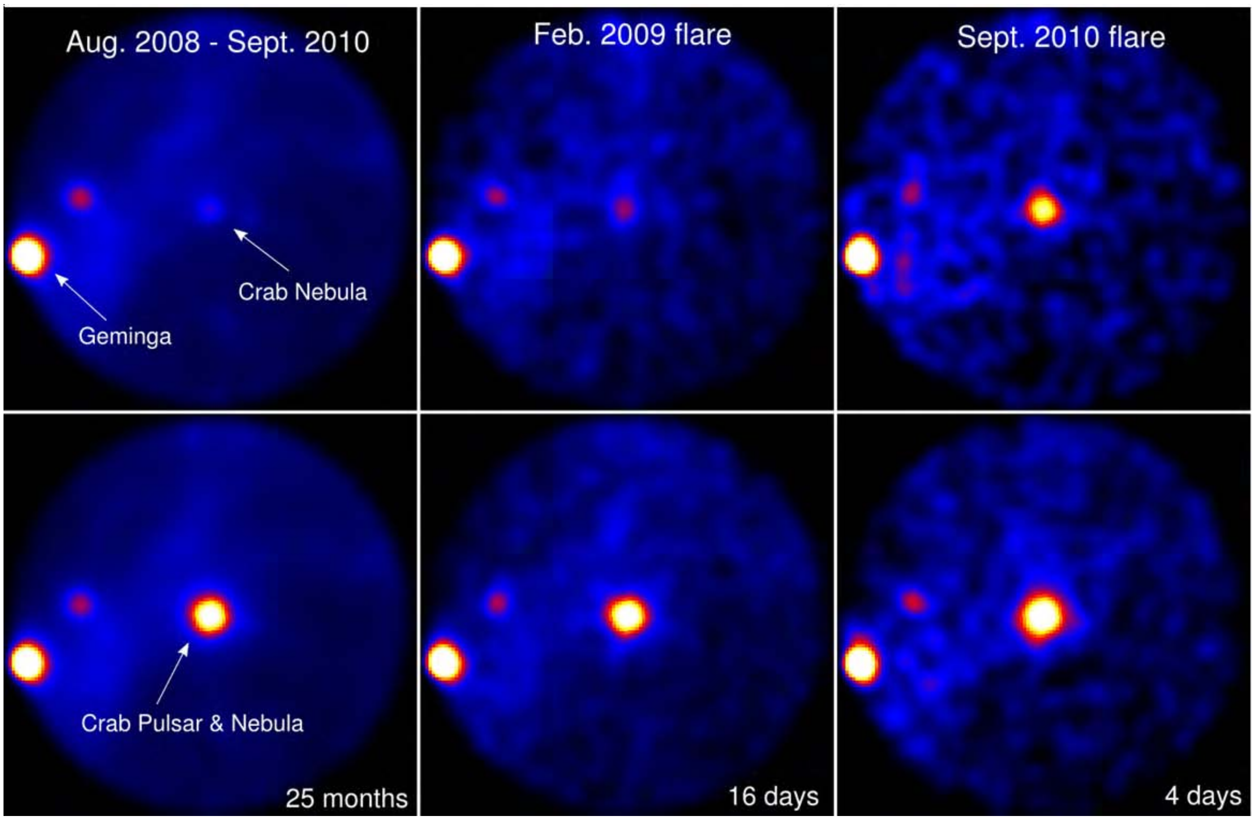
Fermi started the year with a splash! The first Fermi Large Area Telescope (LAT) source catalog was released in January 2010. Dave Thompson and Elizabeth Ferrara played significant roles in the development of the catalog and writing of the associated papers, including the first LAT pulsar catalog. The main catalog paper is the most cited Fermi paper of 2010 (with 130 citations) and the pulsar catalog paper is the third most cited. With 1,451 sources, the 1FGL catalog is by far the largest catalog of high-energy gamma-ray sources yet produced. About half the sources are associated with blazars (~600) or pulsars (~60). Many additional classes of high energy gamma-ray emitters are emerging—globular clusters, pulsar wind nebulae, supernova remnants, starburst galaxies, narrow line Seyferts, and X-ray binaries. Several of these source classes are new to high-energy gamma-ray astrophysics. Intriguingly, the second-largest source population consists of those having no obvious associations with members of known gamma-ray source classes, showing the potential for future discoveries. The Fermi Science Support Center (FSSC) team has made the catalog available in convenient electronic tables (Dave Davis, Don Horner, and John Vernaleo).

Megan DeCesar, Alice Harding, Tyrel Johnson and Christo Venter have focused their attention on various studies of the high energy gamma-ray emission from millisecond pulsars (MSPs) and implications on emission models. The discovery of so many MSPs in the Fermi data came as something of a surprise. PSR J0034–0534 was of particular interest, because the radio and gamma-ray emission sites appear to be co-located in this MSP, unlike the situation for most gamma-ray pulsars that also have radio emission.

Goddard scientists have also been heavily involved in studies of the more familiar young radio pulsars. Johnson, Harding, and Ozlem Celik published a paper describing detailed phase resolved spectra of the Vela pulsar—the brightest steady object in the gam-



With 1,451 sources, the Fermi 1FGL catalog is by far the largest catalog of high-energy gamma-ray sources yet produced.



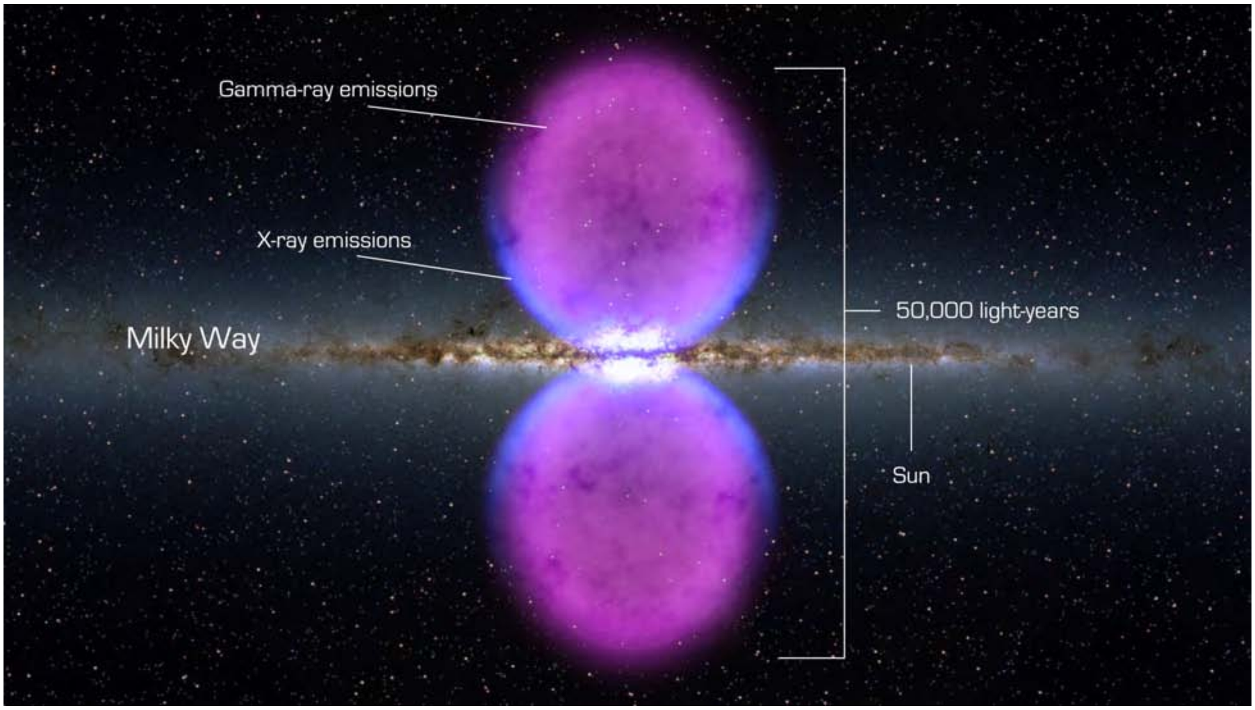
Top row: LAT maps of the Crab Nebula region, selecting the off-pulse nebular component, during normal (left) observations and during two flaring episodes (center and right). Bottom row: LAT maps of the region of the Crab Nebula plus the pulsar for the same time intervals.

ma-ray sky, while Celik and Thompson helped show that LAT observations of three pulsars previously seen by EGRET confirmed some, but not all, features seen with the earlier mission. Elizabeth Ferrara was the lynch pin behind the first Fermi pulsar catalog—an especially important paper given the large number and variety of pulsar detections with Fermi-LAT.

2010 brought several surprises from objects in our Galaxy. In March 2010, Davide Donato performed a Swift follow-up analysis on a new flaring object seen by the LAT in the Cygnus region of the sky. The gamma-ray transient turned out to be a nova, long thought to be improbably weak to produce high-energy gamma rays. The paper was coordinated by Teddy Cheung, with significant contributions from Elizabeth Hays, Robin Corbet, Koji Mukai, Tommy Nelson, Gerry Skinner, and Glen Wahlgren.

A much more familiar source, the Crab Nebula, provided a second gamma-ray surprise. Often considered so stable that it is referred to as a "standard candle" in high-energy astrophysics, the Crab Nebula has produced several flares in the Fermi LAT energy range, with the largest occurring in September. Elizabeth Hays and Jamie Cohen were active in studying this remarkable GeV flare, attributed to synchrotron emitting electrons in inner regions of the nebula. In response to a request from Liz Hays, Fermi executed only its second Target of Opportunity (TOO) in response to this flare. She announced these results in the second of two Astronomers telegrams on Fermi-LAT observations of gamma-ray emission from the Crab Nebula. This transient was of sufficient interest to provoke TOOs by Chandra and Hubble to examine the post-flare structure of the nebula.

Another Galactic surprise from Fermi involves a much larger scale. Harvard astrophysicist Doug Finkbeiner and his colleagues recognized huge "bubbles" of gamma radiation above and below the direction of the Galactic Center. Fermi Project Scientist Julie McEnery contributed to the press telecom about this discovery. The story was listed in the top 10 American Physical Society stories of the year, and the animation short about the bubbles is one of the year's most watched on NASA.gov.



Artist's rendition of the giant gamma-ray "bubbles" showing the scale relative to the Milky Way Galaxy.

Alex Moiseev continued his work on cosmic-ray electrons measured with the LAT, helping confirm in a paper in *Physical Review Letters* that the electron spectrum does not conform to expectations from traditional models of production and propagation. Vlasios Vasileiou is involved in a related study searching for anisotropy in the electron arrival directions that might be related to local cosmic-ray sources.

Looking outside our Galaxy, Donato, Thompson, McEnery, Jeremy Perkins, and Bill McConville and have been pursuing studies of Active Galactic Nuclei (AGN). LAT emission has been seen from both the core and lobes of the nearby radio galaxy Centaurus A (McConville, McEnery). Numerous Astronomer's Telegrams have resulted from AGN flares spotted by Donato while working as a LAT Flare Advocate, and he has also done a number of Swift follow-up observations of flaring AGN. McConville, Perkins, and Thompson have been involved in correlated multi-wavelength studies of individual flaring AGN.

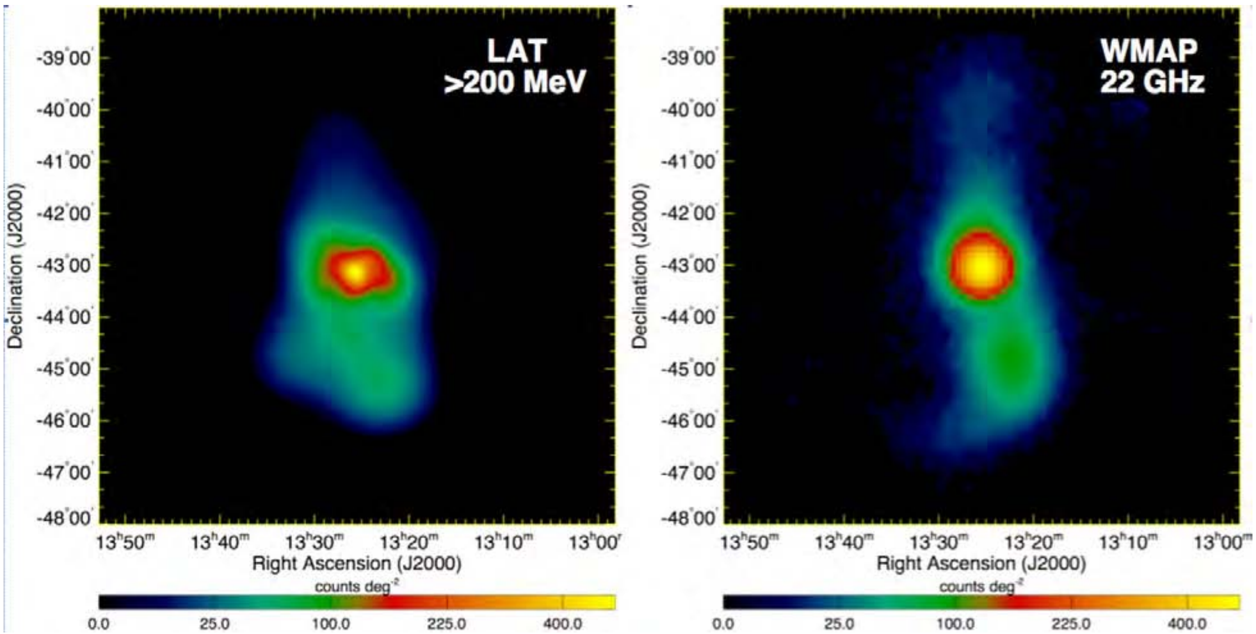
Gamma-ray burst studies continue (Vlasios, McEnery), with bursts seen by the LAT regularly (but not always) showing delayed onset compared to lower-energy gamma rays, GeV afterglows with a power-law decay, and an extra power-law spectral component that extends across the energy range of both Fermi instruments.

Outreach to the Scientific Community

Fermi data analysis workshops were organized by the FSSC and Fermi project in January 2010 at the AAS meeting in Washington, D.C., and at Boston University (Chris Shrader, Elizabeth Ferrara, Elizabeth Hays, Dave Davis, Julie McEnery, Robin Corbet, Dave Thompson, Neil Gehrels, and Alice Harding). These provided Fermi users with an opportunity to learn about high energy gamma-ray analysis and to get tips on how to apply to the Fermi Cycle 3 GI program. The FSSC arranged analysis and proposal workshops in support of GI cycle 4 at Goddard, NYU, U. Mich., and UC Santa Cruz, adding Jeremy Perkins to the group who had supported the Cycle 3 workshops.

Part of the Fermi team (Robin Corbet, Julie McEnery, Neil Gehrels, and Dave Thompson) skipped town during the large February snowstorms and headed to Bangalore, India, for a two-week COSPAR Capacity Building workshop on high-energy gamma-ray science and Fermi data analysis. One of the students from that workshop won a COSPAR fellowship to support a visit to Goddard in April 2011 to continue working with the Fermi team.

Jerry Bonnell, Robin Corbet, and Elizabeth Ferrara developed a list of Fermi-related papers sorted form journal and arXiv submissions that is made available from the FSSC.



Cen A lobes: Fermi LAT gamma-ray map (left) compared to WMAP (right).

Neil Gehrels, Judy Racusin, Nora Troja, Vlasios Vasileiou, Taka Sakamoto, and Julie McEnery were organizers for a Gamma-ray Burst scientific meeting in Annapolis, Maryland. After the Annapolis meeting, Judy, Vlasios, Nora, and Taka organized a joint Swift-Fermi GRB analysis workshop—taking advantage of the co-location of the Swift and Fermi science support center to guide people through the analysis of all 5 instruments across both missions

Instrument and Mission Operations and Analysis

Alex Moiseev, David Green, and Elizabeth Hays have continued studies of the performance of the Large Area Telescope Anticoincidence Detector, a subsystem built at Goddard.

Sylvia Zhu and Julie McEnery performed a study to optimize the configuration of the algorithms to search for gamma-ray bursts on board the Large Area Telescope. Th e new configuration was uploaded in May 2010 and announced via a GCN circular.

Fermi performed its fi rst Target of Opportunity observation to observe an extraordinary fl are from 3C454.3 in April 2010—little did we know that we would observe an even more intense flare in November 2010. At the end of 2010, the scanning mode was modified to add additional exposure to PSR B1259–63, a binary system that was producing high-energy gamma radiation as the neutron star passed through the disk of the Be star.

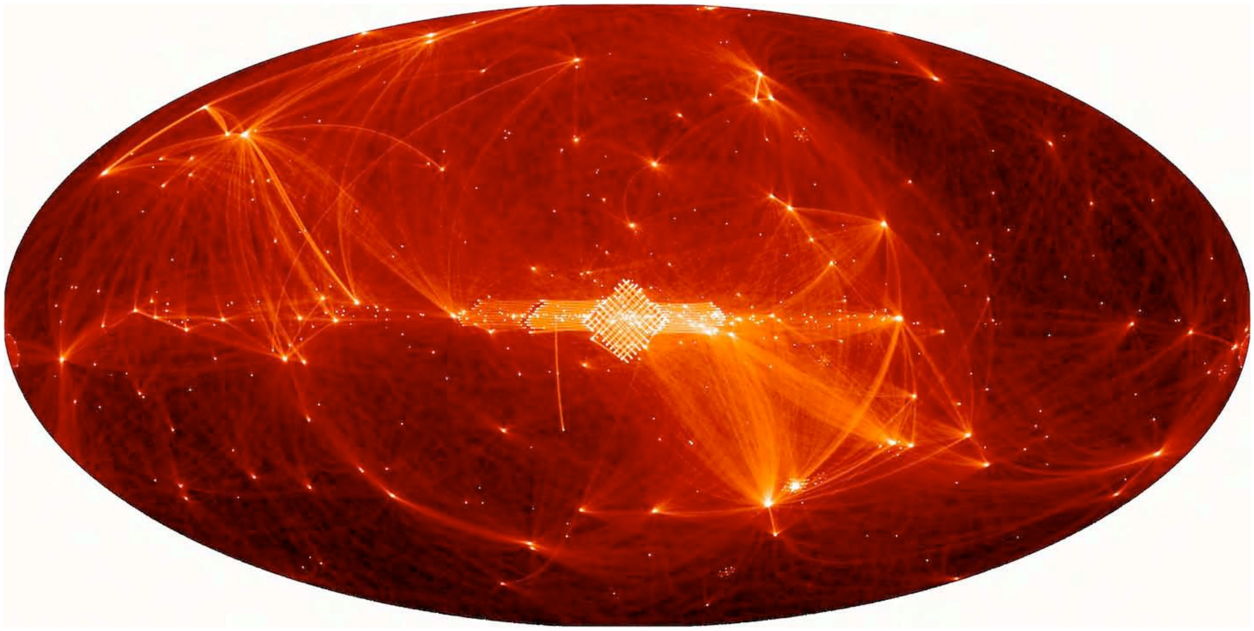
Julie McEnery and Elizabeth Hays continue to work closely with the spacecraft operations team and system experts at Goddard to guarantee that Fermi continues to achieve peak performance throughout the confirmed 10-year mission.

The FSSC released an updated science tools package expanding platform support and including new tools. An update to user-contributed tools includes a handy LAT plotting tool developed by Tyrel Johnson. The FSSC and the LAT team released a new reconstruction of the LAT data, which includes a new lower background sample of photons for studying large regions of sky.

The Rossi X-ray Timing Explorer (RXTE)

The Rossi X-ray Timing Explorer is designed to facilitate the study of time-variable emission of X-ray sources with moderate spectral resolution. RXTE covers time scales ranging from microseconds to months in a broad spectral range from 2 to 250 keV, boasts a large collecting area, and is able to monitor bright sources over the entire sky. RXTE was designed for a required lifetime of two years and a goal of five, but on December 30, 2010, the spacecraft celebrated 15 years in orbit and began its 15th cycle of observations. Of currently operating NASA missions, only Hubble has been in orbit longer.

Tod Strohmayer is the Project Scientist. In its long and productive history, RXTE is responsible for nu-



This image shows RXTE's observation history in galactic coordinates for one decade (Jan. 2001–Dec. 2010), including pointed observations, scanning observations, and maneuvers between pointings. Points are color coded between black (<100 sec per square degree) and white (>30,000 sec per square degree). The RXTE spacecraft bus and the primary scientific instrument, the Proportional Counter Array, were built at NASA Goddard Space Flight Center, and launched in December, 1995. Credit: NASA/RXTE/Craig Markwardt, Jean Swank, Tod Strohmayer, Evan Smith and Divya Pereira.

merous discoveries resulting in four Rossi Prizes—to Bailyn, McClintock, and Remillard (2009); Strohmayer and Chakrabarty (2006); Kouveliotou and Thompson (2003); and Bradt and Swank (1999)—as well as more than 90 doctoral theses and over 2,100 refereed publications.

The observation planning, instrument monitoring, and calibration updates are carried out with the part-time contributions of an experienced team that includes Keith Jahoda, Craig Markwardt, Nikolai Shaposhnikov, and Evan Smith at Goddard. Improvements in background determination and response matrices continue to be made. RXTE observations have been mining the X-ray sky for more than a decade.

The Science Operations Center (SOC), with Frank Marshall as director, assisted by Robin Corbet as Science Operations Facility manager, and the GSFC Mission Operations group have worked together to continue to automate operations and reduce manpower and expenditures, while preserving RXTE's ability to accommodate new information about targets of opportunity (TOOs, implemented by SOF scheduler Evan Smith). RXTE's most used follow-up capability is currently for timescales of 1–2 days. It is possible to have follow-up observations within hours for a select subset of requests, but transients that harbor millisecond pulsars, active periods of magnetars, the lifecycles of galactic black hole transients, and, of course, the active periods of blazars require a response on the order of days that can be sustained for days to weeks. RXTE remains the mission that is requested to carry out these observations.

