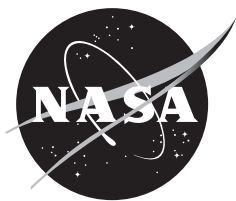
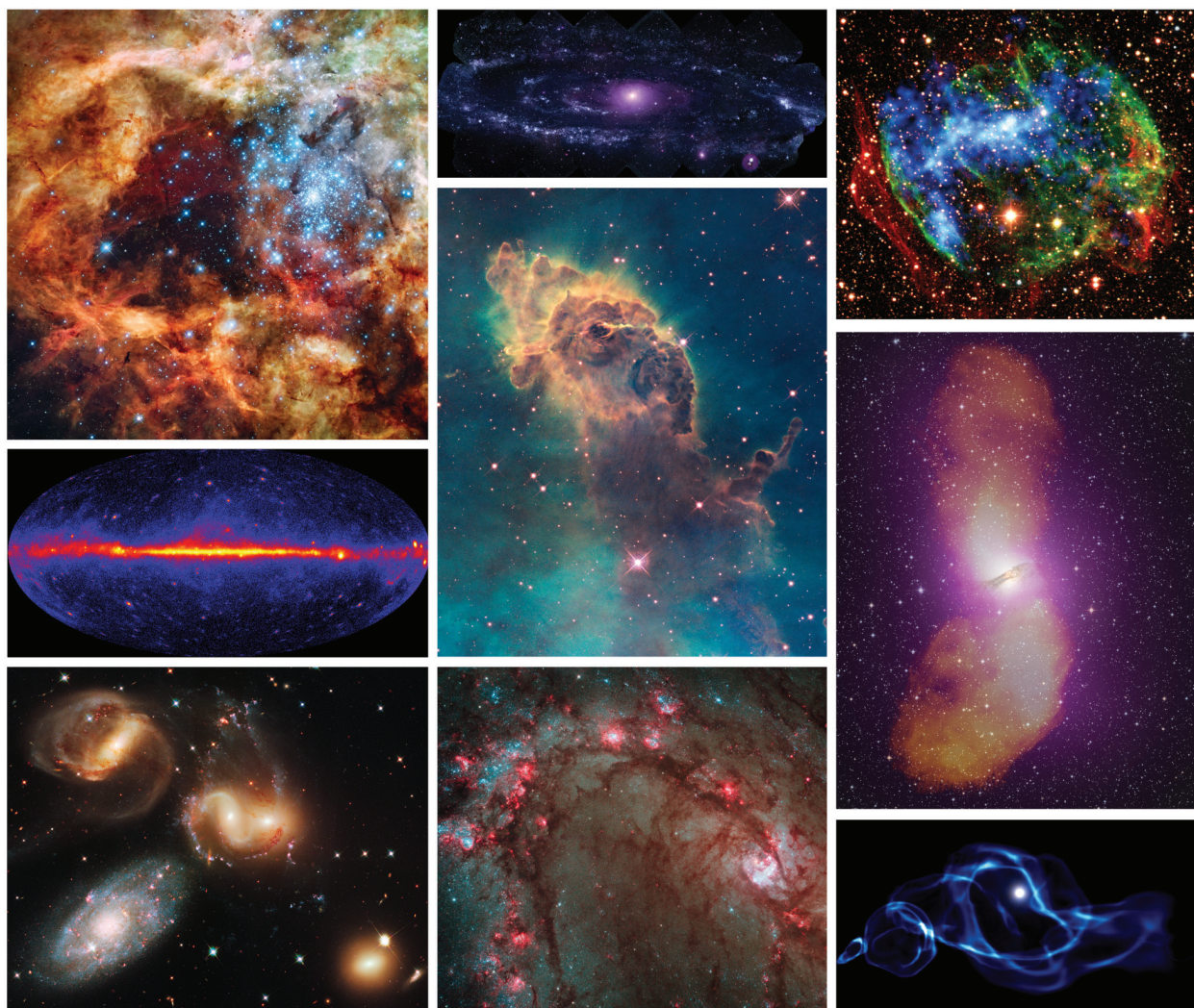


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# The Astrophysics Science Division Annual Report 2009

*William Oegerle and Francis Reddy, Editors*  
*Pat Tyler, Graphical Editor*



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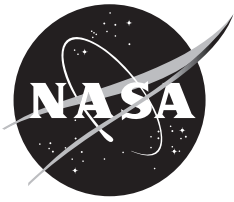
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## The Astrophysics Science Division Annual Report 2009

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## Introduction

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.

ASD has a strong suborbital research program, with four balloon programs and three sounding rocket programs at present. The Division also supports research in the astronomical community through the High Energy Astrophysics Science Archive Research Center (HEASARC), which now also contains Cosmic Microwave Background data, as well as support services for observers using the Fermi, Suzaku, Integral, XMM-Newton, GALEX, RXTE, WMAP, and Swift missions. Finally, ASD has a strong Education and Public Outreach program, to convey the exciting discoveries from NASA missions to school teachers, students, and the public.

ASD staff includes 365 people, most of whom are scientists and engineers, along with a support staff of software programmers, resource analysts, and administrative personnel. There are about 80 civil servant scientists, and a much larger number of contractor and university-based scientists. Several dozen postdoctoral fellows and graduate students are also in residence.

Organizationally, there are five laboratories within ASD: the Astroparticle Physics Lab (code 661; Neil Gehrels, chief); the X-ray Astrophysics Lab (662; Rob Petre, chief); the Gravitational Astrophysics Lab (663; Joan Centrella, chief); the Observational Cosmology Lab (665; Jonathan Gardner, chief); and the Exoplanets and Stellar Astrophysics Lab (667; Jennifer Wiseman, chief). Alan Smale heads the High Energy Astrophysics Science Archive & Research Center (HEASARC) Office, Phil Newman heads the Office of Scientific Computing, and Felicia Jones-Selden leads the Instrument Development Group. Division management includes William Oegerle (Director), Felicia Jones-Selden (Deputy), Curtis Odell (Assistant), Kim Weaver (Associate for Science), and Harley Thronson (Associate for Advanced Concepts).

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.

William Oegerle  
Director, Astrophysics Science Division  
NASA Goddard Space Flight Center



## I. 2009: Year in Review

The year 2009 was an amazing year in ASD, one that saw the culmination of decades of work in the smashing successes of the first year of operation of the Fermi Gamma-ray Space Telescope and the rebirth of the Hubble Space Telescope with Servicing Mission 4. It was also a year of new beginnings with the selection of Gravity and Extreme Magnetism (GEMS) as NASA's next astrophysics Small Explorer. In a look to the future, we expended significant effort to support many teams in the preparation of their mission concept studies to the National Academy's Astro2010 Decadal Survey of Astronomy.