The RXTE project has submitted proposals to each of NASA's Senior Reviews of the Astrophysics Operating Missions since 1994. The 2006 review confirmed RXTE's operations through the 2008 review, by which time the project had developed a program to extend operations through February 2009. The 2008 review concluded that funds were not available for further funding of the longest operating of the competed astrophysics missions. However, continued reductions in operating costs, combined with additional funds and guidance from NASA HQ enabled the mission to operate through September 2010. Operations beyond that were addressed by the 2010 Senior Review, to which RXTE was invited to submit a proposal. The panel did not recommend additional funding for RXTE operations but recognized the continued value and productivity of the mission to NASA and supported continuation if operating funds could be found. Some additional cost reductions were implemented, and funding to continue the mission in FY11 was approved by NASA, along with a Cycle 15 call for proposals. Indeed, the number of proposals received in Cycle 15 grew by ~18 percent, further confirming that researchers still highly value RXTE observations. At present, operation of RXTE beyond FY11 remains uncertain.

RXTE remains the only current X-ray observatory with the capability to routinely measure the millisecond spin periods of accreting neutron stars. Recent observations have led to the discovery of two more of these objects, IGR J17511–305 with a 245 Hz spin rate, and Swift J1749.4–2807 which rotates even faster at 518 Hz. Indeed, Swift J1749.4–2807 is the first accreting millisecond pulsar to show X-ray eclipses. The combination of millisecond pulse and eclipse timing holds great promise for precise measurement of the neutron star mass in this system. Multi-year RXTE measurements of the Crab Nebula and pulsar—long considered an X-ray standard candle—have recently been instrumental in decisively confirming that the Crab is not a constant X-ray source, but shows brightness variations of 5–7 percent. The RXTE data, which has the longest temporal baseline, confirms indications from other observatories, including Swift and Fermi, that the Crab Nebula can vary over months to year time-scales.

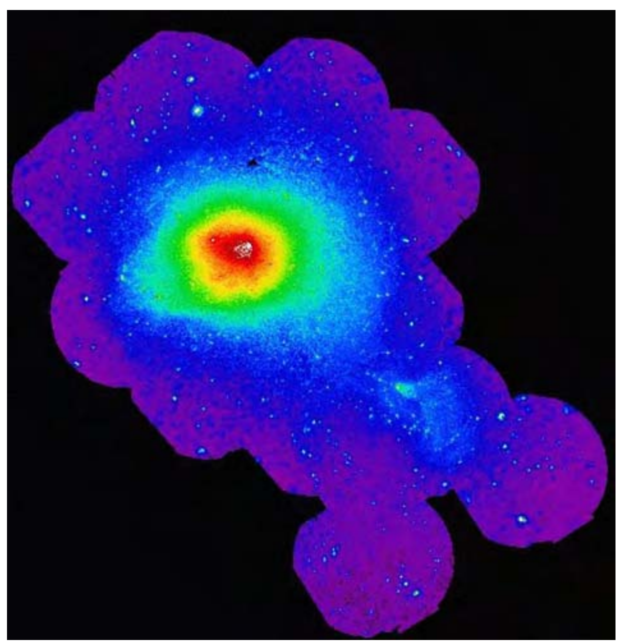
RXTE has found several examples of young, energetic pulsars associated with ultra-high energy TeV sources. These objects may be powered by the relativistic pulsar wind in these systems. Ground-based observatories such as HESS, MAGIC, and VERITAS can find the TeV emission, but RXTE is one of the few X-ray observatories with the sensitivity to detect the pulsar counterparts and measure their spin-down properties. The most recent example is RXTE's detection of a 38.5 millisecond pulsar associated with the TeV source HESS J1849-000.

XMM-Newton Guest Observer Facility

ASD operates the U.S. XMM-Newton Guest Observer Facility (XMM GOF). XMM is a European Space Agency (ESA) X-ray astrophysics mission, and ESA allocates resources to support European XMM users but looks to the GOF to provide support to the large U.S. astrophysics community. GOF activities include facilitating the submission of GO proposals to ESA, distributing proprietary data to U.S. PIs, maintaining the full public science archive, and supplying expertise, analysis software and documentation to U.S. scientists.

The GOF works in conjunction with the ASD GOFs of other high-energy astrophysics missions (e.g., RXTE, Integral, Fermi, Swift, and Suzaku) to lower costs and to ensure consistency in the areas of the budget proposal process, FITS tools, database structure, web pages and archival data access. Cost savings are leveraged by sharing resources, techniques, expertise and reusing software. GOF activities cover a very wide range of endeavors in support of XMM. A U.S. XMM-Newton Users Group under the chairmanship of Prof. Craig Sarazin (U. Virginia) provides community oversight of GOF activities. Dr. Steve Snowden is the NASA Project Scientist, and with Drs. Lynne Valencic and Kip Kuntz provides science support to the U.S. astrophysics community. Brendan Perry and James Peachy provide software support and Michael Arida maintains the U.S. XMM archive.

Kuntz and Snowden are involved in the particle background calibration of the XMM X-ray imagers and the cross-calibration between the XMM instruments and other X-ray observatories (e.g., Chandra, Suzaku, ASCA, and ROSAT), which enhances the utility of multi-observatory data analysis. This has been a major activity over the last several years with XMM GOF participation in the International Astronomical



XMM-Newton EPIC mosaic of the Coma Cluster of galaxies created using the XMM-ESAS software package developed by the XMM GOF.

Consortium for High Energy Calibration (IACHEC). Snowden and Kuntz have developed the XMM-Newton Extended Source Analysis Software (XMM-ESAS) package which is now fully implemented within the mission software suite. This package significantly simplifies and improves the accuracy of data reduction for extended objects and the diffuse X-ray background.

Kuntz produced and maintains (by periodic updates to include recent observations) the Optical Monitor (OM) source catalog (Kuntz et al. 2008, PASP, 120, 740) to compliment the X-ray source catalog produced by the XMM-Newton Survey Science Centre (SSC). The database contains entries for every source detected in OM observations. Kuntz and Arida work with STScI to make the OM catalog and data available through the Multimission Archive at Space Telescope (MAST), considerably increasing the data availability to optical astronomers.

Arida maintains the XMM-Newton archive at the GSFC GOF, which mirrors all public data in the ESA XMM-Newton Science Archive (XSA) at the SOC, as well as proprietary data for U.S. PIs. This mirroring of the data reduces the high data load at the European Space Operations Center site, and provides a much faster data-transfer rate within North America, as well as allowing use of the unique capabilities of the BROWSE database and providing a direct link for the use of XMM-Newton data within the HERA data analysis system.

Valencic maintains the ABC and D Guides which provide an introduction to the scientific analysis of XMM-Newton data, updates the XMM publication list on a quarterly basis—there are now ~1.3 refereed XMM publications per day—and supports the implementation of XMM-Newton analysis software within the HERA data analysis system. The latter includes developing extensive data analysis scripts for the user community.

Perry is an integral part of the ESA XMM mission software (Standard Analysis Software, SAS) development team and also contributes original software to SAS (e.g., XMM-ESAS). Peachy supports the image modeling software Sim-X (used for preparing science proposals), as well as the high-resolution spectral analysis tool Profit.

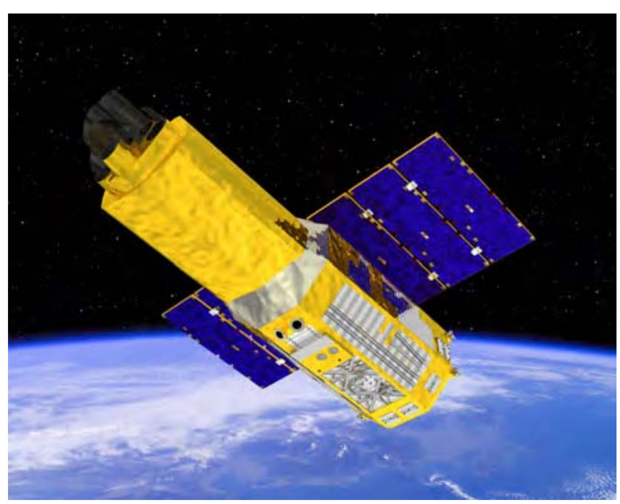
The XMM GOF was successful in the 2010 Senior Review process and will receive continued funding through FY12 for both GOF operations and GO support. Further funding through FY2014 was also recommended by the review.

Suzaku (Astro-E2)

Suzaku is the fifth in a series of Japanese X-ray astronomy satellites, launched by the Japan Aerospace Exploration Agency (JAXA) on July 10, 2005. Like ASCA before it, Suzaku is a joint Japanese-U.S. mission, developed by the Institute of Space and Astronautical Science of JAXA (ISAS/JAXA) in collaboration with GSFC and many other institutions.

Suzaku's scientific payload includes three co-aligned instruments, of which two are functional. The X-ray Imaging Spectrometer (XIS) consists of four imaging CCD cameras, three of which are front illuminated (FI: energy range 0.4–12 keV) and one back illuminated (BI: energy range 0.2–12 keV). Each XIS is located at the focal plane of a dedicated X-ray telescope (XRT). One of the three FI chips was rendered inoperable by a micrometeorite impact in December 2006; a micrometeorite impact in June 2009 made a small portion of a second FI detector unusable. The second functional instrument is a non-imaging, collimated Hard X-ray Detector (HXD) sensitive in the 10–600 keV band. The third instrument, the X-Ray Spectrometer (XRS), ceased operation shortly after launch due to a spacecraft design error.

GSFC's role includes supplying the XRTs and the XRS "insert" (detector, blocking filters, adiabatic demagnetization refrigerator, and LHe cooler), development of data-processing software, operation of the U.S. Guest Observer Facility (GOF), and administration of the U.S. Guest Observer (GO) Program.



Rob Petre is the NASA Project Scientist, and Lorella Angelini is the Deputy Project Scientist. Suzaku has produced an abundance of data from a wide variety of cosmic X-ray sources. Key unique Suzaku observations include: measurement of cluster properties beyond their virial radius; broadband measurements of AGN revealing simultaneously complex absorption, a relativistically broadened Fe K line, and a reflection continuum to 20–40 keV; determination of the spin of Galactic black holes and the radius of accreting neutron stars using their relativistically broadened Fe line; and measurement of the spectrum of a substantial fraction of the AGN detected by Swift.

U.S. observers have access to 50 percent of the observing time (including 12 percent through joint Japan/U.S. observations), as well as access to all archival data. The due date for proposals for the sixth observing cycle (April 2010–March 2011) was late November 2010. Over the most recent three cycles an average of 90 proposals have been submitted, with a time oversubscription of 3.5–4. Included in the submissions are proposals for long programs (observing time > 300 ks) and key projects (observing time > 1Ms). The goal of the key projects is to carry out major, multiyear observing programs that utilize Suzaku's unique capabilities. To date, five key projects have been initiated, three of which have been completed. The completed ones are an extensive mapping of the Galactic center region; a comprehensive study of anomalous X-ray pulsars; and a deep observation of Kepler's SNR to characterize the explosion mechanism through measurements of modest-abundance metals. The two key projects still underway are a census of broad Fe lines in AGN and an extensive mapping of the Perseus cluster of galaxies (the brightest cluster in X-rays) to beyond its virial radius. It is anticipated that additional key projects will be started during the sixth observing cycle.

Suzaku has also developed relationships with other missions. Joint Suzaku-Chandra observations are now available through the Chandra GO program. It is possible through the Fermi GO program to obtain Suzaku observing time to support coordinated observations. The Suzaku team is also collaborating with the MAXI team, following up flaring sources identified by MAXI.

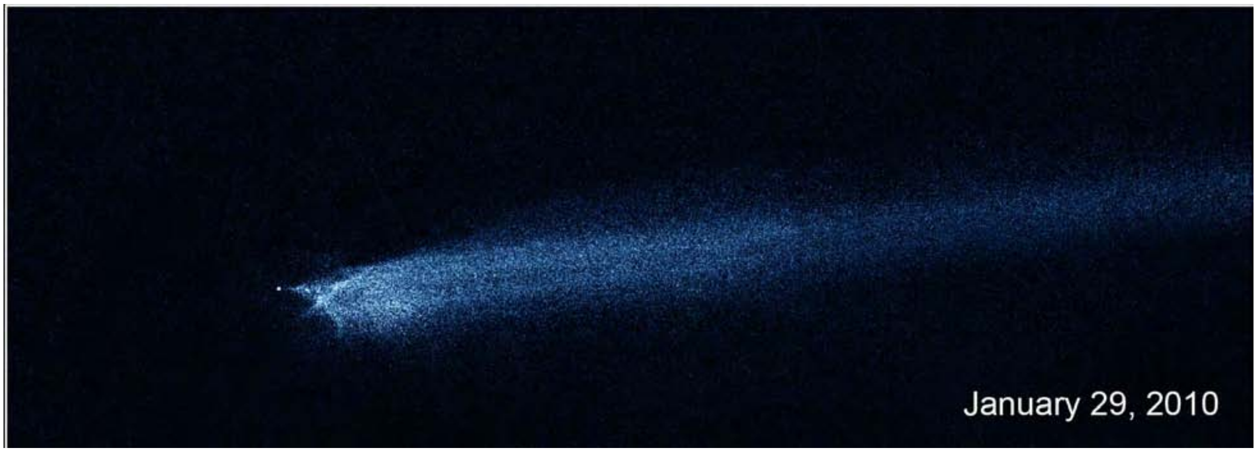
In the 2010 NASA Senior Review of operating missions, Suzaku was ranked seventh out of the nine missions considered. Nevertheless, the review panel recommended continued funding of both the U.S. data center and the GO program through 2014. The Suzaku data center is responsible for processing and archiving the full mission data set and distribution of data to U.S. GOs; development and maintenance of proposal and observation planning tools and documentation; maintaining the calibration database; supporting proposal reviews; assisting GOs in analyzing data; and ensuring grant funds are distributed in a timely way. The data center staff consists of three full-time scientists (Koji Mukai, Kenji Hamaguchi, Katja Pottschmidt) and one programmer, plus part-time support from HEASARC staff.

Hubble Space Telescope

This was the first full year of Hubble science following the amazing success of Servicing Mission 4 (SM4) in May 2009. With a working complement of two spectrographs—the Cosmic Origins Spectrograph (COS) and Space Telescope Imaging Spectrograph (STIS), and two imaging cameras—the Wide Field Camera 3 (WFC3) and Advanced Camera for Surveys (ACS), HST is now more powerful and scientifically well-balanced than at any previous time in its 21 years in orbit. COS and WFC3 are new instruments—installed during SM4—whereas STIS and ACS were both repaired during that mission and returned to service. With science operations anticipated to run at least through the end of calendar 2014, it is difficult indeed to overstate HST's future promise.

The HST Project Science Office is staffed by ASD personnel. In early 2010, Jennifer Wiseman was named to succeed Dave Leckrone in the position of HST Senior Project Scientist. George Sonneborn ably served as acting Senior Project Scientist for nearly ten months between Leckrone's retirement and Wiseman's start date, Ken Carpenter is HST's Project Scientist for Operations, and Mal Niedner served throughout 2010 as the HST Observatory Project Scientist. As the year ended, Niedner was beginning a transition over to the James Webb Space Telescope, to serve as Deputy Senior Project Scientist - Technical. Niedner's long-time outstanding service to the Hubble Program, through multiple servicing missions, the development of new instruments, and the promotion of its countless outstanding scientific achievements, is a major force behind the success of this great observatory.

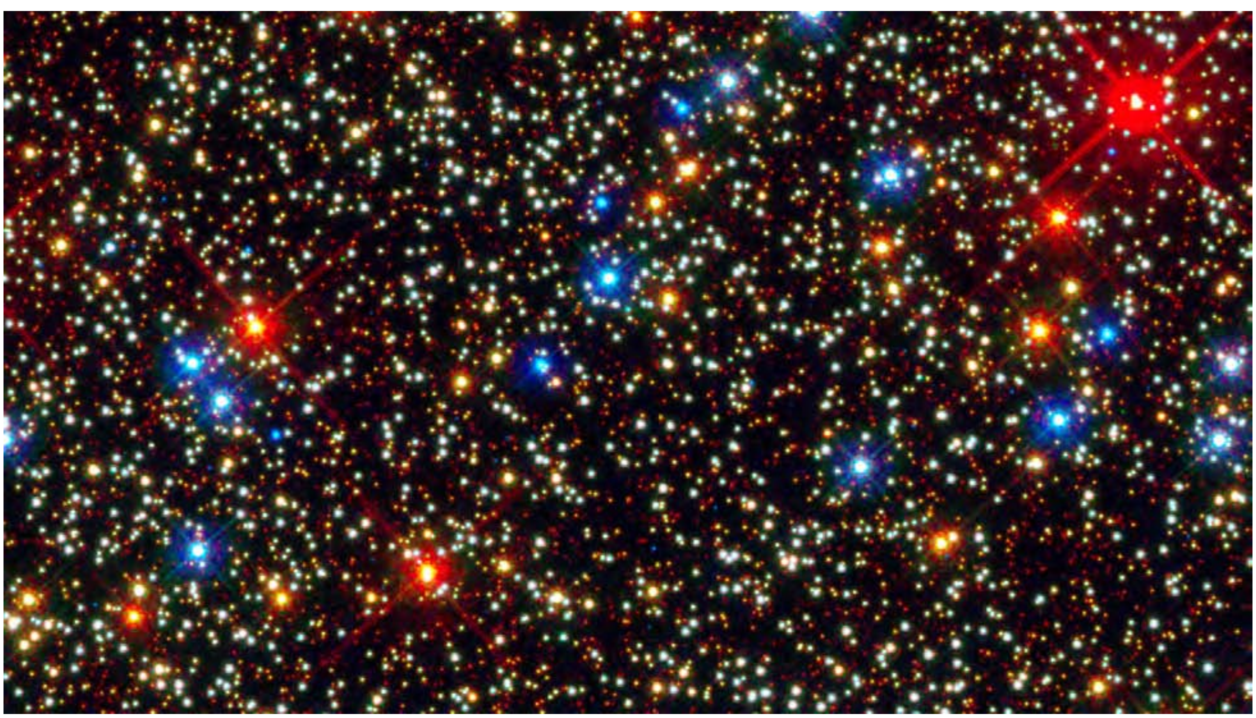
ASD's connections to HST are strong and extend beyond its Project Scientists and the scientists who



WFC3 image of the famous "comet-like asteroid" of 2010. The combination of a point object, an X-shaped pattern, and a long, cometary-like dust tail has never been seen before. Astronomers think this slowly evolving ensemble of structures represents the collision—in February or March of 2009—of a 400–500-foot-diameter asteroid with a much smaller one (~ 10–15 feet wide).

use Hubble (mentioned elsewhere in this 2010 ASD Report). STIS was proposed, developed, and flown in 1997 (SM2) by PI Bruce Woodgate, whereas WFC3 is an SM4-installed, non-PI instrument built under GSFC/ASD's leadership (Randy Kimble, Instrument Scientist). WFC3 is the bedrock of HST's scientific arsenal, and STIS continues—despite its age—to possess unique capabilities that astronomers are delighted to have access to once more.

No orbiting telescope is free of issues, and throughout 2010 the HST Project Scientists worked with the HST Project, the Space Telescope Science Institute, and industry/academia colleagues on several: Neon purge/refill techniques to potentially restart the Near Infrared Camera and Multiobject Spectrometer (NICMOS) cryocooler and restore NICMOS to operational status if scientifically compelling (NICMOS accounted for 1.4 percent of the total HST observ-



WFC3 view of the core of globular cluster Omega Centauri. Comparison of ACS imagery of the same cluster taken in 2002 and 2006 resulted in the secure detection and measurement of proper motions of more than 100,000 cluster stars.

A portion of the well-known Carina Nebula is well captured in this HST 20th- anniversary image, taken by WFC3. Pillars of gas and dust, newly born stars emerging from dusty cocoons, stellar jets, bowshocks and numerous other features, are shown in this extremely dynamic region of space.

ing time when it last did operate, and it retains some unique capabilities, though its IR imaging/grism capabilities have been almost completely subsumed by WFC3); the slowly degrading (but still faster than expected, pre-launch) quantum efficiency in COS's FUV detector; mitigation techniques for ACS's increasing CCD charge transfer inefficiency; and various instrument protection issues stemming from the Science Instrument Command and Data Handling (SI C&DH) Unit lock-ups that occur occasionally and briefly interrupt observations with the telescope. All the above issues are either solved or are minor and manageable, and it is no overstatement to say that HST is functioning superbly. In addition, the staged implementation of Automated HST Operations is going extremely well.

HST addresses, as always, the wide range of astrophysical disciplines expected of an orbiting Great Observatory, and it continues to serve a substantial fraction of the astronomical research community. The response to the Cycle 18 Call for Proposals was extremely gratifying: a near-record 1,049 proposals were received, resulting in the highest-ever oversubscription factor in terms of awarded observing time (9:1). Year

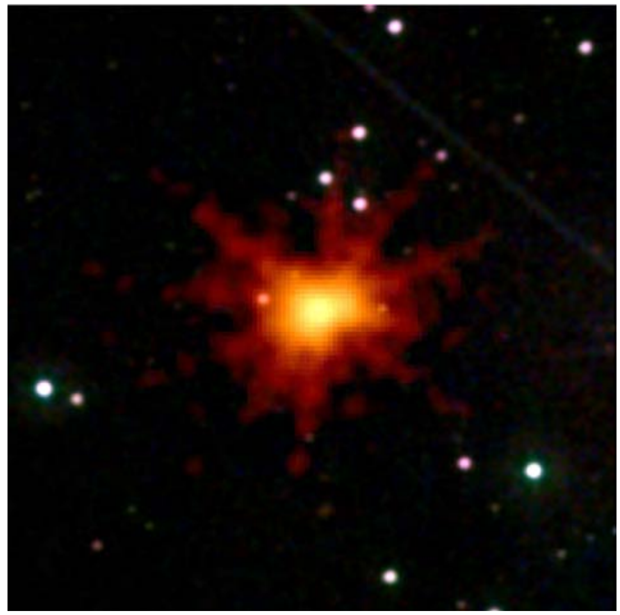
2010 also saw the inception of Multi-Cycle Treasury (MCT) science, comprised—in this first round—of three programs, each extending across three annual observing cycles and utilizing many hundreds of orbits (the range is 525–828 orbits per program). The three selected MCT programs target a range of interesting sources: 25 gravitationally relaxed galaxy clusters, addressing a wide variety of astrophysical questions; the Andromeda Galaxy, featuring a detailed survey of stellar populations over a wide area; and a deep, multi-tiered IR survey to probe galaxy assembly and detect distant supernovae. The purpose of the MCT programs are to push HST science well beyond what was possible with the limited orbit allocations of the past, and to render unnecessary future statements of lament such as: "We wish we had tried some truly Big Science Programs when HST was still operating." The inaugural MCT competition was extraordinarily intense, with an oversubscription ratio of 17:1.