Fermi was launched in mid-2008, and initial science results were already coming out by the end of 2008, but the tidal wave of results did not begin until 2009. Twelve NASA Press releases containing Fermi results were issued in 2009, on a wide-variety of topics: discovery of the most extreme gamma-ray burst ever, release of an all-sky map of gamma-ray sources, observations of flaring active galactic nuclei and blazars, and setting limits on the constancy of the speed of light at different frequencies. A symposium dedicated to the new results from Fermi was held in Washington, D.C. in November 2009, with many scientists from ASD involved in the organization. The event was celebrated by an original music composition ("Cosmic Reflection") and performed at the Kennedy Center for the Performing Arts (see [www.classicalarchives.com/CR](http://www.classicalarchives.com/CR) for more).

After many years of preparation and waiting, HST Servicing Mission 4 finally took place in October 2009. Unless you have been at the far reaches of the Earth, you probably know that this was a phenomenal success—with the installation of WFC3, COS, and the repair of ACS and STIS. The Hubble Project Scientists in ASD (Leckrone, Niedner, Kimble, Carpenter, and Rinehart) were involved for many years in preparation for SM4 and deserve our thanks and recognition for their efforts. A much longer description of the new upgraded Hubble appears later in this document in the "Operating Missions" section.

GEMS (Jean Swank, PI) was selected as a SMEX in June 2009. GEMS will open up a new frontier in astrophysics through its high sensitivity in measuring

the polarization of X-rays. GEMS observations will reveal how spinning black holes affect space-time as matter is drawn in and compressed by strong gravitational fields, what happens in the super-strong magnetic fields near pulsars and magnetars, and how cosmic rays are accelerated by shocks in supernova remnants. The GEMS instrument is being built at GSFC, and there are many ASD scientists involved in the mission and its science (Jahoda, Deputy PI; Kallman, Deines-Jones, Angelini, Hill, Petre, Strohmayer, Serlemitsos, Morris, Soong, and Black). GEMS will launch in 2014.

Significant progress was made during the year on our Soft X-ray Spectrometer (SXS) instrument for the Astro-H mission. Rich Kelley is the SXS PI. SXS combines a lightweight Soft X-ray Telescope (SXT) paired with an X-ray Calorimeter Spectrometer (XCS), providing non-dispersive 7 eV resolution in the 0.3–10 keV bandpass. SXS passed its Key Decision Point-B review in June 2009, allowing the project to enter Phase B. In addition, NASA has accepted a proposal from the team for a "Science Enhancement Option" that will set up a General Observer program to support U.S. scientists. A Guest Observer Facility will be created at GSFC to develop data analysis software, observing support tools and provide GO funding to the community. Astro-H will launch in ~ 2014.

Significant progress is being made in the area of X-ray optics. We are producing the mirror substrates for the NuSTAR SMEX (Harrison, PI), and this is going extremely well—the mirror shapes are better than required. Will Zhang also continues to make excellent progress on glass mirrors for IXO, and so far the limit has been set only by the quality of the mandrels. So, we have optimism that the IXO requirement of ~3 arcsec (half-power diameter) mirrors is attainable.

Significant effort was expended during the year to support requests for information from the Astro2010 Decadal Survey, largely for the strategic missions LISA, IXO, JDEM, EXIST, and ATLAST (a concept for the next-generation large-aperture UVOIR telescope to succeed HST and JWST). Most of the work was completed by August 2009, and then we settled in for the long wait for the final report of the Decadal Survey, to be released in September 2010.



The LISA group (Centrella, Baker, Stebbins, Camp, Livas, Merkwowitz, and Thorpe) continues to develop technologies for that mission. Thorpe is involved in the ESA LISA Pathfinder mission data analysis. This mission will launch in ~2012 to retire some LISA technology risks. Centrella and Baker have begun a new initiative to compute the electromagnetic signatures from merging black holes. Steve Merkwowitz began a detail to OSTP in Fall 2009.

During the year, we did receive one piece of disappointing news—cancellation of our SAFIRE instrument (Moseley, PI) being built to fly on SOFIA. There were no technical reasons for the cancellation; it was solely due to tight budgets in the SOFIA project. The team continues to develop state-of-the-art far-IR instrumentation and looks forward to future opportunities on SOFIA or other missions.

ASD scientists continue to support the development of the James Webb Space Telescope (Mather, Gardner,

Clampin, Greenhouse, Rauscher, Bowers, Kimble, and Sonneborn). The first pieces of hardware for the Instrument module began arriving at Goddard in Fall 2009. We are delivering the NIRSpec detectors and the NIRSpec microshutter assembly to ESA in 2010. Please see the full description of JWST activities in the “Missions Under Development” section later in this document.

In 2009, several ASD scientists were selected to serve on important NASA advisory committees or working groups. Aki Roberge has been appointed to the Exoplanetary Program Analysis Group (ExoPAG). This group reports to the NASA Advisory Committee (NAC) astrophysics subcommittee (APS). Sally Heap serves on the APS. Dominic Benford has recently been selected to serve on the JDEM Interim Science Working Group (ISWG). This working group will advise the JDEM Project on mission concept design and science requirements.

## II. Research

*A few representative research programs in ASD are described below.*

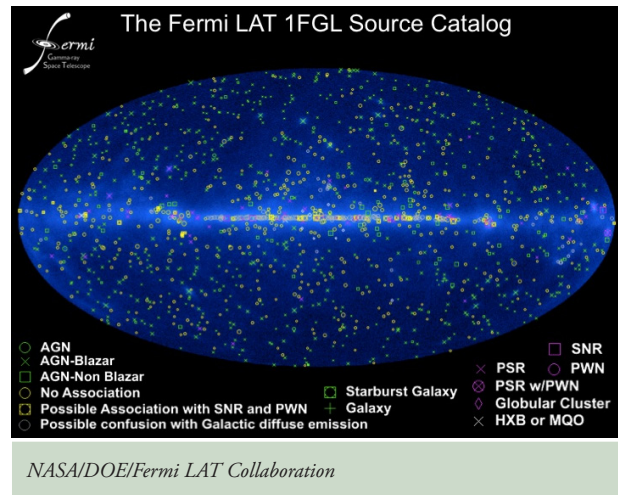
### The Persistent Gamma-ray Sky

Astronomical catalogs are resources that enable scientific discovery, and the first catalog from the Large Area Telescope on the Fermi Gamma-ray Space Telescope is no exception. Based on the first eleven months of data, the 1FGL (Fermi Gamma-ray LAT) catalog contains 1,451 sources, more than five times the number in the third EGRET catalog. The catalog emphasizes the growing diversity of gamma-ray source classes. Some features:

- Although blazars are the largest source class, there are non-blazar Active Galactic Nuclei seen, including radio galaxies and radio-loud narrow-line Seyfert 1 galaxies.
- Pulsars now encompass not only energetic young pulsars, but also millisecond pulsars and pulsars discovered in blind searches of the LAT gamma-ray data.
- New source classes include high-mass X-ray binaries, supernova remnants, globular clusters, and starburst galaxies.

Gamma rays from pulsar wind nebulae (PWNe) and supernova remnants (SNR) are particularly important in revealing sites of particle acceleration to high energies in our Galaxy. The Crab PWN spectrum from the LAT now extends to high enough energies to overlap with ground-based TeV observations, confirming that this inverse Compton emission arises from energetic electrons and is ultimately powered by the spin-down energy loss of the Crab pulsar. The Vela PWN, by contrast, shows that the electrons producing the GeV LAT emission must be a different population from the ones producing the TeV emission, with the LAT emission linked to the radio synchrotron radiation and the TeV-producing electrons related to those that produce the X-rays.

At least three SNR are now seen as spatially resolved sources by the LAT, with morphology and energy spec-



tra indicating that these SNR are, as long expected, sites of proton cosmic-ray particle acceleration. The gamma rays come from the energetic protons interacting with gas clouds near the SNR.

On a much larger scale, detailed observations of the Large Magellanic Cloud and of two starburst galaxies illustrate the importance of gamma-ray observations for studies of star-forming regions. The emission from the LMC is concentrated near the 30 Doradus region, known as a site of intense star-forming activity. Starburst galaxies M82 and NGC253 would not be visible to LAT unless their production of cosmic rays is much stronger than seen in our own galaxy. This cosmic-ray excess is directly connected to the high rate of star formation that gives starburst galaxies their name.

Equally interesting are some of the mysteries that emerge from the 1FGL work:

- Why are clusters of galaxies not seen, when several models predicted gamma radiation from such sources?
- Why do many of the unidentified EGRET sources not appear in the LAT analysis?
- What is the nature of the more than 600 1FGL sources with no clear associations with objects seen at other wavelengths?

Multiwavelength studies of many of these gamma-ray sources should help extend results on known source classes and answer the questions raised by the catalog.

## The Transient Gamma-ray Sky

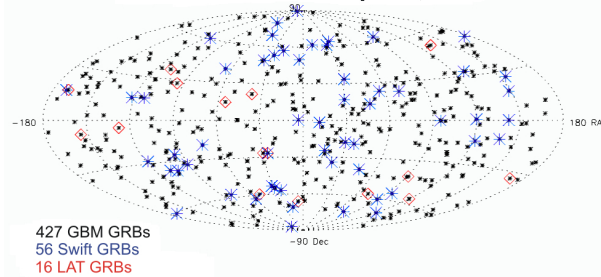
The study of gamma-ray bursts (GRB) and other short-duration transients combines the power of both instruments on Fermi. Observations with the Large Area Telescope (LAT) have more than tripled the number of bursts detected above 100 MeV. The Gamma-ray Burst Monitor (GBM) ties the frontier high-energy LAT observations to the better-known properties at lower energies by providing light curves and spectra from 8 keV to 40 MeV.

**High-energy gamma-rays seen by LAT always continue for a longer time than the low-energy gamma-rays, in some cases exhibiting behavior that is reminiscent of the afterglows observed in the radio, optical, and X-ray bands.**

There is a saying that “when you have seen one gamma-ray burst, you have seen one gamma-ray burst.” In other words, that each one exhibits quite unique properties. Interestingly, this has not been the case for the high-energy gamma-ray behavior being explored in detail for the first time by the Large Area Telescope (LAT) on Fermi. The onset of the LAT emission above 100 MeV consistently lags that of the GBM and the brightest LAT-detected gamma-ray bursts all show evidence of a distinct additional spectral component (indicating a distinct emission mechanism). This may naturally suggest that the high-energy gamma-rays could be produced by a population of relativistic protons, which compared to the electrons responsible for producing the soft gamma-rays, have a longer acceleration time. This would explain both the time delay and the separate spectral component. We may be getting closer to the holy grail of identifying extragalactic sources of high-energy cosmic-ray acceleration.

An additional common theme is that the high-energy gamma-rays seen by LAT always continue for a longer time than the low-energy gamma-rays, in some cases exhibiting behavior that is reminiscent of the afterglows observed in the radio, optical, and X-ray bands. The presence of high-energy photons ( $> \sim 30$  GeV) observed by LAT during the afterglow phase is extremely challenging to explain with conventional synchrotron

Fermi GRBs as of April 6, 2010



Map of the sky in celestial coordinates showing the locations of the GBM-detected gamma-ray bursts, as well as those detected by Swift and LAT.

models, as it would require a huge bulk Lorentz factor, high upstream magnetic fields, and extremely efficient particle acceleration. These observations may require us to change our thinking of emission mechanisms during GRB afterglow. Simultaneous multiwavelength observations, which so far we have had only with GRB090510, will be needed to understand the physical conditions and emission mechanisms in this phase of the GRB.

Of course, the most unique feature of the LAT observations is the detection of high-energy photons (typically up to around 30 GeV). The dominant absorption process for high-energy gamma-rays is pair production with lower-energy photons. The degree of attenuation depends on the density of lower-energy photons, which appears enormous in GRB. If we can detect these high-energy photons, then the physical conditions in the emission region must be such that the photons can escape. This implies a constraint on the density of lower-energy photons, which in turn implies a lower limit on the bulk relativistic motion (so that the photon flux in the rest frame of the source is lower than that inferred from the observer frame observations). The lower limits on the bulk Lorentz factor for LAT-detected bursts are very high ( $\rightarrow 1000$ ) for both long- and short-duration GRB, suggesting that the short bursts are just as highly relativistic as long ones—an open question prior to Fermi’s launch.

The very high photon energies, large distances, and short durations of gamma-ray bursts makes them unique probes of some properties of intergalactic space. By looking for differences in the arrival times of high- and low-energy gamma-rays, we can set constraints on the constancy of the speed of light. The