Hubble science was frequently in the news in 2010 with many press releases that covered the gamut of astrophysics. A very partial list includes the bizarre "comet-like" object that resulted from an asteroid collision in our solar system; simultaneous coverage of Saturn's northern and southern aurorae; several high velocity, "runaway stars" in our galaxy; modeling of position-dependent stellar formation histories in a nearby dwarf galaxy; a determination of individual stellar proper motions and projected velocities in the globular cluster Omega Centauri using HST imaging data spanning only a four-year (!) baseline; galaxy cluster studies that probed the growth of clusters and the influence of Dark Energy; the importance of the hard-UV radiation field produced by early quasars in completing cosmic reionization (i.e., of Helium) 11 billion years ago; the comet-like gas tail of an evaporating exoplanetary atmosphere; and the discovery of young blue stars in elliptical galaxies once thought "red and dead." A photo release many will long remember was the HST 20th-anniversary image of the Carina Nebula, taken by WFC3.

Without a doubt, the year 2010 was an extremely rewarding and productive one for HST. The dream of SM4 continues to be realized.

Swift

Swift is a NASA Explorer mission, with international participation, that is designed to find gamma-ray bursts and study them over a wide range of wavelengths, from gamma-rays to optical light. It was launched in 2004 and is in its extended mission phase with re-entry no earlier than 2020.



The brightest gamma-ray burst ever seen in X-rays temporarily blinded Swift's X-ray Telescope on 21 June 2010. The image merges the X-rays (red to yellow) with the same view from Swift's Ultraviolet/Optical Telescope and shows a field of 5 arcmin × 5 arcmin.

Gamma-ray bursts (GRBs) are the most luminous explosions in the universe since the Big Bang. They come randomly from all directions in the sky and last from a few milliseconds to a few hundred seconds. GRBs are believed to occur in the collapse of some massive stars into supernovae or when two neutron stars merge. The details of how such intense bursts of radiation are produced are still not well understood.

There are three telescopes onboard Swift: the Burst Alert Telescope is a coded-aperture gamma-ray detector that operates between 15 and 150 keV. It detects GRBs and rapidly localizes them to approximately two arcminutes. Immediately afterwards (usually within one minute), the spacecraft slews to point its two narrow-field instruments at the burst. The X-Ray Telescope measures the 0.2–10 keV X-ray flux from the GRB's afterglow and localizes the source to within two arcseconds. The Ultraviolet/Optical telescope collects data between 1,600 and 6,000 Angstroms and provides a sub-arcsecond position for the burst. Swift distributes these positions for each GRB to other observatories within seconds of obtaining them.

This view of Comet Lulin (C/2007 N3) merges data from Swift's Ultraviolet/Optical Telescope (blue and green), the X-Ray Telescope (red) and a Digital Sky Survey image of the star field.

In the six years since launch, Swift has detected and localized approximately 600 GRBs. Some of the mission's key scientific accomplishments have been:

• Detecting the most distant known object in the universe, GRB 090423, with a redshift of 8.2. This burst occurred more than 13 billion years ago when the universe was only about 630 million years old.

• Observing GRB 080319B, a GRB with an afterglow that was bright enough to see with the naked eye from a dark site.

• Discovering more than 55 short and hard GRBs, about half with likely host identifications and/or redshift estimates. These observations provided support for the theory that these bursts are due to the merging of binary neutron stars.

• Making metallicity measurements of star-forming regions at high redshift (z > 5) using GRBs.

• Discovering the X-ray flash of the shock breakout from a star's surface during a supernova.

Swift is a powerful and versatile observatory to study transient sources and is increasingly being used for non-GRB science. To date, more than 2,200 targets-of opportunity (TOOs) were performed as a result of requests from the community. Many of the TOOs are often made within a few hours of being requested.

By the end of 2010, more than 1,000 refereed papers have been published that are based on Swift results. These Swift papers have a very high citation rate of around 20 per paper on average (> 20,000 total). About half of all Swift papers are from non-GRB fields with an increasing fraction. A few examples include: performing multiwavelength observations of comets; stellar flares, CVs, and novae; obtaining ultraviolet light curves for more than 130 supernovae of all types; observing galactic transients and AGNs; performing a survey of nearby galaxies in the optical, UV, and X-rays; and undertaking the most sensitive all-sky hard X-ray survey yet performed.

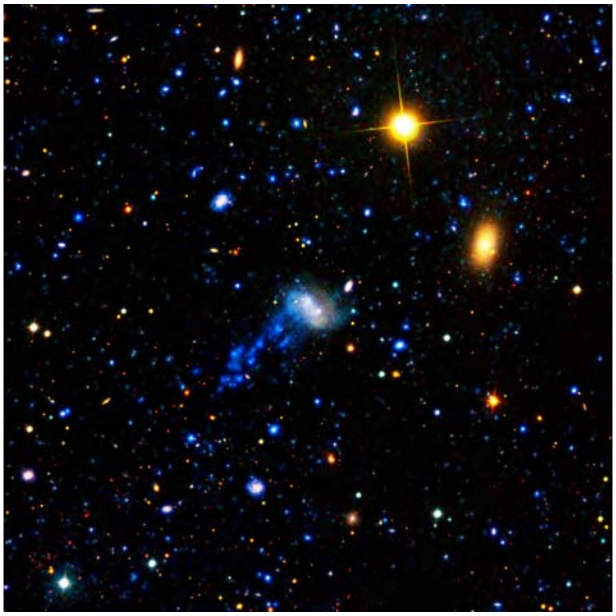
Swift has been widely recognized as a groundbreaking mission. It was ranked four in the 2010 Senior Review. The PI Neil Gehrels and the Swift Team won the 2007 Rossi Prize, the 2009 Muhlmann award of the Astronomical Society of the Pacific, and GRB 080319B (the naked-eye gamma-ray burst) was named one of the top ten science news stories of 2008 by the American Institute of Physics.

The Swift Guest Investigator Program adds an important component to the Swift research and includes both GRBs and non-GRBs science. During the 2010 Cycle 7, 182 proposals were received, requesting $4.9M in funds and 17.3 Ms total exposure time for 1,111 targets. The oversubscription rate has grown to a factor of 4.1 for non-TOO proposals and the TOO category had an oversubscription factor of 5.0.

Galaxy Evolution Explorer (GALEX)

The GALEX observatory is a Small Explorer (SMEX) that consists of a telescope, two detectors, and a spacecraft. It collects wide-field (1.2 degree) images of the night sky in two ultraviolet broad bands and is now in its eighth year of science operations. All flight and ground systems are currently healthy with the exception of the Far-UV detector.

GALEX is primarily a survey instrument, designed to obtain large, homogeneous imaging samples in two bandpasses (Far-UV, 1350–1800Å, and Near-UV, 1800–2800Å) that are sensitive tracers of recent star formation. The resulting samples are cross-matched with wide and deep surveys at other wavelengths, with the Sloan Digital Sky Survey providing a particularly rich match. GALEX also can provide wide-field low-resolution spectroscopy that is useful, for example, in identifying HST/COS targets or for variable objects in the Kepler field. Time-tag capabilities allow observers to determine a sampling time after the fact, which is



A GALEX image of IC 3418, a galaxy falling into the Virgo cluster. Active star formation is occurring in a 17-kpc turbulent wake of gas that has been stripped from it the galaxy by ram pressure. The center of the cluster is toward the upper right. Blue indicated Far-UV emission (135–175 nm) and yellow indicates Near-UV emission (175–275 nm).

True-color SDSS image from Hester et al. 2010. GALEX is extremely effective at identifying recent star formation in the low-surface-brightness regime.

useful for identifying flare timing or stellar pulsation modes.

Most of the GALEX science operations are at Caltech, and the core of the science team is also there, with smaller groups at Columbia, JHU, UCLA, Carnegie, and Goddard. Before 2011, approximately one-third of GALEX observing time was dedicated to a robust Guest Investigator program, operated by Goddard (30 to 35 GI programs annually). The GI program was discontinued at the end of 2010; researchers may now request funding for GALEX-based research through the ADP. Susan Neff (ASD) is the GALEX Mission Scientist.

In 2010, GALEX delivered its sixth (annual) GALEX Data Release (GR6) to MAST (Multi-Mission Archive at Space Telescope), which serves all GALEX data to the scientific community. The first release of two definitive catalogs of GALEX-detected point and extended sources (up to 1 arcmin) will be delivered to MAST in spring 2011. These catalogs are expected to become the go-to reference for UV detections, similar to the SDSS and 2MASS catalogs: They will contain 10 million sources with exposure time greater than 800 sec and more than 100 million sources with exposure time less than 800 sec. The catalogs will be updated with each future major GALEX data release.

The primary GALEX mission, which was completed in late 2007, had the goals of calibrating UV observables to the star-formation rate (SFR), measuring star-formation history ($0 < z < 1.5$), and exploring the ultraviolet universe. The GALEX Extended Mission (EM), endorsed by the 2006, 2008 and 2010 Senior Reviews, is carrying out two Legacy Surveys designed to:

- Extend the UV/SFR calibration to low-mass, low-metallicity, transitional, or rare galaxies
- Relate star-formation history to other variables, such as environment, mass, halo mass, assembly history and star-formation regime
- Determine the relative importance of the primary drivers of star formation, such as galaxy assembly history, feedback from AGN, contributions from dust, or fractions of different gas phases.

In the 2010 Astrophysics Senior Review, the GALEX project was directed to discontinue the GI program and to focus on extending the GALEX Legacy Survey (GLS) to cover as much sky area as possible. About 5,000 deg^2 had been imaged to GLS depth by the end of 2010; another 16,000 deg^2 could be safely observed by GALEX. The community is providing recommendations on survey prioritization, with a focus on optimizing the long-term value of the GALEX archive.

GALEX observations have been used to determine the star-formation (SF) history in the nearby universe, and to show that while SF occurred mostly in massive galaxies over the period $1 < z < 4$, after that it moved to less and less massive hosts (Martin et al. 2007; Schiminovich et al. 2005; Arnouts et al. 2010, in prep).

The UV-optical color-magnitude diagram (UVOCMD) is a powerful tool for separating and relating galaxy types, properties, and evolutionary histories, largely because of the great leverage obtained with the UV (SFR)—optical/NIR (stellar mass) color. The UVOCMD can be measured accurately in very distant samples, and may be considered an Hertzsprung-Russell diagram for galaxies in which stellar mass is the major predictor of galaxy properties. GALEX UVOCMDs first identified the tendency of AGN to occur preferentially in the "green valley" and demonstrated that galaxies migrate both directions across the valley (Wyder et al., 2007; Schiminovich et al., 2007; Martin et al., 2007). More recent GALEX work has shown that low-mass galaxies in the green valley are mostly moving from blue to red ("quenching"), while higher-mass galaxies are more evenly split between "quenching" and "bursting." This is consistent with small galaxies losing their gas and massive galaxies undergoing microbursts of star formation as they accrete new material (Martin et al. 2010).

Using GALEX data, Heckman et al. (2005) discovered a rare population UV-luminous Lyman-Break Analogs (LBAs), which are the fastest-evolving component of the UV galaxy population (Schiminovich et al., 2005). Their lack of dust (relative to other local starbursts, such as ULIRGs) suggests an early stage of chemical evolution (Basu-Zych et al. 2007; Hoopes et al. 2007). HST images show that they represent a complex merger of multiple, lower-mass, gas-rich subunits that echo the morphology and physical properties of high-z LBGs, but seen in much more detail (Overzier et al. 2008; Basu-Zych et al. 2009). Recently, a new color-selected approach has identified a few hundred more UV-luminous galaxies that may be LBAs or may be a new type of object (Hutchings and Bianchi 2010); follow-up observations are in progress to determine the nature of these new objects (Basu-Zych, Neff, Hutchings).

GALEX has opened several new lines of investigation in the low-density regime. GALEX observations of Extended UV (XUV) disks have shown that these are frequent, occurring in ~30 percent of late-type galaxies (Gil de Paz et al. 2007, Thilker et al., 2007, Zaritsky and Christlein, 2008). In these XUV disks, GALEX detects star formation occurring at gas densities lower than those previously suggested as a "threshold" level. Thilker et al. (2010) have found a new type of dwarf galaxy forming out of a possibly primordial cloud of HI. Recent work by Madore et al (2010) has found that XUV disks also occur in early-type galaxies. Bigiel et al. (2010, in prep) and Wyder et al. (2009) have found that the outer low-density regions of spirals and low-surface brightness galaxies as a group fall below the extrapolation of the "standard" star-formation relationship to gas density. Meurer et al. (2009) and Lee et al. (2009) have used GALEX data to show that, in low-surface-brightness regions/low-mass galaxies, the IMF may be top-light relative to assumptions about a universal mass function. The GALEX project sponsored a conference on variable IMF's in June 2010 which was well attended.

GALEX is currently planning for closeout in 2013. However, if all systems remain healthy, the project will return to the 2012 Astrophysics Senior Review to request continuing operations until the GLS has been completed (~2014).

High Energy Astrophysics Science Archive Research Center (HEASARC)

The HEASARC is the primary archive for NASA missions dealing with extremely energetic phenomena, from black holes to the Big Bang. Having recently merged with the Legacy Archive for Microwave Background Data Analysis (LAMBDA), HEASARC includes data obtained by NASA's high-energy astronomy missions from the extreme ultraviolet through gamma-ray bands, along with missions that study the relic cosmic microwave background.

Since 1990, the HEASARC has been an essential element of NASA's astrophysics missions. The archive services allow scientists to identify, display, cross-correlate, download and analyze data from a variety of past and current missions—including ASCA, BeppoSAX, Chandra, CGRO, Einstein, Fermi, INTEGRAL, ROSAT, RXTE, Suzaku, Swift, WMAP, and XMM-Newton—and provide access to a wide range of multiwavelength sky surveys, astronomical catalogs, and other resources. The HEASARC's scientific and technical staff produces a variety of widely used software packages, provides expertise in the analysis of archived data, and helps to evolve archive interfaces to better serve the science community. The data and software standards developed by the HEASARC provide the underlying infrastructure for the interpretation of data from a wide variety of missions, substantially reducing mission costs while increasing science return.

The HEASARC archive is now in excess of 30 Terabytes (TB), having grown by 5 TB in 2010, and contains data from eight active missions as well as about 30 space-based missions and sub-orbital experiments that are no longer operational. Papers using HEASARC data comprise around 10 percent of the total astronomical literature and include some of the most highly cited papers in the field. The HEASARC Office is led by Dr. Alan Smale, with Project Scientists Dr. Lorella Angelini (HEASARC) and Dr. Gary Hinshaw (LAMBDA). Dr. David Chuss takes over as LAMBDA Project Scientist, effective January 2011.

In 2010 the HEASARC was in the vanguard of the ASD transition to a virtualized computing system. All HEASARC web and database servers were transitioned to a virtualized environment significantly reducing the physical and environmental footprint for the HEASARC. At the same time the HEASARC servers were transitioned into a new security configuration. Dr. Thomas McGlynn led the effort to validate HEASARC services in the new environment, ensuring minimal impact on HEASARC users.

McGlynn is also leading the effort to update the HEASARC's central data archive access services. The new Xamin tool is now available to the community in a limited release. From the HEASARC's perspective, the Xamin interface allows for the development of thematic interfaces to data, integrates access that had previously been spread in nearly a dozen distinct interfaces into a single system, and is engineered to much higher standards. For users, Xamin allows uploads of persistent user tables, integrated access to both HEASARC and Virtual Observatory data sets, easy correlations of two or more tables, clean integration of plotting, user-defined columns, the ability to save and return to queries, and a host of other capabilities. The primary user interface is a Rich Internet Application, emulating a desktop application through the Web. A keyword oriented interface is also available and other interfaces may be developed.

The HEASARC is a core partner in a joint NSF/NASA program to manage and operate the U.S. Virtual Astronomical Observatory. McGlynn leads the HEASARC's involvement in the VAO, and serves as the VAO Lead for Operations. He and his staff have developed applications which monitor the health of VAO and other VO services and inform responsible parties of issues as they arise. The HEASARC is also responsible for a number of tools for browsing and displaying data from the virtual observatory, notably DataScope and SimpleQuery. In addition to supporting access by local users, the Xamin system also supports access to HEASARC catalogs and data through Virtual Observatory protocols including Cone Search, the generic Table Access Protocol (TAP) and a test implementation of the Observatory Core data model under development within the VO. This ObsCore model should eventually allow users to query for data from the HEASARC according to instrumental characteristics like resolution and sensitivity over all missions (and using VO protocols for non-HEASARC data as well).

In addition, McGlynn continues to manage the SkyView virtual observatory. SkyView servers followed the HEASARC's into the ASD's virtual environment. The number of images generated by SkyView in 2010 more than doubled over the previous year to over 5 million dynamically generated images. In addition to surveys hosted locally, SkyView provides access to SDSS, FIRST, and 2MASS data hosted at other NASA archives.

During 2010, HEASARC programmers under the direction of Dr. William Pence coordinated three online public releases of the HEASOFT data analysis software package, which is essential for deriving new scientific results from the HEASARC's large data archive. The HEASOFT package contains about 2.5 million lines of code contained in 550 individual analysis tasks for data from 11 high-energy missions supported by the HEASARC as well as general analysis of astronomical data from other missions. More than 2,000 registered individual or institutional users downloaded the HEASOFT package in 2010 for installation on their local computers. The HEASARC also introduced a new web-based analysis service in 2010 which enables users to run most of the HEASOFT tasks using only a Web browser. This service utilizes the compute servers in the Hera computer system at the HEASARC to provide the disk space and CPU resources needed to analyze the data.

Dr. Steve Drake worked on the creation and/or updating of 70 Browse tables in 2010, of which about two thirds were brand new, bringing the total number of tables in Browse to just under 600 unique tables by the end of 2010. Among the newly created tables, 10 were Chandra source lists and the others included a broad range of missions including XMM-Newton, ROSAT, WMAP, AKARI, and INTEGRAL, as well as tables of stars, galaxies and quasars, and radio sources. Drake has also continued to support a variety of the HEASARC's web pages, perhaps most importantly the HEASARC's RSS feed, which also populates the HEASARC's Latest News page. This RSS feed combines feeds from a number of our projects ranging from XMM-Newton through WMAP, and also contains a number of wider interest items such as upcoming proposal and meeting deadlines. A new feature in 2010 was the addition into the RSS feed of links to selected press releases on topics of interest to the HEASARC community, coordinating with the ASD Senior Science Writer, Francis Reddy. In 2010, about four new items per week appeared in the HEASARC RSS/Latest News, providing an important and timely resource to the astronomical community.

Dr. Mike Corcoran continued to serve as Fermi Archive Scientist for the HEASARC. There are currently 10 Fermi tables incorporated into the HEASARC Browse tables, and the HEASARC FTP archive contains all Fermi GBM data, along with LAT weekly data files (which can now be searched and downloaded via Browse). An update to the Fermi calibration data for the GBM and LAT instruments was released by the Fermi project and included in the HEASARC calibration database (CalDB) by Corcoran. In 2010, there were a total of 35 updates of the Swift, Suzaku, Chandra, RXTE, and Fermi CalDB areas. As CalDB manager, Corcoran implements these updates and maintains the HEASARC CalDB website. Corcoran also writes the HEASARC Picture of the Week website, and administers a HEAPOW Facebook group which currently has over 100 members from around the world. Corcoran also maintains the Astro-Update website, used by scientists to keep track of updates to important high-energy astrophysics software packages. In 2010, Corcoran was PI of a successful Chandra and RXTE proposal, and gave two invited talks, one at the 39th Liege Astrophysics Colloquium, and one at George Washington University in D.C., and was first author on a published ApJ. paper.

In 2010, Dr. Keith Arnaud participated in the releases of versions 6.8, 6.9, and 6.10 of HEASOFT. This included a new release of XSPEC (v12.6) that featured a substantial improvement in plotting capabilities, particularly for data outside the traditional X-ray energy ranges. New models were added and the Compton reflection code overhauled to improve control over numerical accuracy. Working with programmer Craig Gordon, Arnaud is building a Python interface for XSPEC. When finished, this will allow XSPEC to be loaded into Python as an external package. Working with colleagues at CfA, MIT, and JHU, Arnaud has led the creation of a new handbook for X-ray astronomy, to be published by Cambridge University Press in 2011. This book is intended to provide a basic background to X-ray data analysis for young researchers as well as providing a reference for the more experienced.

Throughout 2010, Dr. Steve Sturner maintained the INTEGRAL public data archive at the HEASARC. This archive is a mirror to the public data archive maintained at the ISDC. He performed this task first as the lead of the INTEGRAL Guest Observer Facility and subsequently as a member of the HEASARC. The ISDC has public data releases approximately once per month which are downloaded and installed in the HEASARC archive. Additionally, the ISDC reprocessed the entire public archive to Revision 3 status in 2010, and Dr. Sturner oversaw the complete replacement of the Revision 2 HEASARC INTEGRAL archive (6.9 TB) with these Revision 3 data.

Within the HEASARC, the Legacy Archive for Microwave Background Data Analysis (LAMBDA) is NASA's thematic archive devoted to serving Cosmic Microwave Background (CMB) and related data sets to the research community. The major holdings of LAMBDA include data from NASA's two CMB missions: the COsmic Background Explorer (COBE) and the Wilkinson Microwave Anisotropy Probe (WMAP). Other holdings include data from the Submillimeter Wave Astronomy Satellite (SWAS); the InfraRed Astronomical Satellite (IRAS); numerous ground and balloon-based CMB experiments; and a collection of diffuse Galactic emission maps that are needed to enable foreground subtraction from CMB data.