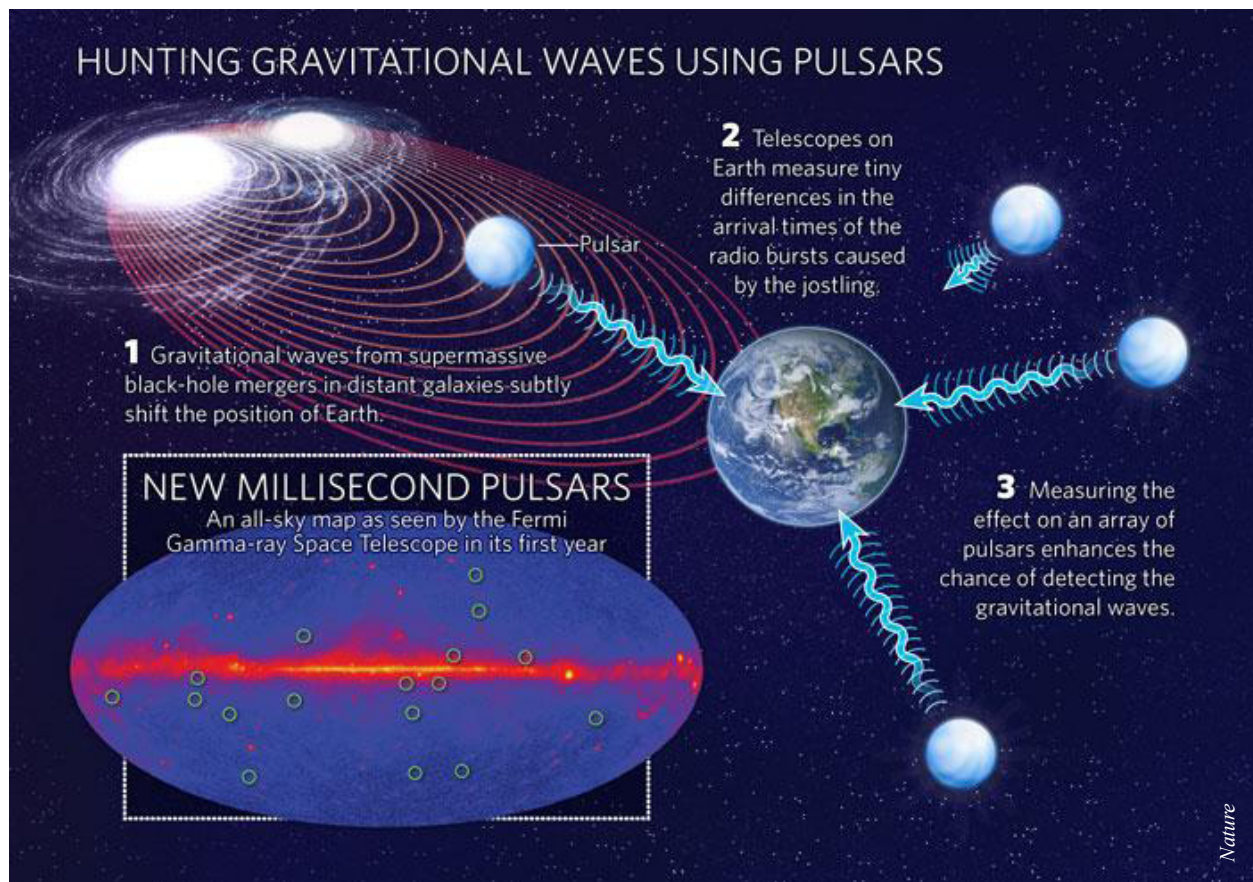


very large distances to GRB mean that even small changes in the photon propagation speed may result in measurable delays. The very high photon energies make this constraint interesting because some models of quantum gravity allow an energy-dependent speed of light of the form:  $v_{ph} = c - E_{ph}/M_{QG}$ , where  $M_{QG}$  is expected to be less than or equal to the Planck mass of ( $2.43 \times 10^{18}$  GeV/c<sup>2</sup>).

The highest-energy photon in GRB 090510 arrived in time with the low-energy gamma-rays, so no evidence of dispersion. This photon arrived 900 ms seconds after the onset of the GRB. The redshift (and thus distance) of the GRB was known from optical spectroscopic observations of the GRB afterglow to be 0.9. By making an assumption that the high-energy photon could not have been produced before the GRB started, we can set a constraint on the maximum time delay (900 ms) and thus obtain a lower limit on  $M_{QG}$ , which exceeds the Planck mass and thus rules out a family of quantum gravity models. Lorentz invariance is not violated. Einstein still rules.

### Pulsar Discoveries with Fermi

Since its launch in June 2008, discoveries of new gamma-ray pulsars by the Fermi Gamma-Ray Space Telescope have increased the population by a factor of 10. The pulsed emission from rotation-powered pulsars, which are compact neutron stars spinning with periods between a few milliseconds and several seconds, is dominant at gamma-ray energies and such pulsars are the most numerous gamma-ray sources in our galaxy in the GeV (billion electron-volt) band. Since there were previously only seven rotation-powered pulsars known to produce pulsed gamma rays, this will produce a huge leap in our understanding of pulsar physics. Of the 62 currently detected gamma-ray pulsars, 24 have been discovered through a blind frequency search using Fermi data alone; the rest were discovered using radio or X-ray ephemerides. Since only three of these have subsequently been found to also be weak radio pulsars, the majority are thought to be either radio-quiet or radio-weak.



A surprisingly large number of the new gamma-ray pulsars (15) have millisecond rotation periods, part of a population of “recycled” pulsars that have been spun up by accretion of matter from a binary companion. The first nine gamma-ray millisecond pulsars (MSPs) were found by use of radio timing solutions. More recently, new millisecond pulsars have been discovered through radio searches at the locations of unidentified Fermi sources. To date, 18 MSPs have been discovered in this way, with the expected gamma-ray pulsations having been detected from five of them using the derived radio ephemerides. It is expected that all of these will turn out to show gamma-ray pulsations when their radio timing solutions are in hand. Since most of the new MSPs are in binary systems, the gamma-ray pulsations would be impossible to find with blind search alone. In fact, a sizeable number (at least 4–5) are in “Black Widow” systems, where the MSP wind is ablating its companion.

Beyond their importance for understanding pulsar emission, these new MSPs will aid in the direct detection of the stochastic gravitational wave background due to merging black holes. Those that achieve radio timing to less than 100 ns accuracy will become part of the MSP timing arrays that may make the first direct detection of gravitational waves.

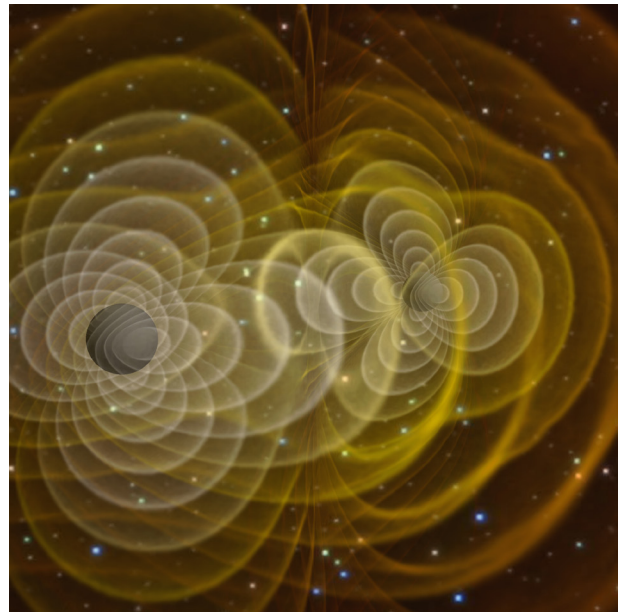
Resolution of a 30-year controversy has come through study of the light curves, spectra, and population characteristics of Fermi gamma-ray pulsars. From them, we have learned that the emission is being produced in the outer magnetospheres of the pulsars, rather than near the neutron star surface at the polar caps. Most of the gamma-ray light curves show sharp and narrow double peaks, as predicted by outer magnetosphere models to arise from special relativistic effects as the pulsar rotates. Phase-resolved spectroscopy in finer phase bins is now possible with Fermi for a number of the brighter pulsars, and study of the spectral variations with pulse phase will be able to probe the structure of the magnetosphere and the geometry of the emission. Modeling of the light curves of the millisecond pulsars, which resemble those of young pulsars, suggest that the emission comes from narrow acceleration gaps in the outer magnetosphere in most cases. This was a surprise since MSPs, with their very low spin-down rates, were not expected to have such narrow radiation gaps that require robust pair cascades.

The new Fermi results will require an overhaul of our previous ideas of electron-positron production from pair cascades in these sources and may imply that the MSPs have an unusual magnetic field structure or evolution.

### Observable Signatures of Merging Black Holes

The numerical relativistic astrophysics group and the LISA data analysis group of the ASD Gravitational Astrophysics Laboratory continue studies of merging binary black hole systems. These are predicted to be among the most energetic astronomical events, releasing energy as much as  $10^{55}$  erg/s in the form of gravitational radiation. Consequently, they are among the key target sources for gravitational wave observation.

Mergers of stellar-scale systems occur in the sensitivity band of ground-based observatories such as the Laser Interferometer Gravitational Wave Observatory (LIGO). The Laser Interferometer Space Antenna (LISA) will be sensitive to mergers of massive black hole systems ranging from roughly 10,000 to 10 million solar masses at cosmological distances (to  $z \sim 10$  and beyond). These observations form the basis for many of LISA’s science goals.



Frame from a three-dimensional simulation of black hole mergers produced on the Columbia supercomputer at NASA’s Ames Research Center.



Einstein's theory of General Relativity (GR) allows clear predictions for the physics of these mergers, but a full theoretical understanding of these energetic events and the gravitational-wave signals they produce requires detailed supercomputer simulations integrating the equations of GR. Following major advances in the basic techniques for these simulations in 2005–2006, Goddard's numerical relativistic astrophysics group (Baker, Centrella, Kelly, McWilliams, Van Meter, Boggs) continues numerical studies of a variety of configurations of comparable-mass binary systems.

**The description of the merger radiation provided by these numerical simulations, while still incomplete, provides a basis for drawing stronger inferences from gravitational wave observations.**

Several of these studies have focused on providing a detailed characterization of the gravitational waveform signals generated in binary black hole mergers. These studies first focused on developing a thorough understanding of the gravitational-wave radiation generated by mergers of non-spinning black hole systems. In collaboration with researchers and the University of Maryland, the Goddard team developed an analytic representation of the waveforms that is consistent with the post-Newtonian approximation that applies before GR effects become too strong, but also provides a close approximation to the numerical results describing the strong radiation generated in the final moments of merger. Currently, the team is working toward a thorough description of a broader class of spinning black hole systems, as well as an extension of the analytic waveform model to describe this broader class of systems.

The description of the merger radiation provided by these numerical simulations, while still incomplete, provides a basis for drawing stronger inferences from gravitational wave observations. Building on the source modeling work, the LISA data analysis group (Baker, Thorpe, Arnaud, Littenberg, Kelly, McWilliams) continues investigating how the merger signal predictions will enhance the precision with which astronomers will be able to estimate the parameters of merging systems, including sky position and distance,

with careful analysis of LISA data. In 2009, the team completed an investigation of this enhancement on a restricted class of non-spinning mergers, finding typical improvement by a factor of three in the determination of parameters for appropriate systems. A new study, extending this analysis to more general spinning mergers is underway.

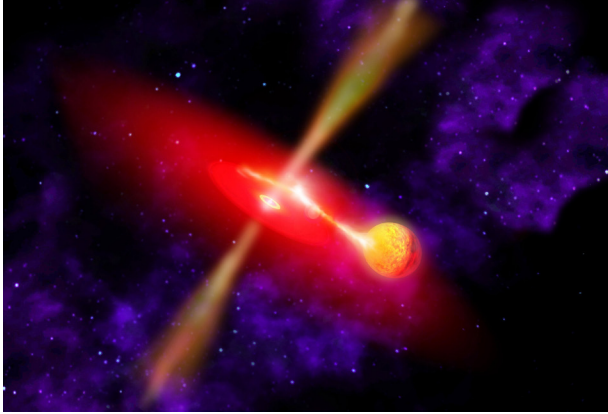
How well and when black hole binary parameters can be measured by LISA will have a direct impact on how LISA may operate in conjunction with other future instruments. LISA will be able to announce, even forecast, the time and location of merger event, which can then be followed up with electromagnetic observations.

It is not yet clear what potentially observable effects the strong dynamical gravity of these merging systems could have on any surrounding gas or other matter. Another Goddard team has completed an exploratory investigation, tracing the trajectories of particles in the vicinity of the merging black holes. The team (Centrella, Giacomazzo, Van Meter), in collaboration with additional researchers at the University of Maryland, is extending these studies to more realistic models of possible surrounding gas, as warranted by the preliminary investigations.

The large amount of gravitational energy produced in these mergers can lead to a significant back-reaction force on the remnant black hole when the radiation is emitted asymmetrically. Numerical relativity simulations indicated that this “kick” imparted to the merged black hole can be larger than 2,000 km/s in particular cases. Such large kicks would have a dramatic impact on the relation between a merged massive black hole and its host galaxy or proto-galaxy, impacting astronomical expectation beyond gravitational waves. The Goddard team continues to study these kicks with attention to the dependence of the kick on the binary parameters, particularly the ratio of the two black holes' masses. These results will impact the likelihood of large kicks in generic merging systems.

### **NGC 5408 and the Case for Middleweight Black Holes**

Astronomers have uncovered compelling evidence for the existence of at least two classes of black holes. The



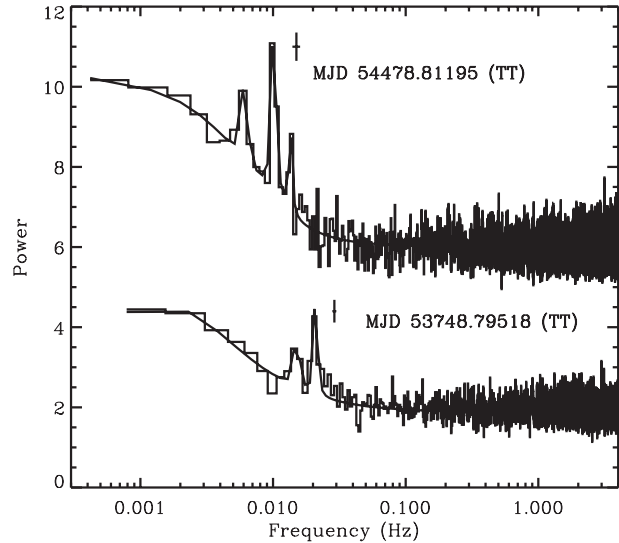
Artist's concept of NGC 5408 X-1.

supermassive variety that lurk at the centers of most galaxies—including the four-million-solar-mass behemoth at the heart of the Milky Way—and the solar-mass variety that are the products of the evolution of massive stars. This latter group have weighed-in in the range from about 4–25 solar masses. But what about the middle ground? Where are the black holes with masses of about a thousand solar masses and more? Do they even exist?

Theory suggests that the first generation of star formation in the early universe could produce black holes of several hundred solar masses, and that, due to mergers of these “primordial” holes, a whole spectrum of masses should have been produced that would populate the present black hole “desert” in the range from 100–10,000 solar masses. Still other thinking suggests that such black holes could form in the present-day universe in very dense star clusters. If either of these ideas is valid, then where are these black holes hiding, and if they do exist, how can we find and weigh them?