In 2010 LAMBDA hosted the fourth data release from the WMAP mission, incorporating 7 years of observations. The WMAP team submitted 6 scientific papers to the Astrophysical Journal summarizing the seven-year data. These papers are appearing in the February 2011 issue of the Supplement Series, but since appearing as preprints on LAMBDA and astro-ph, they have already accumulated a total of 1,052 citations. The most important WMAP product downloaded by cosmologists is the WMAP likelihood function, which gives the likelihood of a cosmological model (as measured by the angular power spectrum) given the WMAP seven-year data. This code has been downloaded nearly 2,000 times. Additionally, the seven-year sky maps have been downloaded over 400,000 times. WMAP data continue to provide the most stringent constraints on cosmological models, and are still in very active use in the research community.

2010 saw the first release of CMB data from the recently commissioned Atacama Cosmology Telescope (ACT), a six-meter CMB telescope operating on the Atacama Plateau in Chile. ACT complements WMAP by observing the CMB at much finer angular resolution than WMAP. Together, these experiments can measure the angular power spectrum of the CMB over the multipole range l=1–10,000 (from the full sky down to angular scales of ~1 arcmin). The first products released by ACT, now being served by LAMBDA, are the ACT likelihood function, the angular power spectrum, and several ancillary data sets, including a preliminary catalogue of galaxy clusters detected via the Sunyaev-Zeldovich (SZ) effect. Since its release in late 2010, the ACT likelihood has been downloaded over 100 times. Another important CMB experiment that is currently taking data is the South Pole Telescope (SPT), which has similar attributes to ACT but covers a different portion of the sky. SPT has released a few small data sets to date and LAMBDA is preparing to serve those and is in discussions with the SPT group to formally serve future, more complete, SPT data releases. The combination of WMAP, ACT, and SPT offer the most scientifically productive collection of CMB data to date.

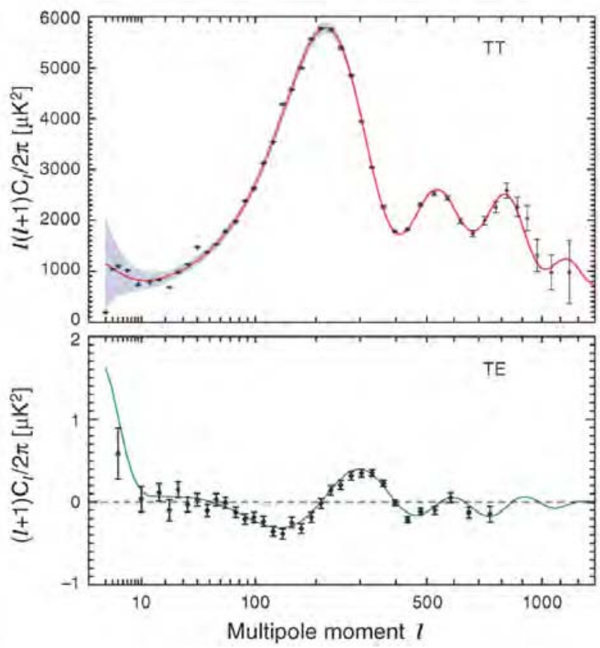
Within the next five years, the HEASARC will ingest observations from eight currently operating missions and several upcoming missions, simultaneously serving data from these and more than 30 archival missions to the community. Priorities within the 2011–2015 timeframe include the development and implementation of archival support for NuSTAR, Astro-H, and GEMS data under the direction of Angelini, continuing support for the HEASARC's exponentially growing data holdings and retrievals, a closer integration of archive access and analysis tools, and increased interoperability with other archive centers and the Virtual Observatory.

WMAP Seven-Year Results

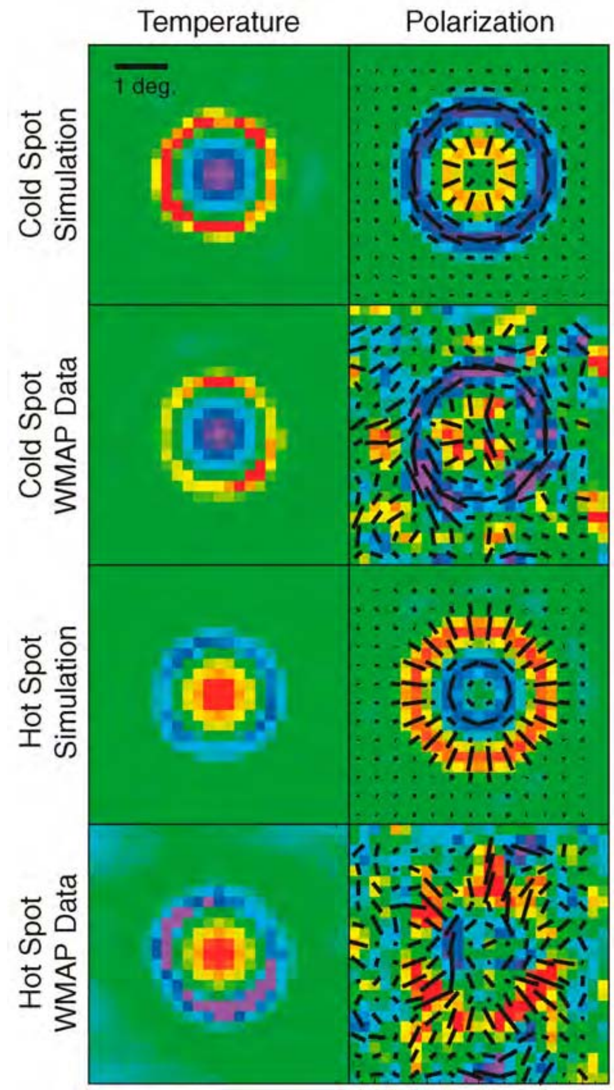
WMAP helped establish a simple and comprehensive cosmological model that connects the physics of the very early universe to the properties of the universe today. In this standard model, the universe is flat, homogeneous and isotropic on large scales. The universe is composed of radiation and atoms, but it is currently dominated by dark matter and dark energy. It is believed to have undergone a period of rapid inflation at its beginning, expanding by more than 50 e-foldings in a fraction of a second.

The first results from WMAP, based on one year of data, were released in 2003 and were followed up by three-year results in 2006, and five-year results in 2008. In 2010, the WMAP team released six papers with results based on seven years of data. These papers are being published in a dedicated issue of the Astrophysical Journal Supplement Series (February 2011). As of this writing, the six seven-year papers have already accumulated more than 1,100 citations. The WMAP team at GSFC includes ASD scientists

Best-fit ΛCDM parameters with seven-year WMAP data		
ΛCDM Parameter	**WMAP data only**	**WMAP+BAO+H0**
Matter density, $\Omega_m h^2$	0.1334 ± 0.0055	0.1349 ± 0.0036
Baryon density, $\Omega_b h^2$	0.02258 ± 0.00057	0.02260 ± 0.00053
Cosmological constant, Λ	0.734 ± 0.029	0.728 ± 0.015
Scalar index, n_s	0.963 ± 0.014	0.963 ± 0.012
Optical depth, τ	0.088 ± 0.015	0.087 ± 0.014
Amplitude @ $8h^{-1}$ Mpc, σ_8	0.801 ± 0.030	0.809 ± 0.024



The angular power spectrum measured with the seven-year WMAP data. The top panel shows the temperature spectrum with an improved measurement of the third acoustic peak and data up to multipole moment l=1200. The bottom panel shows the correlated temperature-polarization spectrum with a clear indication of a second dip near l~500.

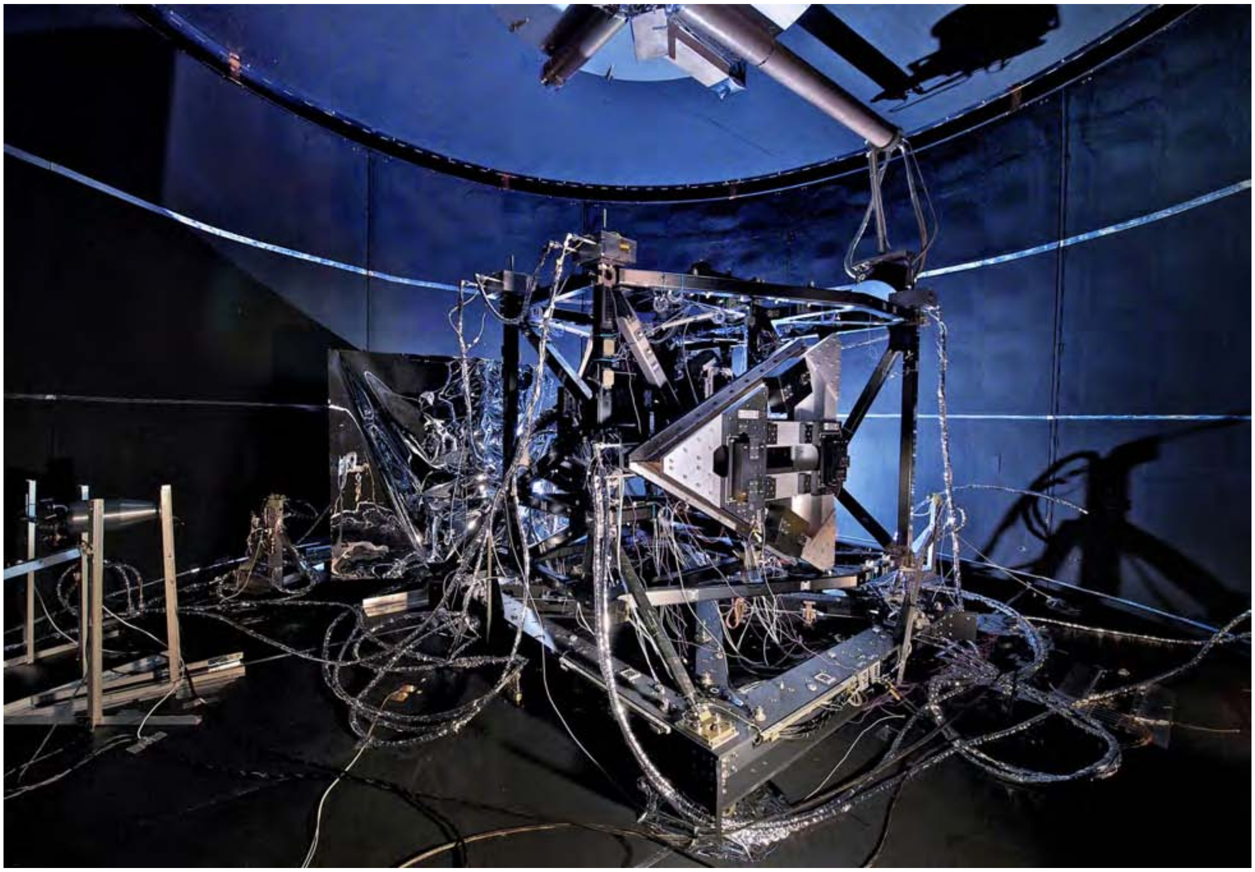


Stacked temperature and polarization maps produced from the seven-year WMAP data. The left column shows the average of all the hot and cold spots in the map over a ~5 degree square. These maps clearly exhibit the concentric pattern of acoustic oscillations in the data. The right column shows the polarization maps stacked over the same positions as the left column. This exhibits the concentric rings of alternating radial and tangential polarization around the temperature extrema.

Hinshaw (now at UBC), Wollack, Kogut, and Bennett (now at JHU).

For Gaussian random-phase fluctuations, the angular power spectrum encodes the full statistical information in the map. Classic papers (Peebles and Yu, 1970; Sunyaev and Zeldovich, 1970) relate the parameters of the universe to the structure in the angular power spectrum. The standard ΛCDM model, defined by the six parameters given in the table below, is a good fit to the seven-year WMAP spectrum, with a reduced chi-square of 1.047 for 1170 degrees of freedom. WMAP has improved its measurements of subdegree scale fluctuations, especially the third acoustic peak. As a result, the seven-year data shrinks the allowable volume of the six-dimensional ΛCDM parameter space by 50 percent over the five-year results. The age of the universe as measured by WMAP is 13.75 ± 0.11 Gyr—a better-than-1-percent measurement.

The new WMAP data are now sufficiently sensitive to test dark energy, providing important new information with no reliance on previous supernovae results. The combination of WMAP data with measurements of the Hubble constant and of baryon acoustic oscillations (BAO) in the galaxy distribution, limits the extent to which dark energy deviates from Einstein's cosmological constant. The simplest model (a flat universe with a cosmological constant) fits the data remarkably well. The new data constrain the dark energy to be within 14 percent of the expected value for a cosmological constant (w= -1.1 ± 0.14), while the geometry must be flat to better than 1 percent ($0.99 < \Omega_{tot} < 1.01$, 95% CL) if the dark energy is a cosmological constant.



The ISIM in the Helium Shroud, where it underwent cryogenic test. The NIRSpec Mass Simulator is attached to its left side. Credit: NASA/GSFC/Chris Gunn

One of the key predictions of the hot big bang model is that most of the helium in the universe was synthesized in the hot early universe only a few minutes after the big bang. Previously, cosmologists studied old stars to infer the helium abundance before there were stars. WMAP data, in combination with smaller-scale data from the ACBAR and QUaD experiments, show the effects of helium in the microwave patterns on the sky indicating the presence of helium long before the first stars formed. This is a fundamental test of Big Bang cosmology.

The seven-year WMAP data places new constraints on the number of relativistic neutrino species in the early universe. Neutrinos are nearly massless elementary particles that permeate the universe in large quantity but they interact very weakly with atomic matter. Nonetheless they leave an imprint on the microwave fluctuations and the new WMAP data, together with BAO and H_0 data, show that the effective number of neutrino-like species is 4.34 ± 0.87. The standard model of particle physics has 3.04 effective species of neutrinos.

The improved sensitivity in the noise-limited polarization measurement has made possible a visual detection of the CMB polarization signal in the seven-years sky maps. When the polarization maps are dissected into regions centered on hot and cold spots in the temperature map, and then stacked, the telltale pattern of polarized rings around the spots are exhibited for the first time.

The CMB temperature in the direction of known galaxy clusters is expected to be slightly cooler than the average CMB temperature, due to interactions between CMB photons and the gas in the clusters. This effect has been observed in aggregate by WMAP and is consistent with analogous observations by the South Pole Telescope. Both observations are in conflict with extrapolated X-ray observations of clusters (X-rays probe a smaller volume of cluster gas than the CMB observations) and with numerical simulations, which must be missing some of the complex gas physics in the outer regions of the clusters.

For all of these cosmological results to be meaningful, the systematic measurement errors must be

The coated flight tertiary mirror for Webb. Credit: Ben Gallagher (Ball Aerospace) and Quantum Coating Incorporated.

extremely well understood. Enormous effort has been expended to characterize the WMAP experiment: its calibration, systematic errors, noise properties, and foreground signals. These activities, which are intricate, challenging, and time-consuming, are the focus of the WMAP Team's effort.

In Development

James Webb Space Telescope

The James Webb Space Telescope (JWST) is a large (6.5m), cold (50K), facility-class, general-purpose observatory that will be launched into orbit around the Sun-Earth L2 point. It is the successor to the Hubble and Spitzer space telescopes. Its science goals range from detecting the first galaxies to form in the early universe to exoplanets and objects in our solar system. Time on the telescope will be allocated to the community through annual peer-reviewed proposals in a manner similar to Hubble. The prime contractor is Northrop Grumman; the Science and Operations Center is located at the Space Telescope Science Institute. JWST is a partnership between NASA and the European and Canadian Space Agencies.

The ASD provides scientific direction for JWST through 10 project scientists. The Senior Project Scientist is John Mather, his deputy is Jonathan Gardner and his technical deputy is Malcolm Niedner. The other members of the team: Matthew Greenhouse (Instrumentation), Bernard Rauscher (deputy); Mark Clampin (Observatory), Charles Bowers (deputy); Randy Kimble (Integration and Test); George Sonneborn (Operations) and Jane Rigby (deputy).

Mather chairs the JWST Science Working Group (SWG), and the Project Scientists are thoroughly integrated with the management and engineering teams, participating in reviews, project meetings, serving on change-configuration boards, and participating in decisions. The JWST SWG published a thorough description of the JWST science goals and technical implementation as a special issue of the refereed journal, Space Science Reviews (Gardner et al. 2006). It has since also updated and extended the science case in a series of white papers that include astrobiology, dark energy, exoplanet coronagraphy, exoplanet tran-

A Ball Aerospace optical technician inspects six Webb primary mirror segments—one with its gold coating —prior to cryogenic testing in the X-ray and Cryogenic Facility at NASA's Marshall Space Flight Center. Credit: NASA/MSFC/David Higginbotham

sits, first-light galaxies, resolved stellar population, solar system observations and the role of JWST in the decadal survey, New Worlds, New Horizons. The white paper on exoplanet transits is being revised and prepared for refereed publication. The Space Science Reviews paper and the white papers are available from jwst.gsfc.nasa.gov/scientists.html.

The JWST Project is now in phase C/D, and the project successfully completed its Critical Design Review (CDR) in mid-2010. All four flight instruments have passed their CDRs and are in the integration and testing phase. Engineering units of the instruments were delivered to Goddard in 2010 and three of the flight instruments will arrive in 2011. The Integrated Science Instrument Module (ISIM) flight structure began testing at Goddard in 2010, and the facilities for testing the ISIM with its instruments are in development. The GSFC Space Environment Simulator (SES) cryogenic vacuum chamber was modified by the JWST project with a liquid helium shroud. The project is currently integrating the cryogenic telescope simulator that will be used in the SES chamber to test the ISIM.

The 18 primary mirror segments, three spare segments, and the secondary, tertiary, and fine steering mirrors have been constructed out of lightweight beryllium, and have completed fine polishing and initial cryogenic testing. Five of the primary mirror segments have completed polishing and testing and have been coated with gold; the others are in the final stage, known as cryo-polishing.

Development of the ground system at Space Telescope Science Institute is progressing. They recently formed the JWST Space Telescope Advisory Committee to give advice on the readiness for science operations, and to represent the General Observer community.

The ASD is directly responsible for two hardware items, both within the Near-Infrared Spectrograph (NIRSpec), an instrument that is part of the ESA contribution to the mission. The Microshutter Assembly (MSA) is led by PI Harvey Moseley with contributions from a number of contractor scientists. The MSA will enable simultaneous spectra of more than 100 objects—the first time that a true multi-object spectrograph has flown in space. The detectors in the

NIRSpec are also being built at Goddard, under the leadership of Bernard Rauscher. The flight MSA and flight detectors were both delivered to ESA in 2010. Rauscher and Moseley are members of the NIRSpec Science Team and will participate in their Guaranteed Time Observations.

Astro-H

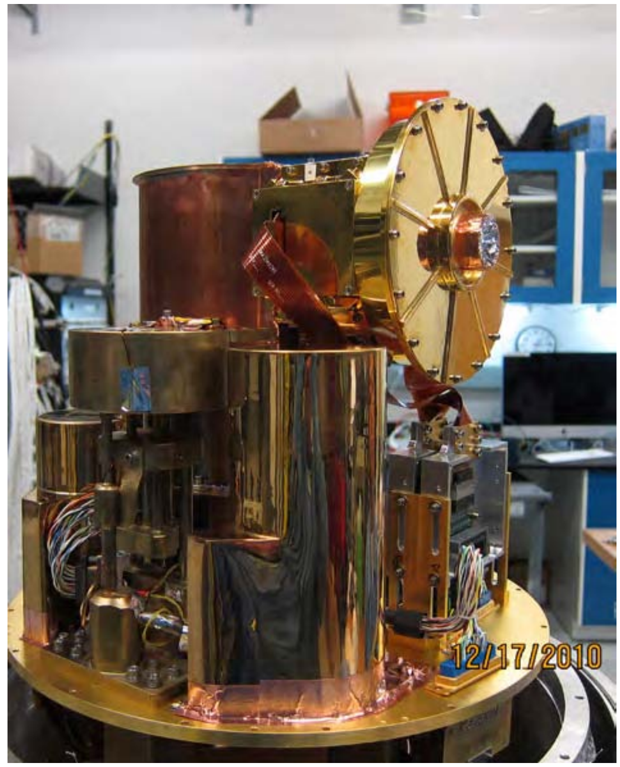
The X-ray Astrophysics Laboratory is collaborating with ISAS/JAXA to implement an X-ray calorimeter spectrometer for the Astro-H mission. The project, headed by Richard Kelley of the X-ray Astrophysics Laboratory, is implemented as an Explorer Program Mission of Opportunity to provide key components of a high-resolution X-ray calorimeter spectrometer that will constitute one of the observatory's primary science instruments. Among laboratory scientists, Caroline Kilbourne and Scott Porter are responsible for the detector subsystem, and Peter Serlemitsos and his team of Takashi Okajima and Yang Soong are responsible for the X-ray mirror. Rob Petre is the Project Scientist. Megan Eckart and Maurice Leutenegger are developing the calibration system for the detector system with assistance from Jean Cottam. Prof. Dan McCammon of the University of Wisconsin, a long-term collaborator with the X-ray Astrophysics Laboratory and a pioneer in X-ray calorimeters, is developing new generation blocking filters for the instrument.

The Soft X-ray Spectrometer (SXS) will consist of a 36-pixel X-ray calorimeter array with better than 7-eV resolution to provide high-resolution X-ray spectroscopy over the 0.3–12 keV band with moderate imaging capability. The Goddard team is to provide the detector system, adiabatic demagnetization refrigerator (50 mK operational temperature), electronics, blocking filters, and X-ray mirror, while ISAS/JAXA is responsible for the dewar system and the rest of the science instruments, the spacecraft, launcher, and mission operations.

The dewar will be a hybrid cryogen/mechanical cooler system for redundancy, and the X-ray mirror will build on the Goddard legacy of providing lightweight, high-throughput mirrors.