**Weighing black holes is no simple proposition. For the ULXs in nearby galaxies this proposition is extremely daunting.**

The answer to this puzzle may tie in with a current conundrum in observational high-energy astrophysics. The question concerns the nature of a population of extremely bright X-ray sources found in nearby galaxies. These objects have been dubbed Ultra-luminous X-ray sources (ULXs) because of their extreme lumi-

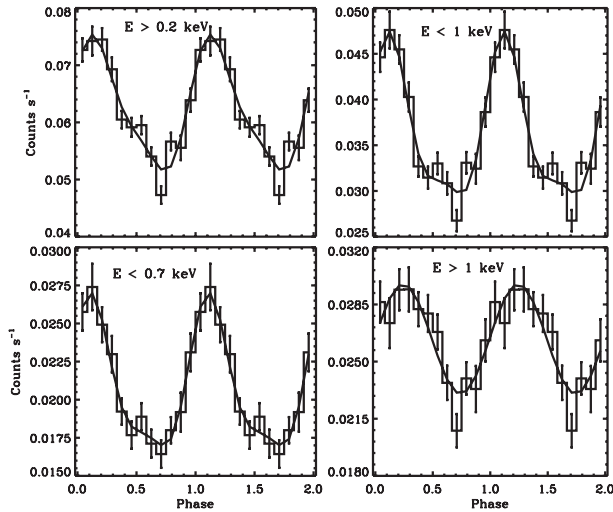


Power spectra from XMM-Newton data of NGC 5408 X-1 showing QPO peaks at 0.01 and 0.02 Hz. The change in frequency accompanied by changes in the X-ray spectrum are also seen in Galactic black holes, but the QPO frequency is about 100 times smaller in NGC 5408 X-1, while the luminosity is 100 times larger, suggesting that NGC 5408 X-1 harbors a middleweight black hole.

nosities. These objects have also shown short-time-scale variability of the kind that can only be produced by a physically compact source, like a black hole. Indeed, many astronomers believe they are black holes, but the question is: How massive are they? Because in some cases they can be up to 100 times brighter than the stellar black holes we observe in the Milky Way, one suspicion is that some of them could be the missing middleweight black holes theory predicts.

Weighing black holes is no simple proposition. For black holes in the Galaxy, the most reliable method is to observe the motion of its binary companion star. By observing its orbital motion, astronomers can use Kepler's laws to deduce the mass of the black hole. For the ULXs in nearby galaxies, this proposition is extremely daunting because the companion stars are so very faint, so other means must be devised.

Tod Strohmayer and Richard Mushotzky (now at University of Maryland, College Park) have been exploring new ways to estimate the masses of ULXs by measuring their X-ray timing properties and comparing



Variations in the X-ray flux as a function of orbital phase in NGC 5408 X-1, from Swift X-Ray Telescope monitoring observations. Four different energy bands are shown. The variations with energy are further evidence of orbital modulation. The inferred orbital period is 115 days.

them with the population of Galactic black holes of known mass.

Many black holes in the Galaxy, whose masses we know, show periodic variations in their X-ray fluxes. The periods of these oscillations—technically called quasiperiodic oscillations, or QPO—appear to correlate with the mass of the black hole. This is perhaps not surprising, as the time it takes for an oscillatory wave to propagate in a cavity depends on the size of the cavity; bigger, more massive black holes basically have bigger resonance cavities. Strohmayer and Mushotzky have been using the XMM/Newton observatory to search for similar QPOs in ULXs and have found them in two objects so far: M82 X-1 and NGC 5408 X-1. In each case, the periods of the QPOs are longer than seen in Galactic black holes, suggesting more massive black holes in the ULXs.

The most intriguing case is that of NGC 5408 X-1. Recent observations spaced two years apart found that the QPO period in NGC 5408 X-1 had increased. The period increase was accompanied by a drop in the X-ray flux from the accretion disk, the same behavior that has been observed in the Galactic black holes, suggesting that the same physical processes are being observed. Whereas the typical oscillation period in

the Galactic black holes is one second, in NGC 5408 X-1 it is 100 seconds. Moreover, the X-ray luminosity is also about a 100 times greater in NGC 5408 X-1 than comparable Galactic black holes. These relatively simple arguments suggest that NGC 5408 X-1 is at least 100 times more massive than stellar-mass Galactic black holes, and would make it one of the best candidates for a middleweight black hole of more than 1,000 solar masses.

The only way NGC 5408 X-1 can be so bright is that it must be devouring lots of matter. This amount of matter could only come from a binary companion star, and likely a rather massive one. Strohmayer has been using the Swift observatory to monitor the X-ray flux from NGC 5408 X-1 about twice per week for almost two years now. Swift is the only current observatory with both the imaging sensitivity (provided by its X-ray Telescope) and the observing flexibility to carry out such a monitoring campaign.

Enough data has now been collected to show that the flux from NGC 5408 X-1 varies with a 115-day period. This is very likely the orbital period of the black-hole binary. The relatively long orbital period indicates that the companion star must be a “bloated” giant or supergiant. Only such a star would be big enough to be able to lose the requisite amount of matter to the black hole. More XMM-Newton observations are in the works to further pin down the mass of NGC 5408 X-1, but so far it represents one of the best cases for the elusive middleweight black holes.

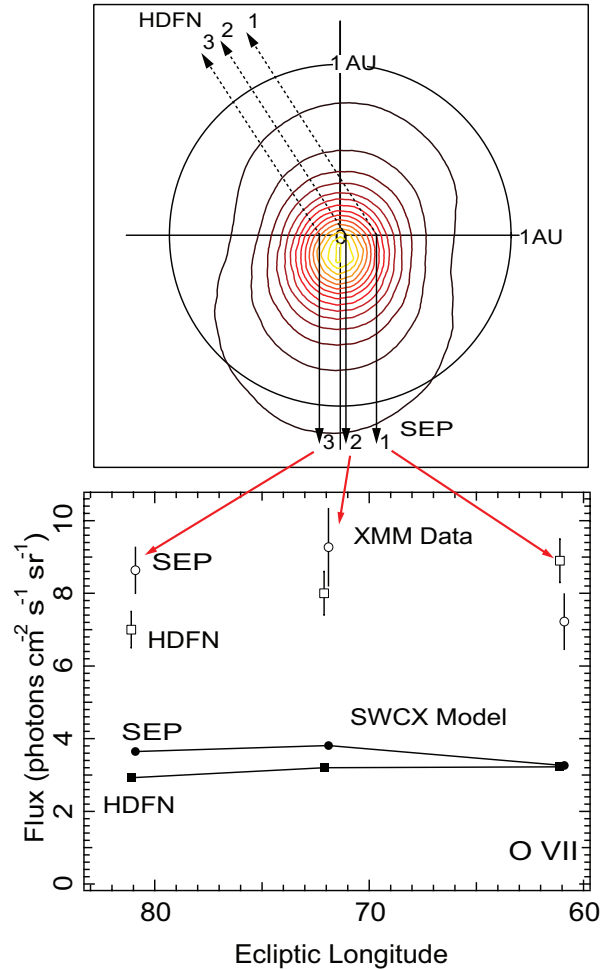
### Solar Wind Charge Exchange X-ray Emission

In the last few years, solar wind charge exchange (SWCX) emission from the heliosphere and Earth’s magnetosheath has been identified as a significant contributor to the diffuse X-ray background at energies less than 1 keV. This signal can be of interest in studies of the solar system—or serve as an unfortunate contamination component in studies of the hot, diffuse plasmas in the Milky Way and beyond. To understand this emission, Dimitra Koutroumpa, Steven Snowden, and collaborators are pursuing both modeling and observational approaches, the most recent being a study of SWCX emission from the interplanetary helium-focusing cone.