Astro-H is a facility-class mission to be launched on a JAXA H-IIA into low Earth orbit in 2014. The Astro-H mission objectives:

- Trace the growth history of the largest structures in the universe

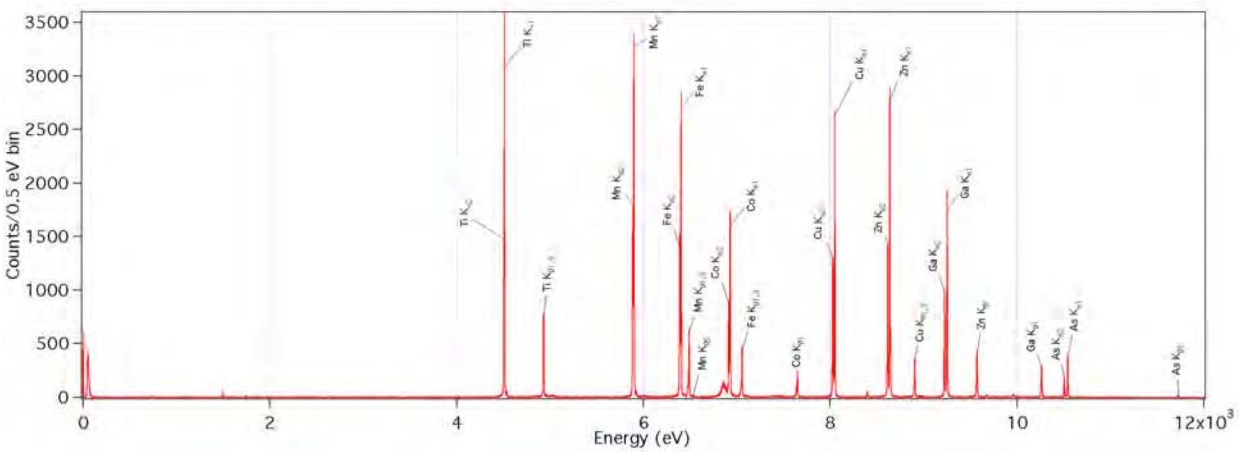


The engineering model detector assembly of the Astro-H Soft X- Ray spectrometer is being readied for testing in Building 34. The unit contains a 6x6 array of microcalorimeters and the first stage of read out, and was assembled in the new clean room facilities. The device will be integrated with the adiabatic demagnetization refrigerator and shipped to Japan in summer 2011.

- Provide insights into the behavior of material in extreme gravitational fields
- Determine the spin of black holes and the equation of state of neutron stars
- Trace shock-acceleration structures in clusters of galaxies and supernova remnants
- Investigate the detailed physics of jets

Achieving these objectives requires the SXS and three additional scientific instruments to provide a very broad, simultaneous energy bandpass. The Hard X-ray Imager (HXI) will perform sensitive imaging spectroscopy in the 5–80 keV band; the non-imaging Soft Gamma-ray Detector (SGD) extends the Astro-H energy band to 300 keV, and the Soft X-ray Imager (SXI) expands the field of view with a new-generation CCD camera.

The SXS science investigation comprises building and delivering the SXS instrumentation and carrying out a six-month observing program in collaboration with ISAS/JAXA. The baseline mission includes two



This laboratory X-ray spectrum obtained with the Astro-H Soft X-Ray Spectrometer engineering model detector assembly illustrates the enormous spectral dynamic range obtainable. The spectral resolution is 4.2 eV over the entire array and is achieved over the full energy range where astrophysically abundant atomic transitions will be detected (less than about 8 keV), providing a resolving power of about 1400 at 6 keV. The required resolution is 7 eV.

years of funding for the SXS science team and support for processing and archiving the SXS data for a total of three years. A Science Enhancement Option (SEO) was approved to provide the U.S. community with access to Astro-H beyond the baseline program. Under the SEO, U.S. scientists will be able to propose for Astro-H observing time and obtain grant support.

Working collaboratively with JAXA, a U.S. Guest Observer Facility will process, distribute, and archive data from all four Astro-H instruments, and provide observers with analysis tools and support. Lorella Angelini is responsible for developing this component of the project.

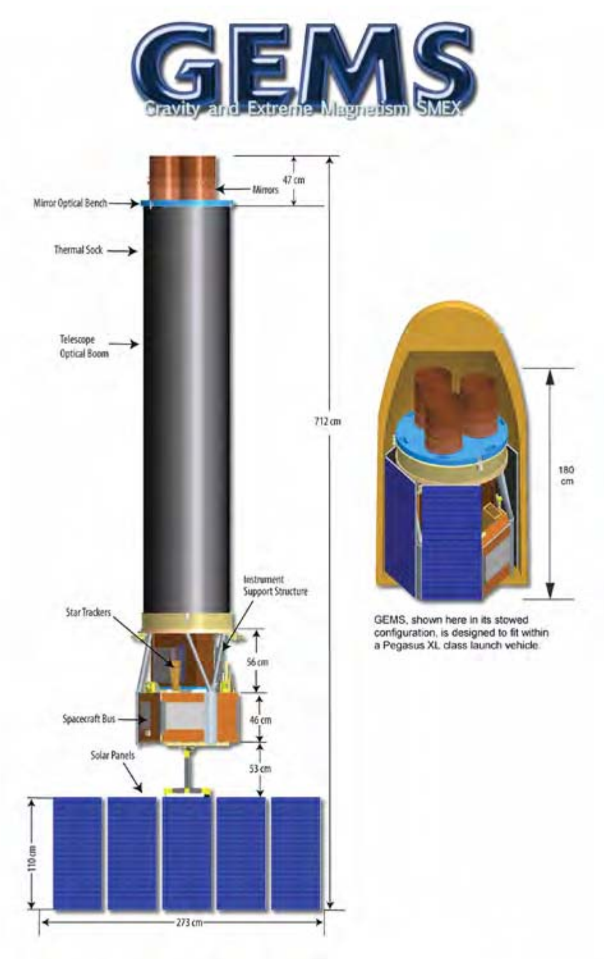
There were several major accomplishments this year. These include successful conclusion of the preliminary design review and subsequent project confirmation by NASA Headquarters in June 2010. The team is now producing engineering model components to be integrated here at Goddard and then delivered to Japan in late summer 2011. The detector system has been completed and performs superbly, with an energy resolution of 4 eV and very high uniformity across the array. Meng Chiao supervised much of the daily assembly work, and is gearing up for the flight development.

The engineering model X-ray mirror system is under construction now. X-ray reflector production is complete and the next step is to begin assembly and deliver to Japan in May 2011. Further, it has been agreed to by NASA that the X-ray mirror team will also provide an identical mirror for the ISAS/JAXA Soft X-ray Imager. All of this work has been done during the move from Building 2 to 34, which presented, and continues to present, logistical challenges for the team. These include moving the contents of clean rooms with delicate instruments and flight hardware, setting up new low-temperature labs, the establishment of a new X-ray reflector production facility in Building 22, and setting up a new X-ray beam facility out at Area 200.

Gravity and Extreme Magnetism SMEX (GEMS)

GEMS was selected in June 2009 as a Small Explorer (SMEX) to be launched between April 2014 and October 2015. A plan was developed to launch in April 2014, with a slow ramp up during an extended formulation phase. Between October 2009 and October 2010, the core team focused on developing, understanding and documenting the requirements and on building engineering test units for the elements of the instrument payload, which depends on new technology (the polarimeter and the telescope boom).

While polarization of radio, optical and ultraviolet fluxes often has been utilized to constrain the emission mechanisms and the geometry of astrophysical sources, this information has only been accessed in the X-ray band for the Crab Nebula and pulsar (for the latter, above 100 keV). In 2008, Jean Swank (PI), Keith Jahoda (Deputy PI), Timothy Kallman (chair of the science working group and now the Project Scientist), and other scientists in the X-Ray Astrophys-



GEMS deployed (left) and stowed for launch.

ics Laboratory proposed GEMS to carry out a survey of X-ray sources sensitive enough to make significant constraints on our physical models. GEMS was among those selected for a Phase A study, completed in 2009, and was selected to proceed to flight.

X-rays are the electromagnetic probe of black holes from closest to the event horizon and are thus the best probe of black-hole effects on spacetime. Current models for the X-ray production and propagation predict X-ray polarization behavior. GEMS can test these predictions and provide determinations of spin complementary to determinations from spectra or timing. The X-rays from supermassive black holes may come from coronae at significant distances from the black hole, and the geometry of this corona has been a question for over 30 years. X-ray polarization has the potential to determine it. Black hole sources range from the brightest transient X-ray binaries to quasars and Seyfert Galaxies, the brightest of which have X-ray fluxes a few thousandths of the Crab Nebula.

Neutron star X-ray sources also range nearly a factor of a thousand in X-ray brightness, from the classical accreting pulsars to pulsed non-burst flux of magnetars. The determination of the orientation of the magnetic poles of classical X-ray sources will give answers of long-standing questions; for example, X-ray production mechanisms from magnetars has been a subject of speculation since the discovery of these objects some 15 years ago.

Polarization will test models of the structures of emission regions around compact objects, which will not be resolved spatially before the advent of X-ray interferometry. X-ray polarization also can be used to study diffuse sources, such as supernova remnants. GEMS will use telescopes with grazing-incidence mirrors that focus X-rays onto polarimeters designed to maximize sensitivity. One consequence of this is that the polarimeters do not form images of the sky, but the field of view of the telescope is about 12 arc minutes, which allows coarse spatial mapping of large supernova remnants.

It has been shown from spectra that the shocks in outer shells accelerate cosmic ray electrons in magnetic fields amplified from the swept-up interstellar fields, but the order and orientations of the fields responsible for synchrotron X-rays is not known and can be addressed with polarization information. In pulsar wind nebula, there are jet flows from the pulsars. INTEGRAL measurements of the gamma rays from the Crab pulsar indicate synchrotron radiation from electrons in fields perpendicular to the jet. Other (much fainter) pulsar wind nebulae have jets which probably also determine the fields and the polarization in the nebulae. GEMS observations will measure the coherence of their fields.

The polarimeter design was developed by Kevin Black, Phil Deines-Jones, Keith Jahoda, and Joanne Hill. The polarimeter is a time projection chamber that images the track of an electron ejected by an incoming X-ray in the photoelectric effect. The distribution of tracks produced by the incoming flux shows the polarization of the source. Joanne Hill has led the polarimeter team in developing engineering test models which will be subjected to testing in the spring of 2011 to assure that they meet the technical readiness required to proceed to flight development. Asami Hayato has been measuring the drift velocities in a laboratory configuration using a modulated X-ray source designed by Keith Gendreau. The drift velocity is needed to convert the time dimension to the second projected spatial dimension of the track. Tod Strohmayer has shown that the data read-out from typical detector events can be accurately deconvolved.

The mirrors will have the focal length of one of the Suzaku mirrors, but with a smaller diameter. Yang Soong, Takashi Okajima, and Rob Petre have been developing the design for GEMS that is evolved from the foil mirrors first flown by Peter Serlemitsos on the the Broad-Band X-Ray Telescope, a shuttle payload, and subsequently on ASCA and Suzaku.

Science Operations of GEMS will be from Goddard, while the spacecraft developer, Orbital, will operate the mission. Craig Markwardt has shown that the observations required to reach the required sensitivities can be scheduled within the constraints on the spacecraft.

A review of the systems requirements on the instrument, the spacecraft, and the operations was completed, a gate to proceeding toward the preliminary design review in fall 2011. Tim Kallman has led the larger science team discussions of the science requirements, from which the GEMS team has derived the engineering requirements.

Mission and Instrument Concepts

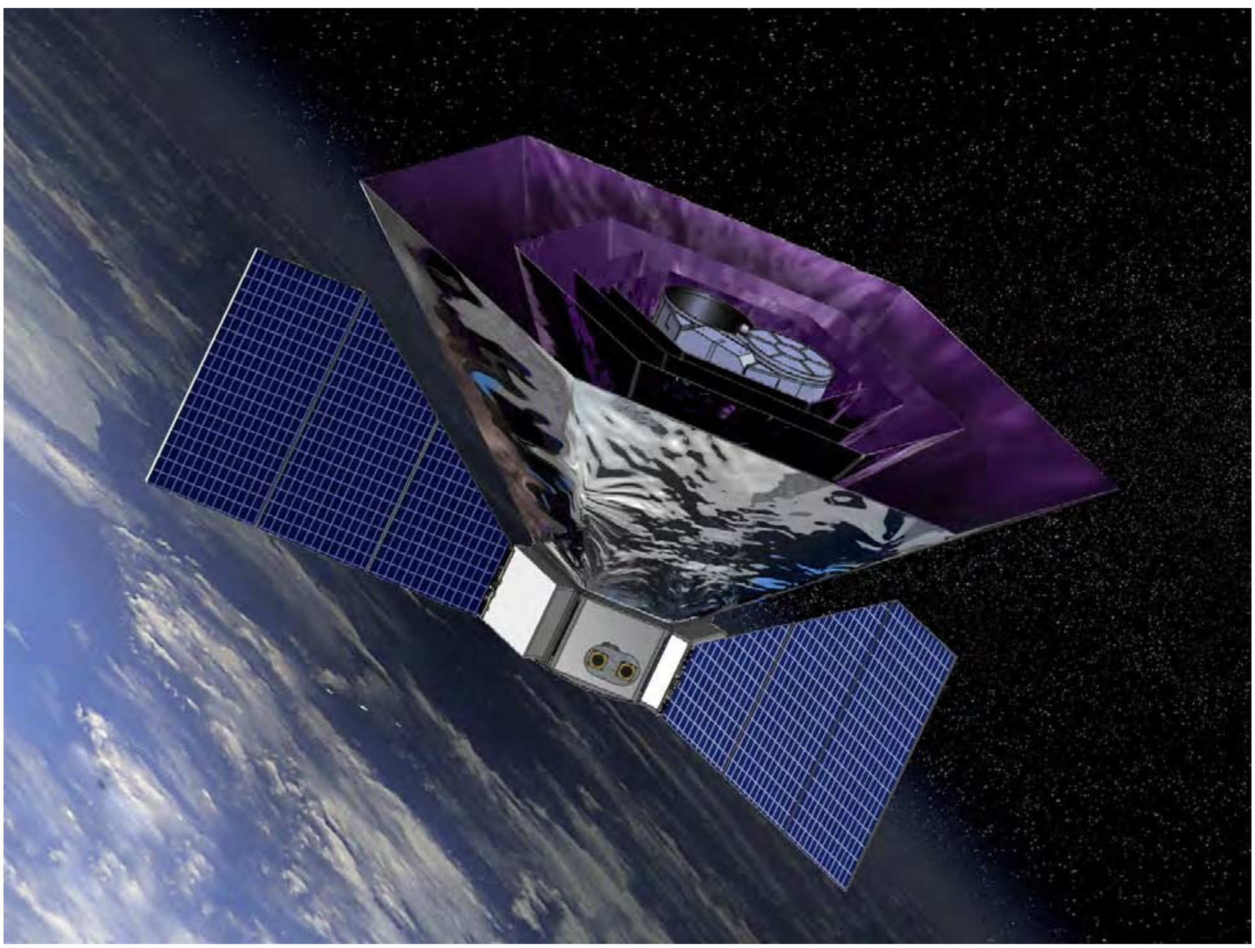
Primordial Inflation Explorer (PIXIE)

How did the universe begin? Humans have asked this question since our species first looked skyward. Recent progress in cosmology suggests that we may have begun to answer this question. We live in an expanding universe filled with microwave background radiation, the leftover heat from the Big Bang. In this "concordance" model, the universe is flat, largely composed of dark energy and dark matter, and seeded with density fluctuations from the early universe.

The concordance model postulates that early in its history, the universe underwent a rapid period of superluminal expansion called inflation. The exponential growth of the scale size during inflation neatly produces the observed conditions of our universe, but relies on extrapolation of physics to energies a trillion times beyond those accessible to direct experimentation in particle accelerators.

The Primordial Inflation Explorer (PIXIE) will test the inflationary paradigm by searching for the "smoking gun" signature of primordial inflation in the linear polarization of the cosmic microwave background (CMB). Quantum fluctuations in the space-time metric during inflation create a stochastic background of gravity waves, which in turn imprint a distinctive spatial signature in the CMB. The amplitude of the gravity waves depends on the energy scale at inflation. Detection of the gravity-wave signature would establish inflation as a physical reality, provide a model-independent determination of the relevant energy, and probe physics at energies near the Grand Unified Theory scale (10^{16} GeV). The search for the inflationary signal is widely recognized as one of the most compelling questions in cosmology, endorsed as a priority for the coming decade in the 2010 Decadal Survey of Astronomy and Astrophysics, *New Worlds, New Horizons*.

PIXIE is an Explorer mission intended for launch in 2017. Principal Investigator Alan Kogut (Observa-



Artist's conception of the PIXIE observatory.

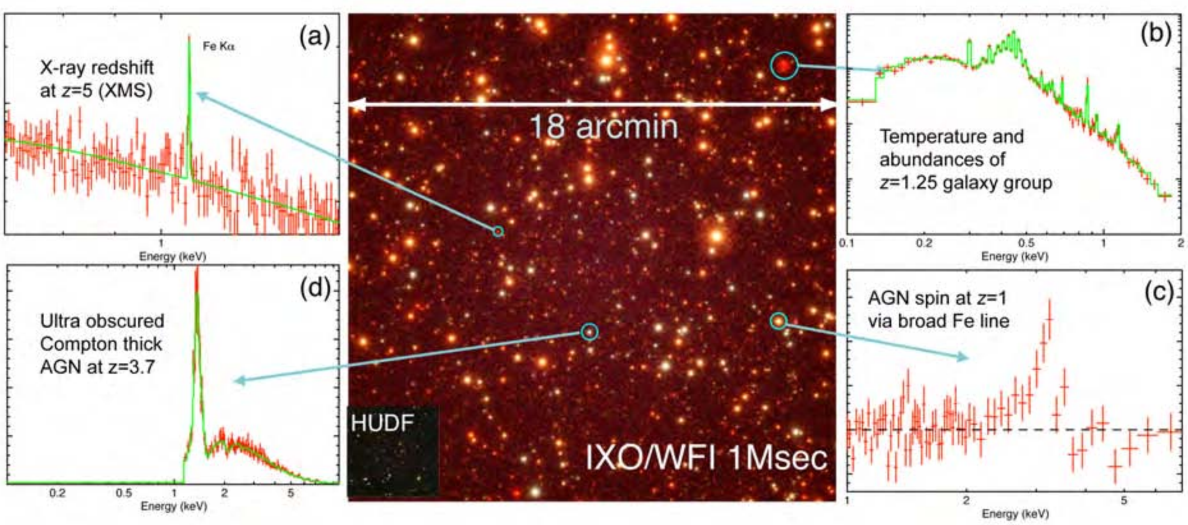
tional Cosmology Laboratory) leads a team including GSFC Co-Investigators D. Chuss, E. Dwek, D. Fixsen, S.H. Moseley, and E. Wollack. PIXIE's innovative design uses a multi-moded "light bucket" and a polarizing Fourier Transform Spectrometer to measure the differential spectrum between two co-aligned beams in orthogonal linear polarizations. PIXIE will measure the frequency spectra in 400 spectral bands from 30 GHz to 6 THz for each of the Stokes I, Q, and U parameters in each of 49,152 independent pixels covering the full sky. The combination of sensitivity and broad spectral coverage answer exciting questions across cosmic history. PIXIE will measure both the temperature and ionization fraction of the intergalactic medium at redshifts 5–30 to determine the nature of the first luminous objects in the universe. Measurements of the spectrum and anisotropy of the far-IR background test models of star formation at redshift 2–4. PIXIE determines the properties of the diffuse dust cirrus and maps the far-IR line emission from the molecules and ions that cool the interstellar medium within the Galaxy.

International X-ray Observatory (IXO)

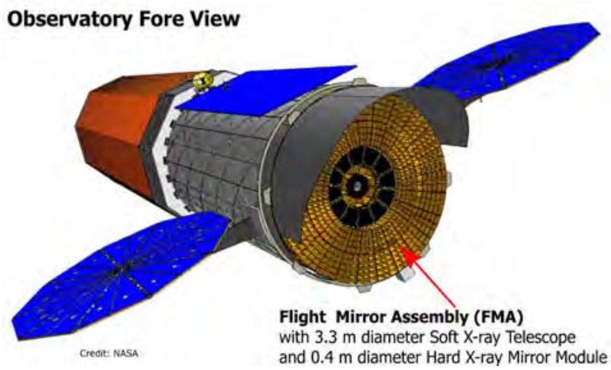
IXO is an international flagship X-ray observatory with joint participation from NASA, the European Space Agency (ESA), and Japan's Aerospace Exploration Agency (JAXA). The mission was created in 2007 by the merger of NASA's Constellation-X and ESA's XEUS. IXO is a facility-class mission for launch in the 2020's that will address the leading astrophysical questions in the "hot universe" by providing breakthrough capabilities in X-ray spectroscopy, imaging, timing and polarimetry.

IXO will measure the spin of black holes, a fundamental property that, for supermassive black holes, reveals whether black holes grow mainly by accretion or by mergers. IXO will reveal the physics of accretion near the last stable orbit, measuring general-relativistic effects in the strong-field limit. For neutron stars, IXO will determine the mass-radius relationship, thereby constraining the equation of state and QCD models of matter at these densities. In galaxy clusters, IXO will measure the velocity structure, mass and metallicity distribution of the dominant baryon component, the hot intracluster gas. Not only will this provide a deep understanding of evolution of large-scale structure, but samples of clusters at various redshifts provide important and independent constraints on the cosmological model and dark energy.

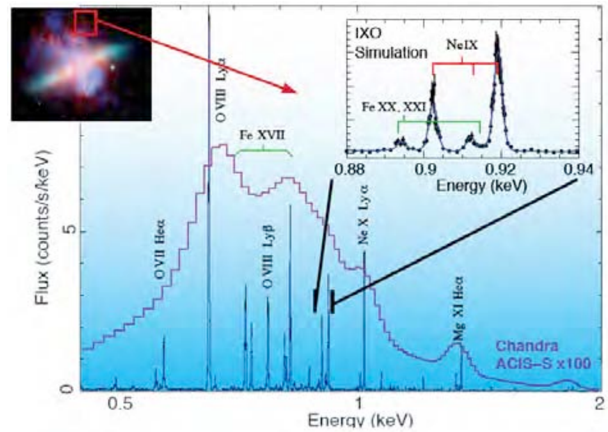
Extending away from clusters and groups is the cosmic web, where half of the baryons in the local universe are expected to reside; they have not been detected because much of the expected emission has very low surface brightness in the UV and soft X-ray, where the universe is opaque. IXO will detect these



IXO WFI Simulation of the Chandra Deep Field South with the Hubble Ultra Deep Field (HUDF) inset. Simulated spectra of various sources are shown, illustrating IXO's ability to (a) determine redshift autonomously in the X-ray band; (b) determine temperatures and abundances, even for low luminosity groups to z < 1; (c) make spin measurements of AGN to z >~ 1; and (d) uncover the most heavily obscured, Compton-thick AGN.



IXO view showing the Flight Mirror Assembly.



Upper left: M82 provides an example of a starburst-driven superwind. Diffuse thermal X-ray emission seen by Chandra is shown in blue. Hydrocarbon emission at 8 μm from Spitzer is shown in red. Optical starlight (cyan) and Hα+[NII] (yellow) are from HST-ACS observations. Right: IXO high-resolution X-ray spectra (blue) showing the metal-enriched hot gas outflowing from the galaxy, a part of the feedback process unresolvable with current X-ray CCD data (magenta). Inset: The He-like emission line triplet of NeIX can be resolved, which means that velocities can be measured and plasma temperatures and ionization states can be diagnosed.

missing baryons with its very high effective area and spectral resolution, allowing WHIM features to be detected along lines of sight to bright quasars. It can test predictions for the formation and topology of the cosmic web. Furthermore, IXO will yield insight into feedback mechanisms in the universe on many scales through studies of supernova remnants, outflows in starburst galaxies, and AGNs across cosmic time. Feedback due to both AGN and starburst activity is a critical component of galaxy evolution that is not easily directly observed, and IXO will provide a unique window into these processes. Both processes are also critical to the enrichment and energetics of the intracluster medium.

Much of this science requires a panchromatic approach. IXO covers the 0.1–40 keV energy range, complementing the capabilities of the next-generation observatories such as ALMA, LSST, JWST and 30m ground-based telescopes. IXO builds on three decades of successful X-ray mirror development, including the currently operating Chandra X-ray Observatory (NASA) and XMM-Newton mission (ESA). The spacecraft configuration for IXO features a single, large X-ray mirror assembly, an extendible optical bench with a focal length of 20 meters, and a suite of focal plane instruments. Areas of technology development include X-ray optics, detector and cooling systems.

The NASA portion of this project is led by GSFC. The Project Scientist is Nicholas White, Deputy Project Scientist is Ann Hornschemeier, and the Observatory Project Scientist is Rob Petre. Project science support is provided by Andy Ptak, Steve Snowden, Tim Kallman, and Tod Strohmayer. Will Zhang leads the mirror technology development; Richard Kelley, Caroline Kilbourne, and Scott Porter lead the calorimeter development.

IXO was ranked as the fourth priority in for NASA in *New Worlds, New Horizons*, the report of the 2010 decadal survey. The scientific topics central to IXO were ranked highly in several panels, as was the need for the measurements IXO will provide. The panel recommended that NASA support a substantial technology development program over the next decade, primarily to mature the X-ray mirror technology. It is expected that this technology program will be led by GSFC scientists and it will likely result in decreased cost estimates as risks are lowered.

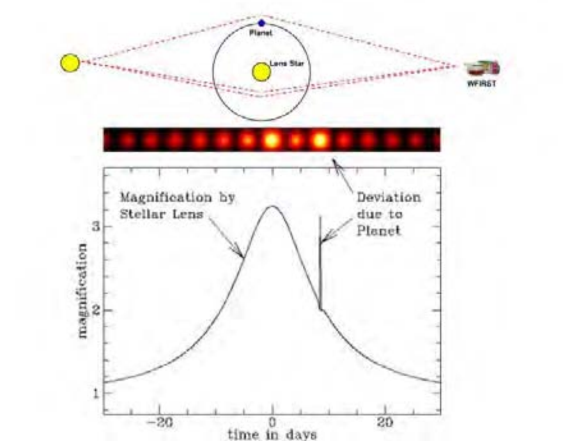
Much effort over the past year has gone into supporting the ESA Cosmic Visions study of L-class missions, of which IXO is one of three finalists. ESA conducted mission feasibility studies, followed by an internal technology assessment. Supporting these studies required the development of a substantial amount of documentation by the U.S. groups responsible for the mirror, calorimeter and grating spectrometer technology development. The IXO project team supported the internal technology assessment by responding to questions from review panel members.

Over the course of the CV process, many of the major concerns raised by the decadal survey have been addressed, such as a better definition of the international partners' roles. The ranking of the L-class missions should be announced in June 2011.

Wide Field InfraRed Survey Telescope (WFIRST)

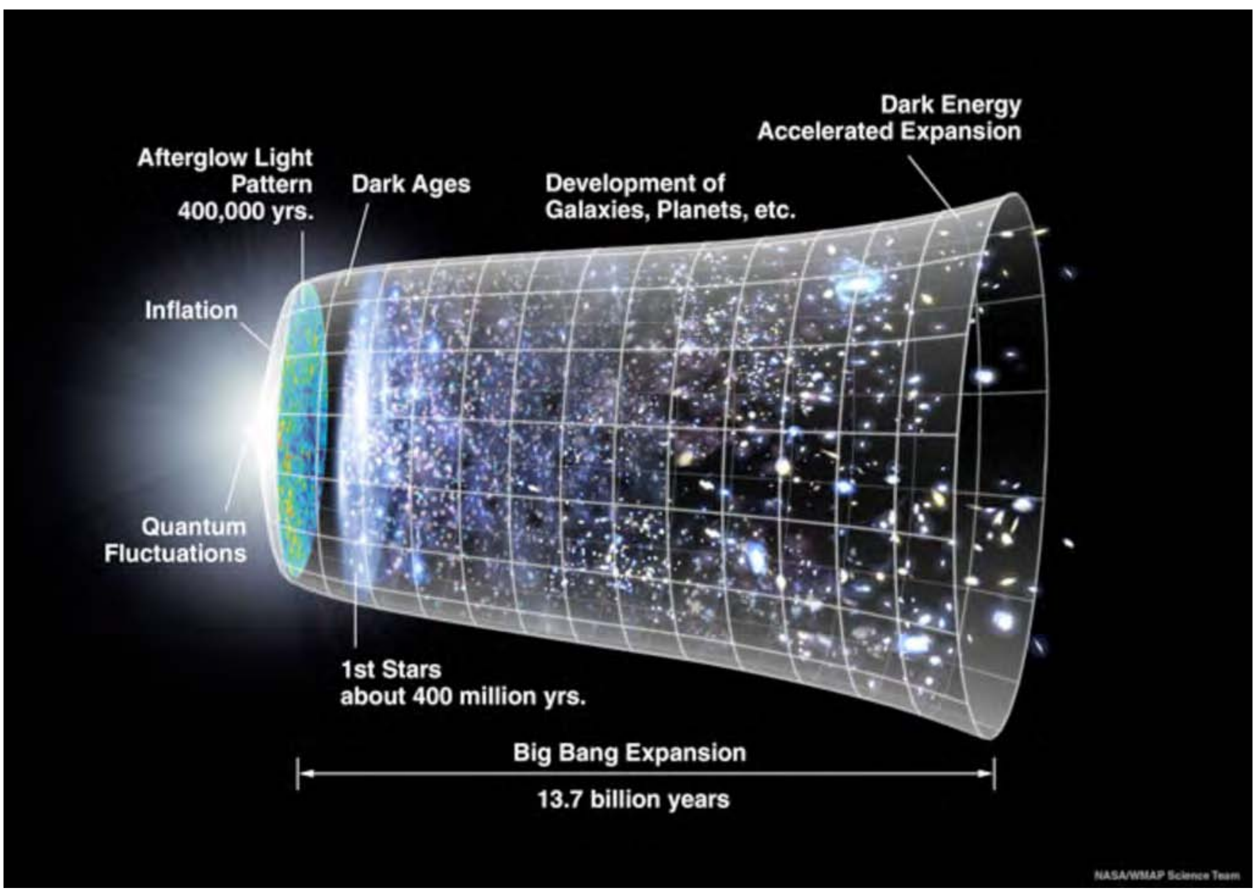
The 1998 discovery that the expansion of space is accelerating was described in the journal *Science* as the breakthrough of the year and one of the most important scientific problems of our time. The implication that three-quarters of the energy in the universe is due to an unknown entity called dark energy may one day revolutionize our understanding of cosmology and physics. Observations with ground-based and space-based assets such as HST and WMAP confirmed the acceleration. However, a new space-based experiment is required in order to extend these measurements of dark energy to the early universe with high precision.

NASA and the U.S. Department of Energy (DOE) joined forces to develop concepts for a Joint

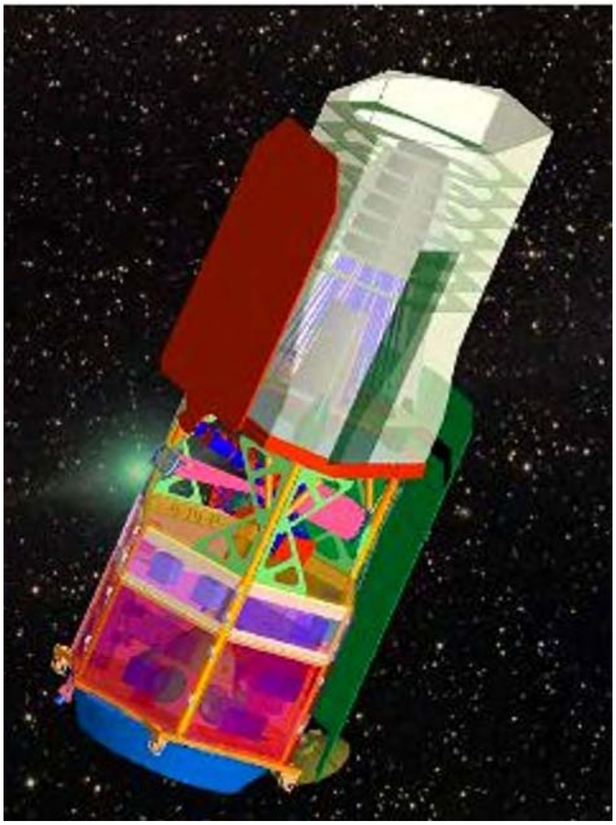


Microlensing gives statistics of habitable- and ice-zone planets around stars.

Dark Energy Mission (JDEM) that would characterize cosmic acceleration. GSFC was the lead NASA center for managing the Project; the DOE team was based at Lawrence Berkeley National Laboratory (LBNL). Two mission concepts that employed three measurement techniques—Baryon Acoustic Oscillations (BAO),



An illustration of how the universe's expansion rate is increasing in the current epoch due to dark energy.



Artist's view of the WFIRST observatory as recommended by the Astro2010 Decadal Survey.

type Ia supernovae, and weak lensing — were developed and submitted to the Astro-2010 Decadal Survey Program Prioritization Panels. While the Astro 2010 panels were deliberating, GSFC and DOE worked with the JDEM Interim Science Working Group at the direction of NASA HQ to develop two additional mission concepts that would measure cosmic acceleration at lower cost by employing two techniques rather than three.

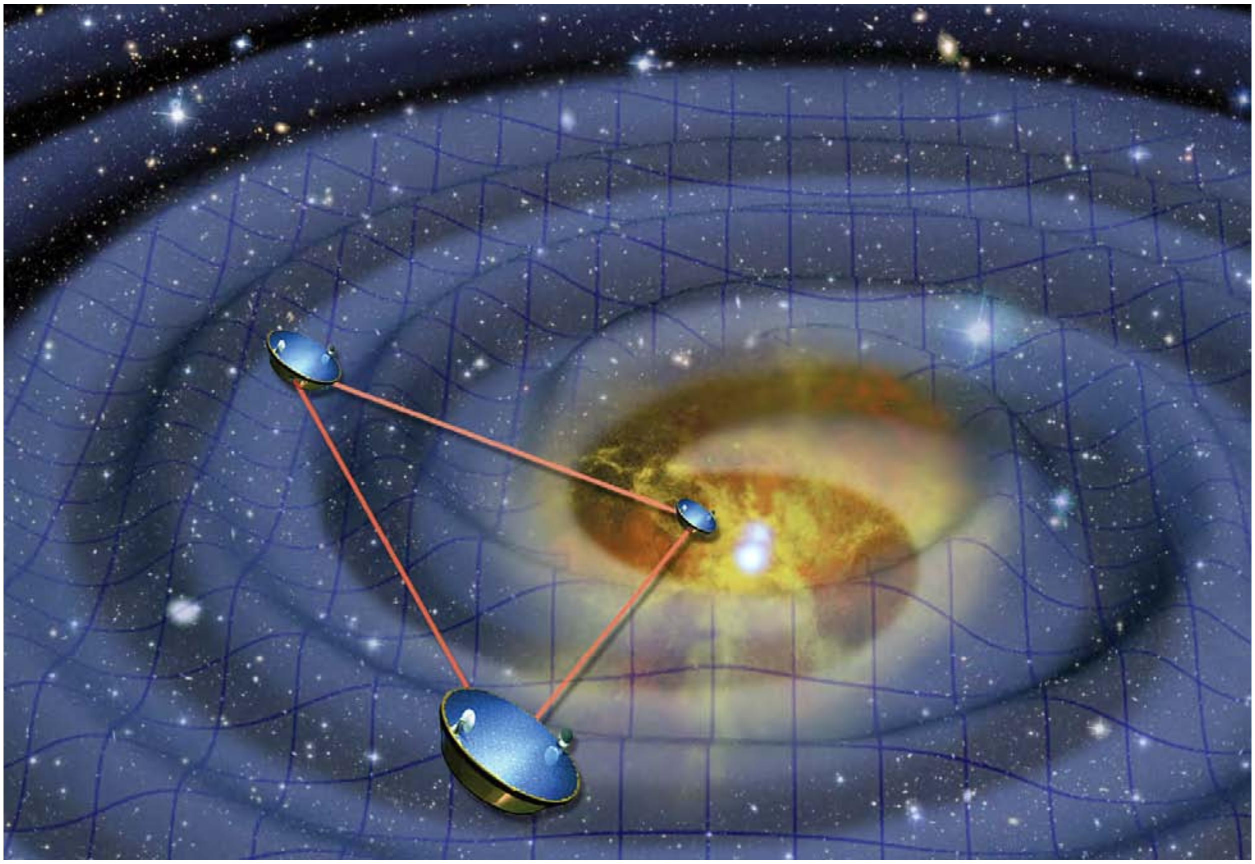
The Astro 2010 report, released August 13, 2010, selected the JDEM Omega design as the top priority for large space missions in the coming decade. This selection was based in part on the Omega design capability for performing measurements of cosmic acceleration, and in part on its capability for performing a wide range of near infrared surveys and for obtaining a census of exoplanets by means of microlensing. In recognition of the increased scope of the science program, the mission was renamed the Wide-Field Infrared Survey Telescope (WFIRST). NASA HQ has designated GSFC as the lead center for managing the WFIRST project, with significant portions of the mission assigned to JPL. A Science Definition Team (SDT) representing the full spectrum of WFIRST science objectives has been appointed to provide scientific advice on optimizing mission performance.

The WFIRST Project science team at GSFC includes Neil Gehrels (Project Scientist), Jeff Kruk (Instrument Scientist), Ken Carpenter, Ed Cheng, Gary Hinshaw, Harvey Moseley, Bernie Rauscher and Ed Wollack. The team plus project engineers and managers developed the Joint Dark Energy Mission (JDEM) inputs to the Astro2010 Decadal Survey, working with the Department of Energy scientists and with members of the community appointed by NASA Headquarters (the Science Coordination Group). They subsequently worked with the JDEM Interim Science Working Group (ISWG) to find a lower cost, yet scientifically worthwhile, "Probe" concept. The scientists from ASD are now supporting the WFIRST Science Definition Team (SDT) to study the implementation of WFIRST. Rauscher and Gehrels are members of the SDT.

Laser Interferometer Space Antenna (LISA)

The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA project to design, build and operate a space-based gravitational wave detector. Space-time strains induced by gravitational waves are detected by measuring changes in the separation of free-falling masses with laser interferometry. Th ree spacecraft form an equilateral triangle with five-million-kilometer-long sides defined by six masses, located in pairs at

The LISA Pathfinder spacecraft (in gold foil) sits atop its propulsion module (silver foil) prior to the thermal balance test campaign.



Artist's concept of the LISA constellation.

the vertices. Changes in the separations are monitored interferometrically to achieve a usable sensitivity in the frequency band between 1×10^{-4} and 1 Hz.

The science objectives of the mission is:

- Understand the formation and growth of massive black holes and their host galaxies
- Make precision tests of general relativity and dynamical strong-field gravity
- Explore stellar populations and dynamics in galactic nuclei
- Survey ultra-compact binaries and study the morphology of the Galaxy
- Probe new physics and cosmology

Although the gravitational wave spectrum has not yet been explored, LISA is expected to make precision measurements of the following sources:

- Merging massive black holes resulting from galaxy and proto-galaxy mergers (10^3–10^7 solar masses, z < 20, tens to 100 per year)
- Stellar mass black hole inspirals (~$10/10^6$ solar masses, z < 1, tens to 100 per year)
- Galactic and extra-galactic ultra-compact binaries (tens of thousands, confusion foreground)
- Cosmological backgrounds, bursts, and unforeseen sources

The LISA Project Office is at GSFC. The Gravitational Astrophysics Laboratory provides the Project Scientist (Robin Stebbins), three Deputy Project Scientists (Stephen Merkowitz, Jeff Livas, Jordan Camp) and about 10 other scientists who support project formulation, mission system engineering, technology development, risk-reduction activities, astrophysical source studies, numerical relativity calculations of source waveforms, LISA data analysis research, and LISA Pathfinder, the LISA technology flight demonstration.

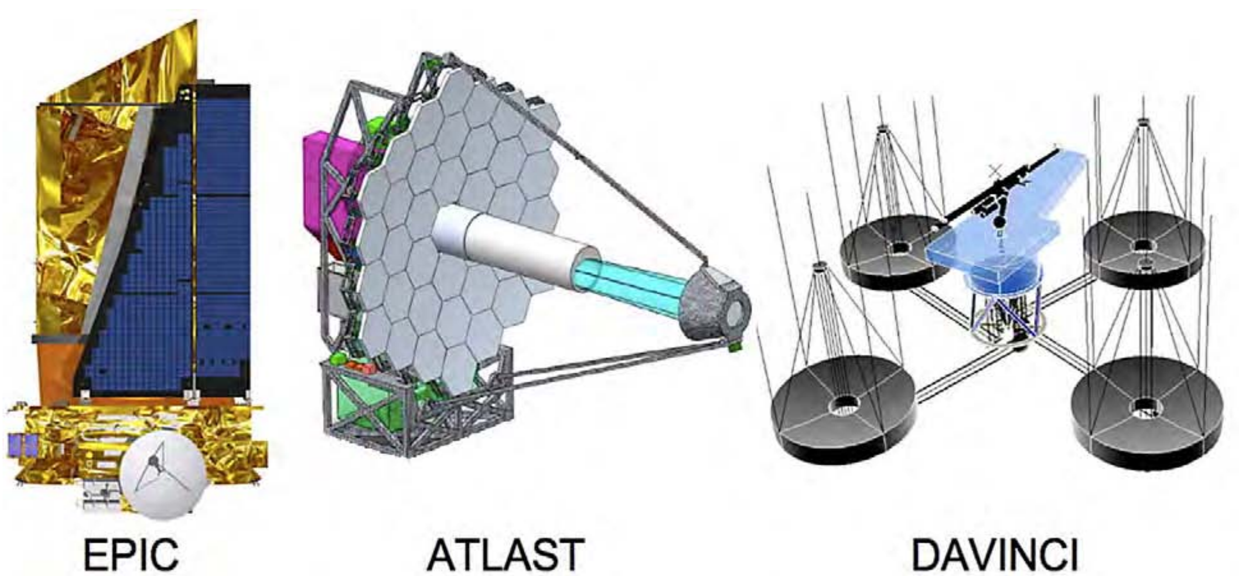
Goddard scientists support all aspects of project formulation, such as requirements development and flowdown, system analysis, system modeling, design of all mission elements and technical trade studies. Goddard risk-reduction activities include lasers, laser frequency stabilization (including pre-stabilization and arm-locking), the telescope pointing mechanism, photoreceiver optimization, telescope construction, control system modeling, and I&T technologies. The numerical relativity group in the Gravitational Astrophysics Lab has led the way in producing merger phase waveforms for inspiraling black holes, a crucial ingredient in LISA data analysis, and predicting LISA's effectiveness in the estimation of astrophysical parameters of merging sources. Improved parameter estimation has shown how the instrument performance can be made an order of magnitude better than previously anticipated.

LISA will be preceded by LISA Pathfinder, an ESA-led mission to demonstrate critical LISA technology on orbit. LISA Pathfinder carries both ESA and NASA instrument packages to demonstrate the Gravitational Reference Sensor (proof mass, reference housing with electrodes, charge control subsystem, caging subsystem, front-end electronics, and vacuum subsystem), drag-free control laws, two types of micronewton thrusters, a master oscillator laser, various aspects of interferometer construction, and, most importantly, the acceleration noise model. LISA Pathfinder is currently scheduled for launch in 2013. The project has passed its mission CDR, the spacecraft is completely integrated and the propulsion module is complete. Two lab scientists are working on the analysis of data from the NASA instrument package, called ST-7 Disturbance Reduction System, and the ESA instrument package, called the LISA Technology Package.