SWCX X-ray emission in the heliosphere originates when a high-charge-state ion of the solar wind (SW) interacts with a neutral atom and gains an electron in a highly excited state, which then decays by emission of an X-ray with a characteristic energy of the ion. Within the heliosphere, the target atoms are primarily from the flow of interstellar (IS) neutrals through the solar system due to the motion of the sun through the local IS cloud. This material, a gas of mostly hydrogen (H) atoms with about 15 percent helium (He), flows from the direction  $\lambda, \beta \sim 253^\circ, 5^\circ$ . This places Earth upstream of the sun in the IS neutral flow in early June and downstream in early December every year. Although both radiation pressure and gravity affect the H trajectories, only gravity significantly affects the He trajectories, which execute Keplerian orbits and form a “focusing cone” downstream of the Sun, resulting in a localized downstream enhancement of He observed annually by Earth-orbiting and L1 spacecraft. Heliospheric SWCX models predict an enhancement of SWCX X-ray emission due to the He cone structure.

Koutroumpa and Snowden used multiple XMM-Newton observations of the south ecliptic pole (SEP) as Earth passes over the ISM helium-focusing cone to search for a correlation with the expected variation from models (Koutroumpa et al. 2009). Three observations of the SEP, coupled with three monitoring observations of the Hubble Deep Field-North (HDF-N), were performed with XMM-Newton between late November and mid December 2003. In the soft X-ray energy range of XMM-Newton, SWCX emission mainly contributes to the two oxygen lines at 0.57 keV (O VII) and 0.65 keV (O VIII). The HDF-N observations were used to normalize the SEP data (the scaled SEP data are shown in the figure) to eliminate short-term variation effects of the SW. The SW input to the study is based on in-situ measurements in the ecliptic plane (usually at L1) with the assumption that, on average, the SW conditions are the same for both the northern and southern solar hemispheres, and all along the LOS.

The heliospheric SWCX model was used to calculate the SWCX line emission for the lines-of-sight through the heliosphere, which are dependent on the satellite location and solar activity. The figure shows the viewing geometries of the XMM-Newton SEP ( $\beta = -90^\circ$ ) and HDF-N ( $\lambda, \beta = 148^\circ, 57^\circ$ ) observations associated



*Top:* XMM-Newton south ecliptic pole (SEP) and Hubble Deep Field (HDF-N) look directions overlaid on isodensity contours of the He cone as seen perpendicular to the Sun-Earth direction, in a cut through the He cone central longitude ( $\sim 74^\circ$ ). *Bottom:* Data and model line intensities for the three coupled SEP-HDF-N observations. The SEP data are scaled for the observed variation of the HDF-N flux and then again by the model variation of the HDF-N SWCX flux.

with the He cone structure, as well as the resulting data and model O VII line intensities for each observation. The axis of the He cone angles downward from the ecliptic plane at  $\sim 5^\circ$ , thus the northern directions view less of the cone—and therefore less SWCX emission—while the southern viewing direction should show enhanced SWCX emission from the cone. (Note that the model only accounts for roughly half of the observed fluxes but since the fields are not shadowed



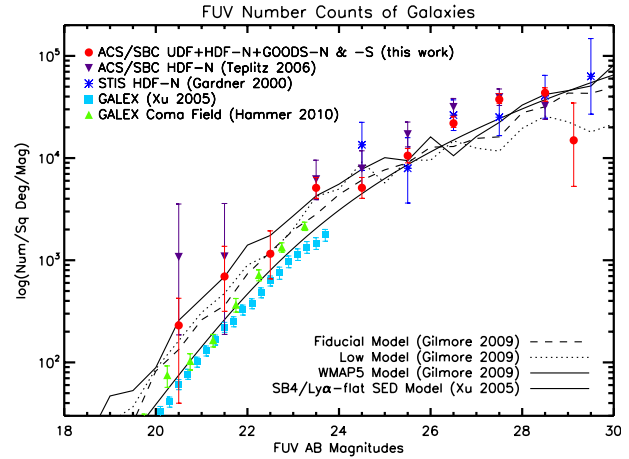
from distant emission, e.g., the galactic halo, additional emission is expected.) The total SWCX enhancement in the He cone is marginally detected in the XMM-Newton data; however, the SEP data show the same trend as the model predictions, with the maximum emission coming from near the central He cone direction (near obs. 2), although the measured variations are much stronger than the predicted ones. This may be due to some residual variations of SWCX emission from the near-Earth environment. However, all three XMM-Newton observations were scheduled very near to the maximum density region ( $\sim 10^\circ$ ) of the He cone (see lower panel in the figure), thus limiting the expectations of a large variation between the on- and off-cone positions.

At present (Nov. 2009 to Jan. 2010), Snowden is PI on a new campaign of four coupled observations toward the SEP and NEP with Suzaku. The new, longer observations cover a larger area of the He cone ( $\pm 25^\circ$  around the central He cone longitude) that will allow a clearer detection of the soft X-ray enhancement in the center of the cone. The observations took place during a different period of the solar cycle with respect to the XMM-Newton observations and will provide new constraints for the SWCX model assumptions on the SW parameter (proton flux, ion abundances, and anisotropy) evolution during the solar cycle.

### Number Counts of Far-Ultraviolet Galaxies

The number counts of far-ultraviolet (FUV) galaxies as a function of magnitude provide a direct statistical measure of the density and evolution of star-forming galaxies. A team of scientists, based in ASD, is carrying out a study of FUV number counts with the Hubble Space Telescope (HST). The team members are Elysse N. Voyer (NASA GSFC Graduate Student Research Program Fellow, Catholic University of America), Jon Gardner (GSFC), Duilia F. de Mello (GSFC/Catholic University of America), Harry Teplitz (NASA/IPAC), and Brian D. Siana (Caltech).