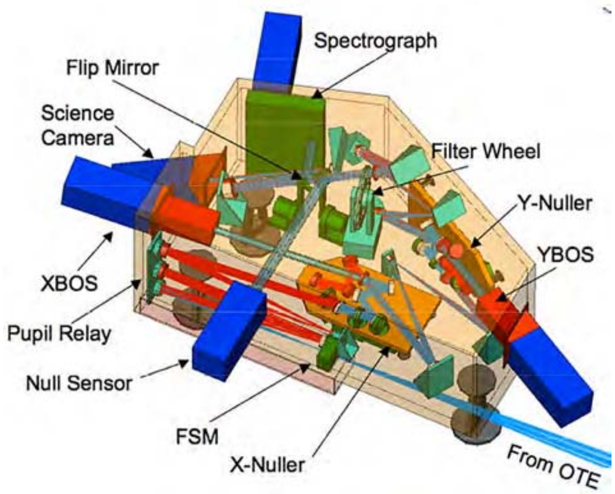
Visible Nulling Coronagraph for Exoplanets

Three of the completed NASA Astrophysics Strategic Mission Concept (ASMC) studies addressed the feasibility of employing a Visible Nulling Coronagraph (VNC) as the prime instrument for exoplanet science. The VNC approach is capable of exoplanet science with filled-, segmented- and sparse-aperture telescopes, spanning all realizable future mission architectures. A hybrid of a classical coronagraph and nulling interferometer, it uses destructive interference to null starlight and has an inherent advantage due to its ability to control amplitude and wavefront errors in near real time. This is because it is *its own interferometer* and as such gives both bright (stellar) and dark (planetary) output channels that enables a direct approach to extreme wavefront control.

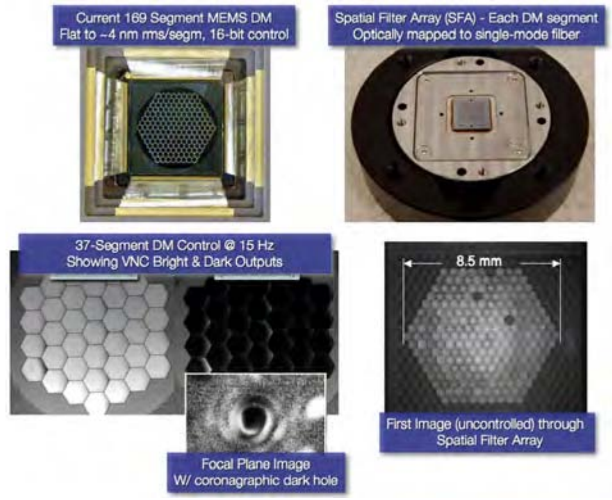
NASA/Goddard Space Flight Center (GSFC) has an established effort to advance VNC technologies an incremental sequence of testbeds and technology development efforts. The VNC, funded with GSFC IRAD for FY08, 09, and FY10, was recently awarded



Astrophysics Strategic Mission Concepts where a visible nulling coronagraph would enable exoplanet science. EPIC is the Extrasolar Planetary Imaging Coronagraph (PI: M. Clampin/GSFC) and is a 1.5-meter filled-aperture telescope studied for a probe-class mission dedicated to exoplanet science. ATLAST is the Advanced Technology Large Aperture Space Telescope (PI: M. Postman/STScI) and would consist of a 9.2-meter segmented-aperture telescope for a large- scale general astrophysics mission encompassing exoplanet science. DAViNCI is the Dilute Aperture Visible Nulling Coronagraph Imager (PI: M. Shao/JPL) and consists of four 1.2-meter aperture telescopes that are optically phased within a visible nulling coronagraph and would be dedicated to exoplanet science.



Potential flight design for a Visible Nulling Coronagraph, together with a science imaging camera and a spectrometer. The critical subsystems are the two nulling coronagraphs (orange), both modified Mach-Zehnder interferometers. The nullers effectively perform suppression of starlight and the critical VNC technologies are all associated with them.



Top left: Photo of MEMS hexagon-packed deformable mirror, each of the 169 segments move in piston, tip and tilt (3 DOF) is ~700 microns tip to tip with 3–5 micron gaps. Top right: Photo of Spatial Filter Array. Bottom left: Bright- and dark-channel VNT pupil plane images. The inset shows the focal plane region of the central dark hole showing an increase in contrast. Bottom right: Image of beam through Spatial Filter Array.

a ROSES Technology Development for Exoplanet Missions (TDEM) for FY10/11. The TDEM, led by M. Clampin and R. Lyon, is to achieve contrast milestones on the GSFC Vacuum Nuller Testbed (VNT). The VNT was developed to lower risk, advance technological readiness, quantify performance, develop and assess control algorithms, and assess internal VNC technologies. It is an ultra-stable vibration-isolated testbed operating under high- bandwidth closed-loop control within a vacuum chamber. It is being used to achieve an incremental sequence of three visible-light nulling milestones of sequentially higher contrasts of 10^8, 10^9 (both in 2011) and ultimately 10^{10} at inner working angles required to characterize exoplanets. Each of the milestones, one per year, is traceable to one or more of the ASMC studies.

The critical technologies needed to realize the VNC are the (i) MEMS based segmented MMA, (ii) spatial filter array (SFA) or a coherent fiber bundle, (iii) achromatic phase shifter, (iv) precision wavefront and amplitude control (WFC), and (v) photon-counting camera.

The MEMS DM has been developed by IRIS-AO (Berkeley, Calif.) under multiple SBIRs with the next DM to be delivered to GSFC March 25, 2011. It consists of 169 segments ~606 microns across (flat-to-flat) and each segment is articulated in 3 degrees-of-freedom (DOF) over the range of 1 micron in steps of 0.015 nm (1-bit) and has stable 16-bit electronics control. Significant advances were made under these SBIRs, including thicker segments, from 10, to 20 and finally 50 microns, to remove print-through and segment flexing. Electronics were advanced from 12, to 14 to 16 bits and segment flatness started at ~20 nm rms/segment and is now at ~4 nm rms/segment; flight requirements are 2 nm rms/segment. Additionally, IRIS-AO won a FY11 phase-I SBIR to begin the design of scaling up the number of DM segments to towards that needed for flight.

The SFA has been developed by Fiberguide, Inc. (Caldwell, Idaho) under GSFC-funded IRAD and will be shortly tested on the VNT. Additionally, a phase-II SBIR was awarded to Luminit Corp (Torrence, Calif.) to develop a separate waveguide-based approach to the SFA and delivery of the first 1,000-element SFA from Luminit is expected in November 2011.

Multiple approaches are possible for achromatic phase shifters, and two approaches have been developed at GSFC with additional approaches under assessment. The first approach was using two dispersive glass plates and developed by G. Vasudevan (LMCO); the second uses five dispersive glass plates and was developed by (M. Bolcar, Optics Branch, and R. Lyon, Exoplanets and Stellar Astrophysics Laboratory). The third approach is to use a double-rhomb, a technique developed in France for IR achromatic nulling that may be amenable to visible light. However, the fourth approach appears to be the most promising: It is to use customized coatings on the interferometer arms, and a design effort for this is underway. The achromatic phase shifters are not initially needed to achieve and hold narrowband contrast on the VNT but will be needed to broaden the spectral bandpass toward what is required for flight.

The current photon-counting cameras are COTS from Princeton Instruments and utilize E2V's L3 chip. Additional advancement of photon-counting cameras are needed for all coronagraph missions.

The precision wavefront control is under development at GSFC and lies at the heart of this effort. It is critical to be able to optimally sense and control the wavefront and amplitude errors, both broad and narrowband, at high enough bandwidth to achieve and hold the contrast by feeding back to the MMA. The stroke of the MMAs, bit depth of the cameras, vibration, thermal drift, coating imperfections, temporal and spatial sampling, quantization, flat fielding, dark current, noise, straylight, approximations and errors in the algorithms, along with other potential effects, all work to corrupt this process. The wavefront control is really a multi-step process that consists of a set of camera calibration algorithms, wavefront sensing algorithms and MMA control algorithms. Wavefront sensing, though, is somewhat of a misnomer because what is important to the science is the contrast. Thus the final control metric is contrast based, and wavefront error is actually an intermediary step, as opposed to converting images to wavefront errors.

The milestones to be achieved under the TDEM are 10^8 narrowband contrast at 2 λ/D inner working angle by April 2011, and 10^9 contrast at 2 λ/D inner working angle by November 2011. The first milestone requires the MMA, precision WFC, and photon counting, and this milestone is designed to assess the performance of the MMA in closed-loop as driven by the WFC. The second milestone additionally requires the use of the SFA to give greater than a factor of 10 in contrast since it effectively and passively filters the higher spatial frequencies from the wavefront, working in concert with the MMA with one MMA mirrorlet mapped to one optical fiber of the SFA.

Stellar Imager (SI)

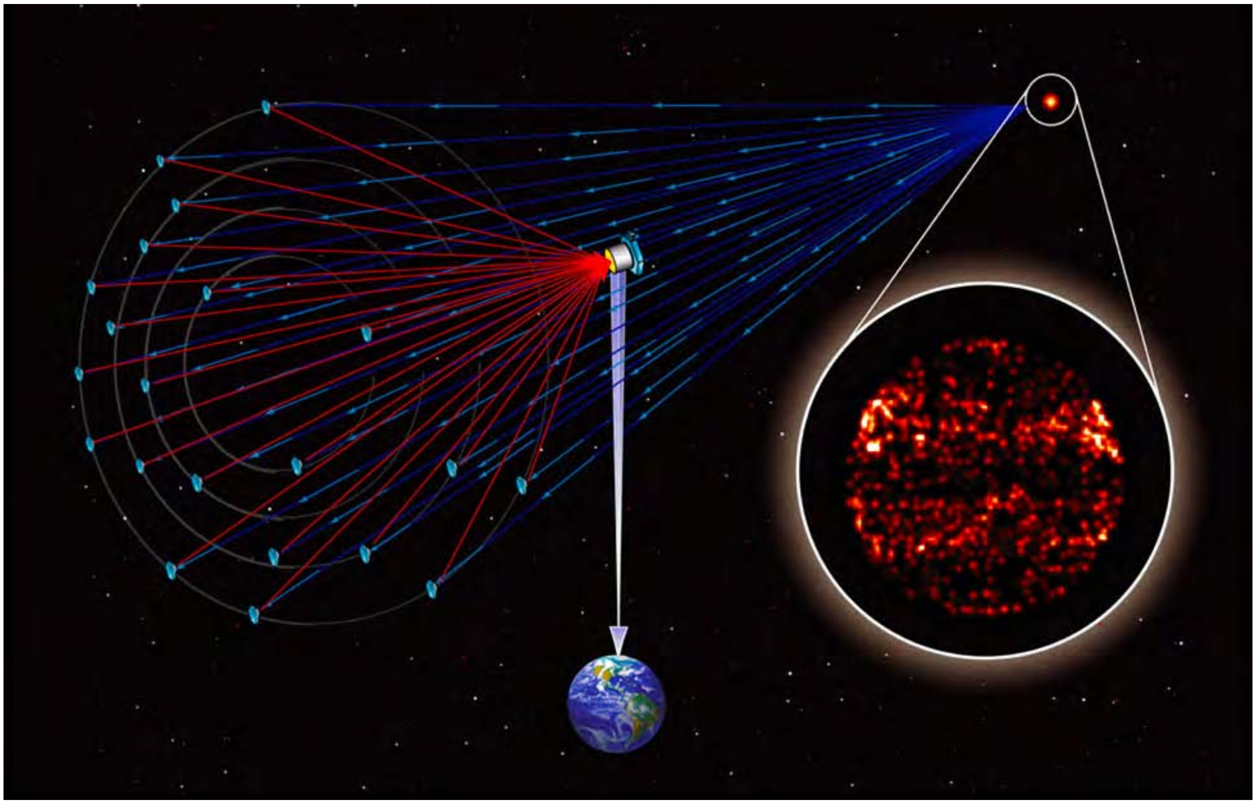
The Stellar Imager (SI) Vision Mission (see **http://hires.gsfc.nasa.gov/~si/** and Carpenter et al. 2005, 2007) is a UV/optical deep-space telescope to image stars like the Sun with 0.1 milli-arcsec resolution, to help understand the solar dynamo, the internal structure and dynamics (via spatially-resolved asteroseismology) of magnetically active stars, how magnetic activity drives space weather on time scales of years to billions of years, and how that affects planetary climates and habitability.

SI is a UV-optical aperture-synthesis spectral imager with ~30 apertures, each at least one meter in diameter, spread over baselines up to a kilometer across, and a central beam-combing hub with focal-plane instrumentation that provides an angular resolution *more than 200 times that of Hubble Space Telescope (HST)*. In addition to providing heretofore unattainable views of the surfaces and interiors of other solar-type stars, it will also reveal the inner regions and winds of Active Galactic Nuclei (AGN), and of the dynamics of many systems and processes throughout the universe.

SI is a cross-theme mission addressing science goals relevant both to the Heliophysics and Astrophysics Divisions. It is a "Flagship/Landmark Discovery Mission" in the 2005 Heliophysics Roadmap. SI's goal is to *revolutionize our understanding* of:

- Solar and stellar magnetic activity and their impact on space weather, planetary climates, and life
- Magnetic and accretion processes and their roles in the origin and evolution of structure and in the transport of matter throughout the universe
- The close-in structure of AGN and their winds
- Exo-solar planet transits and disks

The PI of the Stellar Imager concept development is Dr Kenneth Carpenter (Exoplanets and Stellar Astrophysics Laboratory). He leads a large collaborative team of about a dozen GSFC personnel plus co-investigators at ~18 external institutions (academic, aerospace and international) established for the Vision Mission Study and expanded, at low level of efforts, in the following years. GSFC's role is to continue to foster and coordinate the further development of the science program goals and the mission architecture to satisfy those goals and to pursue and encourage the development of the technologies needed to enable the mission in the late 2020s. Carpenter is also the PI of the GSFC Fizeau Interferometer Testbed (FIT), a



An array of 30 one-meter mirrors fly in precision formation to form a virtual parabola 500-meters in diameter to enable sub-milliarcsecond spectral imaging of a wide variety of astronomical objects, such as the solar-type star shown above in the light of CIV emission lines.

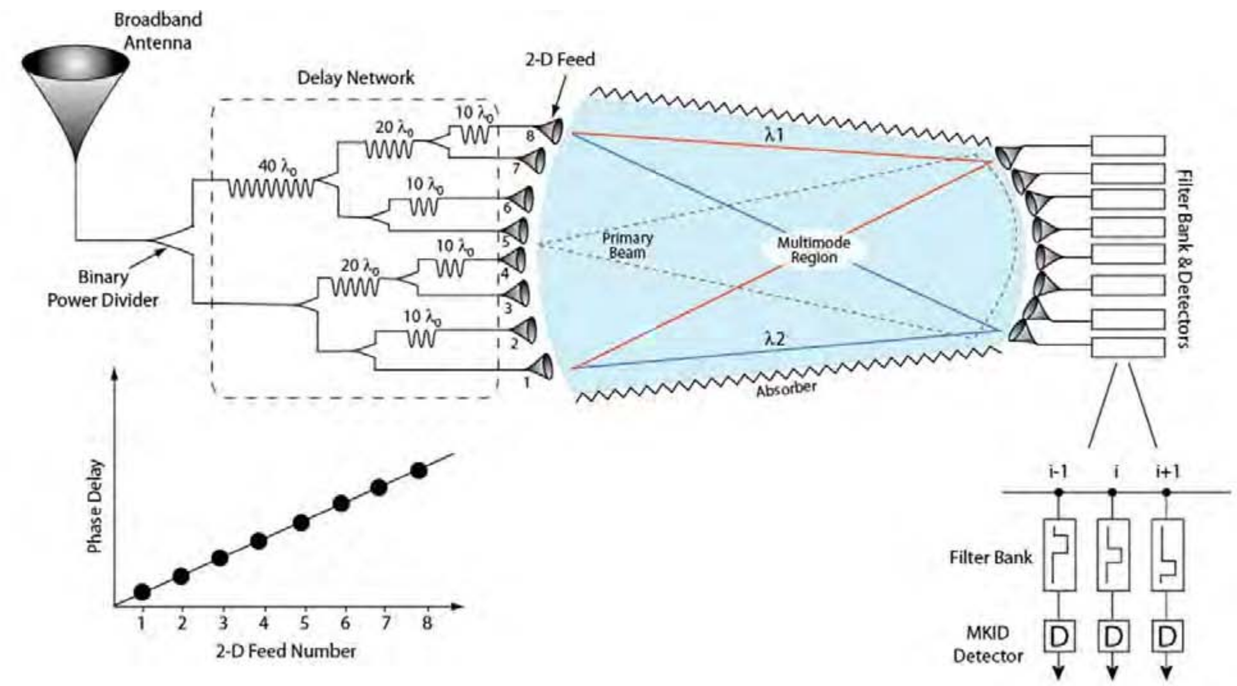
ground-based experiment to develop closed-loop, nm-level optical control of a many-element sparse array.

Major activities in FY10 included the preparation of whitepapers and other input for the Solar and Space Physics Decadal Survey and the continuation of related technology development work. Concept development will continue on a resources-available basis.

Microspec: Integrated Instruments for Submillimeter Spectroscopy

Harvey Moseley and collaborators Dominic Benford, Matt Bradford (JPL), Edward Wollack, Wen-Ting Hsieh, Jack Sadleir, Thomas Stevenson, Negar Ehsan, Kongpop U-Yen, and Jonas Zmuidzinas (Caltech/JPL) are developing fully integrated submillimeter spectrometers based on superconducting transmission lines. The approach will allow the production of spectrometers with resolving powers R~1500, which are characteristically of order 1.5 meters in scale, on a single 4" wafer. The optical system is fully integrated with its detectors, and thus the entire instrument is mass producible through photolithographic processes. This approach will bring high performance submillimeter spectroscopy within the reach of explorer-class space missions, by reducing the mass and volume of the optical system and detectors by more than five orders of magnitude.

A key enabling element for submillimeter spectroscopy in space is the development of detectors with sufficient sensitivity to reach the sensitivity limits set by background photon statistics. For a single mode input and R~1500, we will receive only ~ 100 photons per second, so detectors with noise equivalent powers (NEP) ~ 10^{-20} W/√Hz are required, about a factor of 20 better than has been achieved to date. Development is underway to produce detectors that will reach the single photon sensitivity level in the submillimeter. Photon counting offers significant benefits for implementing a practical experiment: Since we are detecting pulses, most of the signal is at high frequencies, making us much less sensitive to low frequency noise. The system can thus be DC stable without the requirement of reference measurements, resulting in increases



in observing speed of as much as a factor of four compared to power detectors.

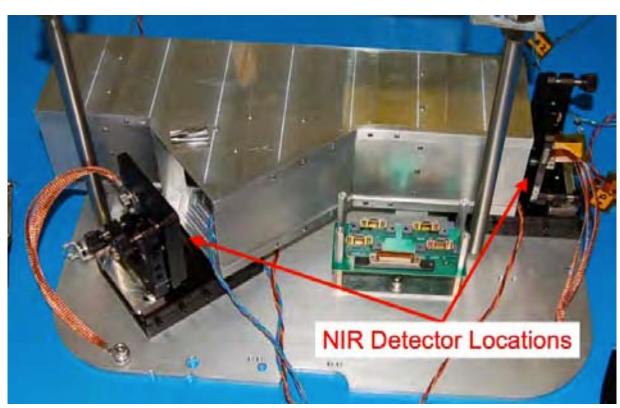
These advances, combined with rapid progress in cryocoolers, promise to open the submillimeter to spectroscopic investigation. Fine structure lines of abundant elements (C,N, S, Si, Fe, and O) and the rotational transitions of hydrides are in the mid- and far-infrared spectral bands. The opening of the submillimeter to high sensitivity spectroscopy allows us to follow the investigation of these lines into the high-redshift universe, much as JWST can follow the discoveries of HST into the higher redshift universe, and allow us to explore initial growth of galaxies and the history of element formation.

The Reionization and Transients InfraRed (RATIR) Camera

RATIR is a new optical/infrared imaging camera that will identify high-redshift Gamma-Ray Bursts (GRBs) to probe the early universe, thus shedding light on the first stars and galaxies. The project is a collaboration between UC Berkeley (PI, N. Butler), NASA GSFC, and the Universidad Nacional Autónoma de México (UNAM). The Goddard team, led by Alexander Kutyrev and supported by Co-I's O. Fox, G. Lotkin, D. Rapchun, D. Robinson, and S. Mathew, leads the design, fabrication, and construction of the infrared portion of this camera.

RATIR will provide rapid (on a few minutes timescale) photometric redshifts for all observable GRBs detected by Swift, which is not capable of measuring the redshifts for extremely distant GRBs. The primary result will be the prompt identification of very-high-redshift (VHR) bursts and potentially "dark GRBs" that are commonly believed to be at cosmological distances. These GRBs, as well as their afterglows, serve to probe the epoch of reionization and locate the first stars and galaxies. Because GRBs fade quickly, the rapid photometric redshifts are very important for selecting targets for high-resolution spectroscopic follow-up observations with large aperture telescopes.

While not all GRBs will be at high redshifts, the resulting low-redshift light curves, combined with X-ray/UV observations, will address several open



questions, including the nature of ``dark GRBs", the global evolution of dust in host galaxies, the cosmic star-formation rate, and the GRB emission mechanism. In between GRB interrupts, RATIR will support ancillary science that requires systematic long-term monitoring. Ultimately, this work will set the groundwork for future space-based missions.

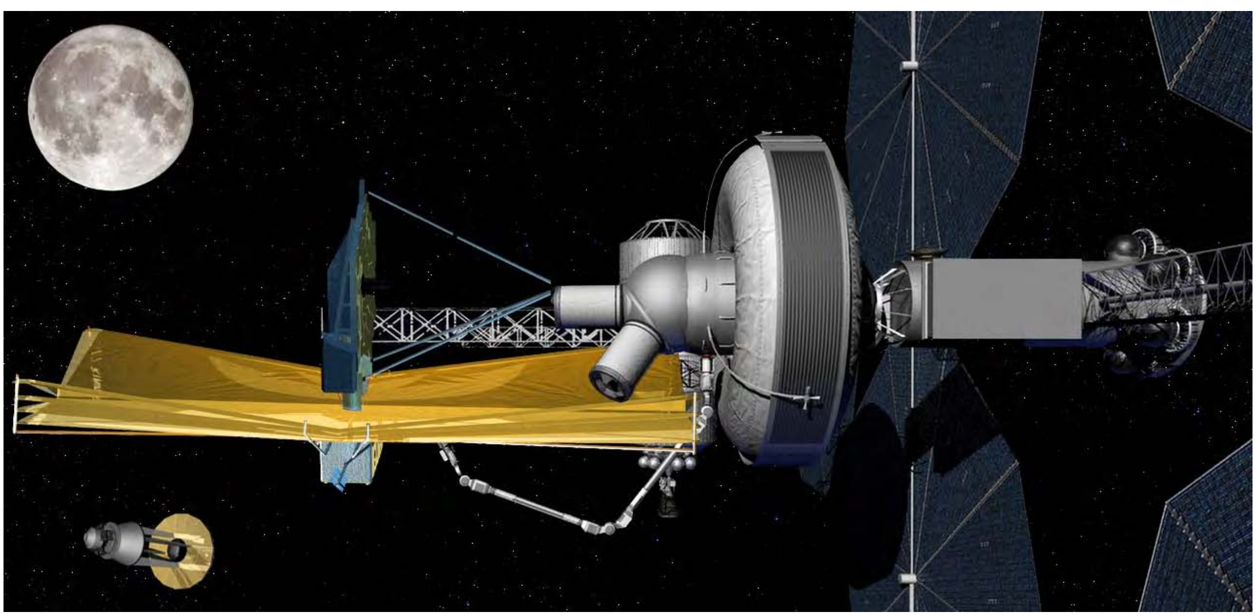
RATIR is a relatively straightforward instrument that has several unique advantages that will make it an ideal instrument for high-redshift transient photometry. First, the design includes 4 detector arms (2 optical, 2 near-infrared) capable of making simultaneous measurements. Each arm has two filters, for a total of 8 photometric bands. These simultaneous optical and infrared observations allow for the determination of the GRB's photometric redshift from the short wavelength ``dropout" caused by the opacity of line-of-sight hydrogen in the intergalactic medium. Second, the camera will be mounted on a *dedicated, fully-automated telescope* with quick response capabilities. Third, the hosting Observatorio Astronomico Nacional of UNAM, located on the Sierra de San Pedro Martir in Baja California, Mexico, is a premiere astronomical site with exceptional seeing quality (≤ 0.8 arcsec), dark skies, and a large number of dark nights, thus increasing the number of detectable Swift afterglows.

RATIR makes use of existing technology and experience at GSFC, specifically near-infrared camera heritage from projects including Spitzer, HST/WFC3 and JWST. Like JWST, the two near-infrared detectors being used are Teledyne's 2048 × 2048 pixel H2RG arrays and readout will be performed using the SIDECAR (System Image, Digitizing, Enhancing, Controlling, and Retrieving) ASICs (Application-Specific Integrated Circuits).

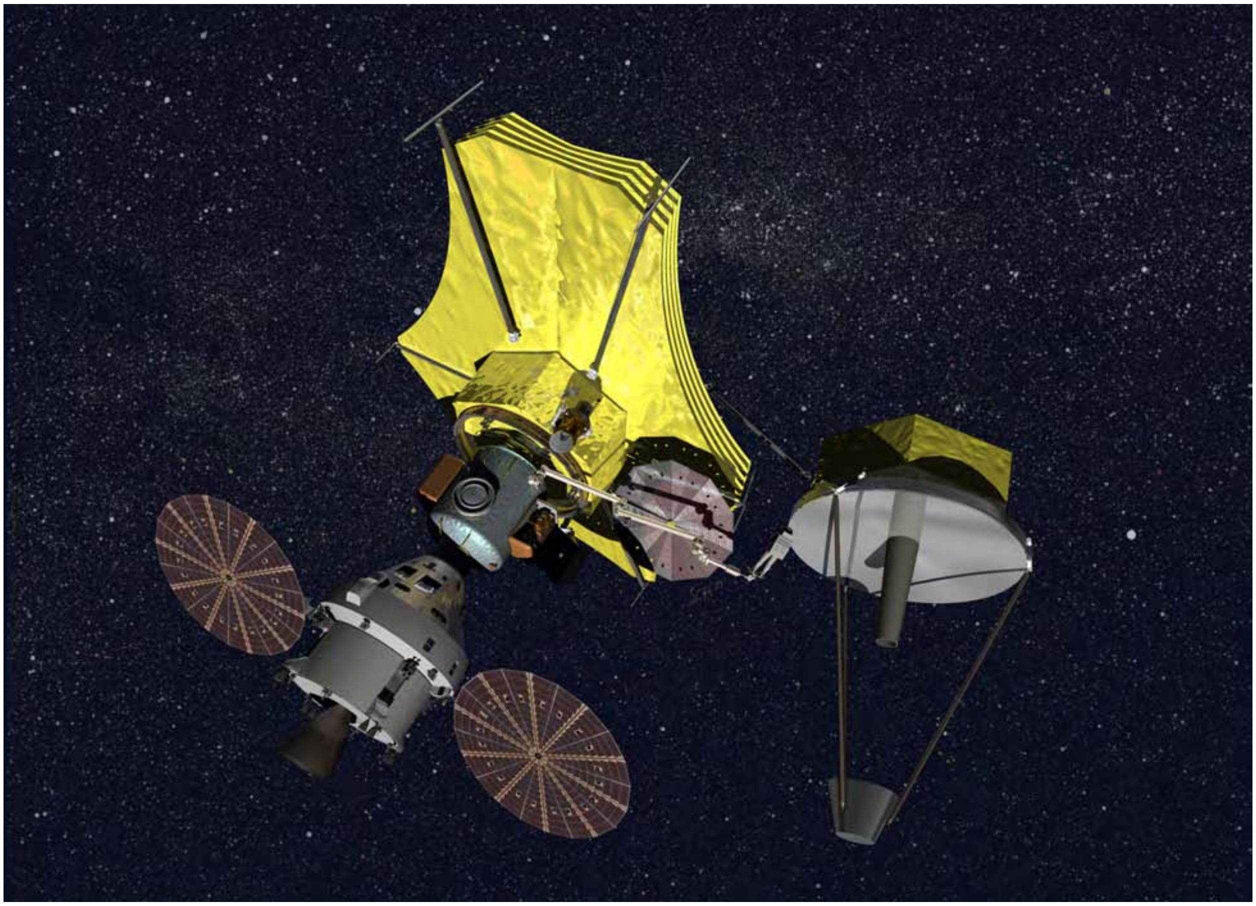
Currently, the detector part of GSFC's infrared camera design and fabrication is nearly complete. The detector assembly mount has completed several cooldowns to its operating temperature at 80 Kelvin. The detectors and readout electronics have been fully integrated and tested at room temperature. In the coming weeks, GSFC plans to perform a final integration and testing of the detector part of the camera at cryogenic temperatures, followed by an alignment of the infrared optics. Simultaneously, the visible cameras are being assembled at Berkeley and are being integrated with software designed to run both the visible and IR cameras. A final integration of the optical and infrared cameras is expected to take place in Spring 2011, followed by commissioning of the instrument in the early Summer.

Human Operations Beyond Low-Earth Orbit to Assemble and Upgrade Large Optical Systems

NASA's human space flight program, although with continuing significant uncertainty in its goals and priorities, consistently identifies operations in free space



Long-duration "Gateway" habitat concept at the Earth-Moon L1 location and the repair and upgrade of a pair of large optical systems in the mid-2020s.



Concept developed in 2009 for an Orion-like crew vehicle, sent to the Earth-Moon L1 venue via a pair of Delta IV Heavy-class vehicles, to repair and upgrade a post-JWST observatory.

beyond low-Earth orbit (LEO) as a priority. Whether as a staging site for long-duration voyages beyond the Earth-Moon system, supporting human and robotic exploration of the lunar surface, or advancing technologies developed on the International Space Station (ISS), continued human operations in free space have been recommended to NASA for decades as a major enabling capability.

Dr. Harley Th ronson continues to lead a small working group of scientists and engineers at Goddard, other NASA Centers, and in industry, which has for several years been developing concepts for how equipment and facilities developed for human space flight might be used to achieve other goals. Such work has a long history at Goddard: In the early 1970s, Frank Cepollina and colleagues persisted in advocating that the space shuttle be adapted to service and upgrade satellites in LEO. This was almost two decades before Cepollina's team used the shuttle to rescue NASA's premier astronomical observatory. Vision and perseverance eventually pays off!

A few years ago, Thronson and his team assessed a concept that used a pair of launch vehicles then under development by the erstwhile Constellation Program. The goal was a mission to take astronauts to the Earth-Moon L1 venue for a two-week upgrade or rescue of a post-JWST observatory in the mid-2020s.

This past year, Thronson's team took on the more ambitious task of designing a long-duration human habitation system for either the L1 or L2 Earth-Moon location. Its primary purpose would be to develop capabilities necessary for safe and comfortable human operations beyond LEO in the 2020s. A major goal for this habitat—dubbed a "Gateway" by its designers—is to support lunar surface operations, either with astronauts or with robots. However, in addition, the capability to repair, assemble and upgrade complex science facilities, including large optical systems, is also under consideration.

ISS as a Testbed for Future Complex Optical Systems

Large and complex space optical systems that may be launched in the 2020s and 2030s will be necessarily much larger than this decade's James Webb Space Telescope. It is likely, therefore, that such missions will require assembly on orbit and may, in addition, be enhanced by subsequent upgrade and servicing. However, whether such challenging tasks are carried out via robots or astronauts—or a combination of both—the required capabilities do not now exist.

Dr. Harley Thronson is leading a small group of GSFC scientists and engineers that is working with colleagues at the Jet Propulsion Laboratory and NASA Johnson Space Center to assess the International Space Station (ISS) as a long-term testbed to develop the capabilities to use astronauts and robots to enable future very large optics. The team has proposed to spend several months this coming year carrying out trade studies, designing basic optical configurations, and exploring simple concepts of operations using the ISS. This activity is intended to evaluate in some depth the opportunities and challenges of using ISS as a site where complex astronaut and robot assembly operations can be evaluated.

Although significant design work still needs to be carried out, the basic notion is to launch to ISS over the course of a few years the components of a modular optical system, including a basic control system and instrument. Astronauts and/or robots would then be used to assemble, test and upgrade the system over a few years. The team intends also to explore whether purely autonomous deployment/assembly would be more cost-effective than using external human or robotic agents.

Concept for a few-meter modular optical system facility, after assembly on the International Space Station.

The resulting optical system on ISS would be capable at best of very limited observations and a very preliminary schedule indicates that it will not be completed until about 2020. Even so, the knowledge and experience gained by attempting the construction and servicing of large, precise structures will be essential in enabling very ambitious optical systems in space in future decades.

Education and Public Outreach in NASA's Astrophysics Science Division

The Astrophysics Science Division supports a strong and vibrant Education and Public Outreach (E/PO) program, encompassing activities in formal education, informal education and outreach. The E/PO team supports various NASA astrophysics missions and programs, including HEASARC, Webb, Suzaku, GEMS and Astro-H. The team also supports broader E/PO efforts that are not mission specific and that cover ASD science and technology. Dr. James Lochner (CRESST/USRA) leads the team.

Afterschool Universe (AU) continues to expand its network of trained providers who run this 12-unit afterschool program in local communities, as well as its network of certified trainers from around the country. Sarah Eyermann (SP Systems, Inc.), Sara Mitchell (SP Systems, Inc.), and Anita Krishnamurthi (Afterschool Alliance) ran three regular local trainings through the year and a "train the trainer" workshop in December. This training was run as part of an Education and Public Outreach for Earth and Space Sciences (EPOESS) grant which the team was awarded last year. In attendance were 30 members of the nationwide afterschool community from a total of 13 different states. They will provide training on *Afterschool Universe* in their communities and work with the AU team and professional evaluator Dr. Allyson Walker (Cornerstone Evaluation Assoc.) to collect data on the effectiveness of the "train the trainer" model over the next two years.

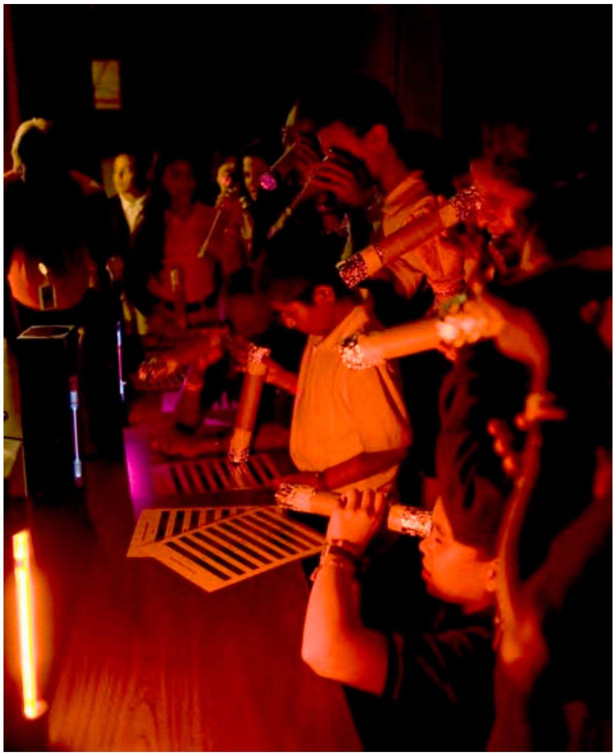
The *Big Explosions and Strong Gravity* (BESG) program, directed by Ann Hornschemeier (GSFC) and Sarah Eyermann (SP Systems Inc.), was broadly expanded this year. This is a one-day event where Girl Scouts aged 11 to 13 meet real scientists and join them for a day of hands-on exploration into supernovae and black holes. April marked the fifth time the program had been run locally with the Girl Scouts of Central Maryland. In July, Sarah Eyermann, along with Sara Mitchell (SP Systems Inc.) and intern Faith Tucker, ran an intensive training for 19 participants from 17 Girl Scout councils around the country. These trainees will share the program with neighboring councils, as well as bring it to their own.

In 2010, *Blueshift* grew from a podcast to a broader new media and social media effort for ASD outreach, led by Sara Mitchell (SP Systems, Inc.). Throughout the year, the Blueshift team and guest bloggers provided a "behind the scenes" look at ASD science, missions, discoveries, and people, as well as coverage of other relevant content. Besides blogging, Blueshift also grew a large audience through Twitter and Facebook, and interacted directly with followers through social media. In September 2010, members of the Blueshift team visited Warner Brothers Studios in Burbank, Calif., to photograph the WMAP beach ball on the set of the popular CBS comedy, "The Big Bang Theory." Their visit generated a great deal of publicity for Blueshift and ASD EPO, culminating in a NASA web feature that was picked up by news outlets worldwide.

The ASD E/PO team supported the GSFC Office of Education's "Middle School Week" in October. Jim Lochner, Sarah Eyermann (SP Systems), and Sara Mitchell (SP Systems) led hands-on activities for approximately 200 area middle-schoolers two of the days. In the 20-minute Astrophysics activity, these middle-school students learned about the elemental composition of the universe, and how we learn what stuff in space is made of. In addition, a number of ASD scientists had lunch with the students during the week, sharing their experiences as scientists.

The Family Science Night, co-run by Sara Mitchell (SP Systems, Inc.) of the Astrophysics Science Division and Emilie Drobnes (ADNET) of the Heliophysics Science Division, wrapped up its four-year pilot effort in June 2010. The project then moved into its dissemination phase for the final year of ROSES EPO grant funding, recruiting several sites around the country to run the program locally and refining the facilitator's guide for nationwide release.

The James Webb Space Telescope E/PO team has participated in several high-profile and high-impact activities and events in 2010. This year's RealWorld/InWorld NASA Engineering Design Challenge (partnering with the National Institute of Aerospace, *USA Today*, and LearnIt TeachIt) is focused on Webb. This project targets students in grades 9–12 and encourages them to explore and build skills essential for successful science, technology, engineering and mathematics (STEM) careers through two phases of project-based learning and team competition. This challenge invites high school students to work cooperatively as engineers and scientists to solve real-world problems related to the Webb telescope. There is a classroom part to the challenge, as well as a virtual portion; Todd Toth (GSFC Educ. Office/IPA), Maggie Masetti (ADNET),



Students examine spectral lamps during Middle School Week.

and Amber Straughn (Oak Ridge Assoc. Univ.) were involved in this project. In June, the Webb full-scale model was on display for a week at the World Science Festival in New York City, with Lynn Chandler (GSFC/PAO), Amber Straughn, and Todd Toth helping to run activities for the public, and scientists and engineers staffing an "Ask A Scientist" booth. Webb received significant pop-culture exposure in 2010, with an 8-minute "Hubble Gotchu" clip on Late Night with Jimmy Fallon, as well as Webb products appearing on the set of the popular CBS sitcom "The Big Bang Theory." Maggie Masetti (ADNET) maintains the Webb team's active web site and high-profile social media presence.

George Gliba (Syneren Technologies) and Todd Toth supported the installation of a 12-inch Meade Go To SCT telescope to the Maritime Industries Academy High School in Baltimore City. Gliba and Toth helped the academy start an astronomy club, and gave suggestions on how to use their newly donated telescope with students to observe the heavens. The telescope was dedicated at the school in May 2010, during which several dignitaries spoke, including the GSFC Center Director, Mr. Rob Strain, the GSFC Director of Education, Dr. Robert Gabrys, Dr. Frederick Tarantino (Pres./CEO USRA), U.S. Representative Elijah Cummings, and Mr. Robert Taylor and Mrs. Vicki Taylor, who donated the telescope.

The ASD E/PO group continues to utilize its Facebook and Twitter accounts to publicize its activities. Barbara Mattson (ADNET) features the High Energy Astrophysics Picture of the Week, division press releases, mission news, and teacher workshops. Our Facebook page has 2500 "likes," a growth of more than 2,000 over the year. Our Twitter account has 310 followers, which doubled over the year.

Barb Mattson uploaded video segments from the award-winning Suzaku educational DVD, "Building the Coolest X-ray Satellite" to YouTube. The available videos include full chapters from the DVD as well as shorter clips that can be embedded into web pages or used in classrooms. The videos are currently available on the Collaboration Across the Globe YouTube (http://www.youtube.com/nasaglobalastro) and TeacherTube channels. The videos have more than 2,500 views on YouTube and over 600 on TeacherTube.

HEASARC E/PO

The HEASARC E/PO program continues to fulfill its mission to bring the science of high-energy astrophysics and cosmology to teachers and their students. In 2010 Drs. James Lochner (CRESST/USRA) and Barbara Mattson (ADNET) concluded their "New Media for Cosmic Times" project, working with a local high school media production club. The students wrote and produced their own videos about Einstein and recorded audio segments on topics related to the 1955 Cosmic Times. Evaluation of the materials revealed that the learning opportunities occur for students producing the videos rather than for students watching the videos. The HEASARC has also continued to distribute the Cosmic Times materials and to do workshops on Cosmic Times at local, regional and national teacher conferences. Most significantly, Lochner and Mattson presented a short course on Cosmic Times to the fifteen Astrophysics Educator Ambassadors at Sonoma State University. These EAs do their own workshops around the country on NASA astrophysics education materials.

As part of his Education and Public Outreach for Earth and Space Sciences (EPOESS) grant, Dr. Lochner produced the 14th edition of the Imagine the Universe! DVD-ROM in 2010, featuring the websites for Imagine, StarChild and Cosmic Times, as well as the 2009 collection of Astronomy Picture of the Day. In addition, working with our evaluator, Dr. Allyson Walker (Cornerstone Evaluation Assoc.), Dr. Lochner conducted a survey of users and found that the predominant respondents are teachers who use it as a resource for student enrichment and to supplement their curriculum. More than half of the users utilize three or more of the sites on the DVD. Seventy percent of the users own more than one of the annual editions (most likely for the APODs). Despite the availability of the sites on the web, users of the Imagine! DVD-ROM value it because they do not need an Internet connection to share/view the sites with others. The report also gave suggestions for additional audiences we might further expand into (such as homeschoolers and museums).

LAMBDA is also serving WMAP data in a variety of formats of interest to the education and outreach communities. For example, the seven-year sky maps are available in Google Sky and have been ported to Science on the Sphere displays in many science museums around the world.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-03-2011

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Goddard's Astrophysics Science Division Annual Report 2010

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Joan Centrella and Francis Reddy, Editors

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Astrophysics Science Division
NASA Goddard Space Flight Center

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA/GSFC

11. SPONSORING/MONITORING REPORT NUMBER
TM-2011-215870

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited, Subject Category: 90
Report available from the NASA Center for Aerospace Information, 7115 Standard Drive, Hanover, MD 21076. (443)757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Astrophysics Science Division (ASD) at Goddard Space Flight Center (GSFC) is one of the largest and most diverse astrophysical organizations in the world, with activities spanning a broad range of topics in theory, observation, and mission and technology development. Scientific research is carried out over the entire electromagnetic spectrum—from gamma rays to radio wavelengths—as well as particle physics and gravitational radiation. Members of ASD also provide the scientific operations for three orbiting astrophysics missions—WMAP, RXTE, and Swift, as well as the Science Support Center for the Fermi Gamma-ray Space Telescope. A number of key technologies for future missions are also under development in the Division, including X-ray mirrors, space-based interferometry, high contrast imaging techniques to search for exoplanets, and new detectors operating at gamma-ray, X-ray, ultraviolet, infrared, and radio wavelengths. The overriding goals of ASD are to carry out cutting-edge scientific research, provide Project Scientist support for spaceflight missions, implement the goals of the NASA Strategic Plan, serve and support the astronomical community, and enable future missions by conceiving new concepts and inventing new technologies.

15. SUBJECT TERMS
Astronomical instruments and techniques; radio, gamma-ray, X-ray, ultraviolet, infrared astronomy; cosmology; particle physics; gravitational radiation; celestial mechanics; space plasmas; and interstellar and interplanetary gases and dust.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19b. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			William Oegerle
Unclassified	Unclassified	Unclassified	Unclassified	112	**19b. TELEPHONE NUMBER** ***(Include area code)*** (301) 286-8801