The team has used measurements of the rest-frame FUV (1500Å) number counts computed from data in the GOODS-North and GOODS-South fields. These data were obtained from the Advanced Camera for Surveys (ACS) Solar Blind Channel Camera (SBC). The SBC survey of these regions covers a total



This plot compares FUV number counts for galaxies in the Ultra Deep Field, Hubble Deep Field-North, and GOODS-North and -South (red dots) with other studies (other colored symbols) and expectations from various models (lines).

of  $\sim 15.94$  arcmin<sup>2</sup>. Specifically, the UDF area of the GOODS-S field was observed by SBC in 28 two-orbit pointings covering 3.7 arcmin<sup>2</sup>, and smaller areas of the GOODS-N and -S fields were observed in 15 five-orbit pointings covering less than 1 arcmin<sup>2</sup> each. Data from the HDF area of the GOODS-N field from Teplitz et al. (2006) that was observed by SBC in 14 two-orbit pointings covering 3.77 arcmin<sup>2</sup> were also included. Included in the counts were 113 FUV sources in the UDF area of GOODS-S, 118 FUV sources in the smaller GOODS-N and -S images, and 100 FUV sources from the HDF area of GOODS-N. The number counts cover an AB magnitude range from 20th to 29th magnitude.

After initially measuring the raw FUV counts, an incompleteness correction was applied. This was done statistically, through simulations using the GOODS V-band galaxy catalog. After applying these completeness correction factors to the measured FUV counts, the results were compared to previous deep FUV number counts (Teplitz et al. 2006, Gardner et al. 2000) and bright FUV number counts (Hammer et al. 2010, Xu et al. 2005). The counts were also compared to the most recent semi-analytical models based on dark matter “merger trees” that trace the growth of supermassive black holes and their host galaxies in the  $\Lambda$ CDM cosmology (Gilmore et al. 2009, Somerville et al. 2008). The FUV number counts and comparisons are plotted in the included figure.



These number counts are, on average, somewhat lower than those from previous studies that used observations from HST's STIS instrument in the HDF-N and HDF-S (Gardner et al. 2000) and the SBC in the HDF-N (Teplitz et al. 2006). The differences in the counts are likely the result of cosmic variance; the new data cover more area and more lines of sight than the previous studies. At FUV magnitude 22.5, the slope of our counts connects better with the faint end of the Coma field counts than with the GALEX counts. This is likely a result of the detection/photometry technique used on the Coma field data by Hammer et al. (2010) that results in better detection efficiency compared to the GALEX pipeline reduction methods.

The new number counts show good agreement with the  $\Lambda$ CDM semi-analytical models, perhaps with a slight preference for the WMAP5 model (Gilmore et al. 2009, Somerville et al. 2008). These models are characterized by both cosmological and galaxy formation parameters that include: photoionization quenching, quiescent star formation, burst star formation, merger remnants and morphology, supernovae feedback, chemical evolution, black hole growth, AGN-driven winds, and radio-mode feedback. The differences in the slopes of the models can be caused by the different primordial power spectrum parameters ( $\sigma_8$ ) that depend on the cosmology of the model, or the number of low luminosity galaxies used in the model.

Previous FUV counts do not match as consistently with any of these models, likely due to the cosmic variance of the fields surveyed. The SB4/Ly $\alpha$ -flat SED model from Xu et al. (2005) is characterized by a UV luminosity evolution,  $L^* \sim (1+z)^{2.5}$ , and has the same UV SED as a no-evolution model except for a flat spectrum between 1200 and 1000Å. The new FUV number counts show better agreement with this model at the faint end than at the bright end.

The team is currently working to further improve the errors of the measured FUV number counts by including even more sources and detection area from several SBC observations in the HST COSMOS field. They are also working to calculate the FUV extragalactic background radiation from the resolved sources in the fields. An interesting extension of this study would be to determine the actual morphologies of the galaxies in this sample to try and pinpoint how galaxy envi-

ronment evolves with star formation at redshifts  $z < 1$ . This has been an important topic of astrophysical research since the mid-1990s, when it was discovered that the star formation rate in the universe began to decline sharply at  $z \sim 1$ .

### MCW 419 and the Keck Interferometer

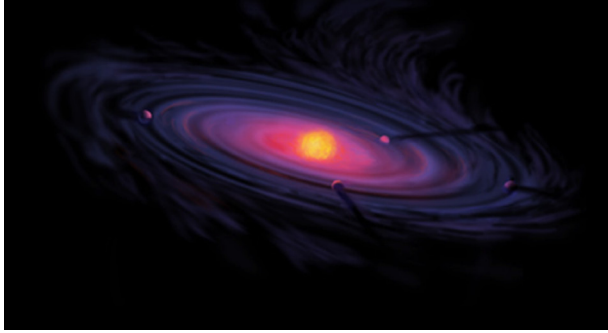
Using the Keck Interferometer, a team of astronomers from Goddard Space Flight Center, (Dr. William Danchi is a leading coinvestigator), Caltech, JPL, and the Keck Observatory have peered far into a young planetary system, giving an unprecedented view of dust and gas that might eventually form worlds similar to Jupiter, Venus, or even Earth. Because the gas, dust, and debris that orbit young stars provide the raw materials for planets, probing the inner regions of those stars lets us learn about how Earth-like planets form. This team recently measured the properties of a young planetary system at distances closer to the star than Venus is to the sun.

**Using the Keck Interferometer, astronomers recently measured the properties of a young planetary system at distances closer to the star than Venus is to the sun.**

The researchers used the Keck Interferometer, which combines the light-gathering power of both 10-meter W. M. Keck Observatory telescopes to act as a single 85-meter telescope—much larger than any existing or planned facility. Nothing else in the world provides us with the types of measurements the Keck Interferometer does. In effect, it's a "zoom lens" for the Keck telescopes.

The "zoom lens" allowed the researchers to probe MWC 419, a blue, B-type star that has several times the mass of the sun and lies about 2,100 light-years away in the constellation Cassiopeia. With an age less than 10 million years, MWC 419 ranks as a stellar kindergartner.

With the interferometer and the increased ability to observe fine detail, the team measured temperatures in the planet-forming disk to within about 50 million



This artist's concept shows the development of planets within a dust disk around a young star.

miles of the star. That is about half of Earth's distance from the sun and well within the orbit of Venus.

For comparison, astronomers using a single telescope have directly observed HR 8799, Fomalhaut, and GJ 758 and their orbiting planets, which are 40 to 100 times farther away from their stars.

These new results were taken in near-infrared light (3.5 to 4.1 micrometers), which is a wavelength slightly longer than red light and is invisible to the human eye. Our team used a newly implemented infrared camera, which is the only one of its kind on Earth, to make the first "L-band" interferometric observations of MWC 419.

This unique infrared capability adds a new dimension to the Keck Interferometer in probing the density and temperature of planet-forming regions around young stars. This wavelength region is relatively unexplored. Basically, anything seen through this camera is brand new information.

With the data, the team measured the temperature of dust at various regions throughout MWC 419's inner disk. Temperature differences throughout the disk may indicate that the dust has different chemical compositions and physical properties that may affect how planets form. For example, in the solar system, conditions were just right to allow rocky worlds to form closer to the sun, while gas giants and icy moons assembled farther out in the system. The results have been reported in *The Astrophysical Journal* (Ragland et al. 2009). The observations are an important first step in a larger program to collect data on young stars that span the lower-mass T Tauri stars, which are the pro-



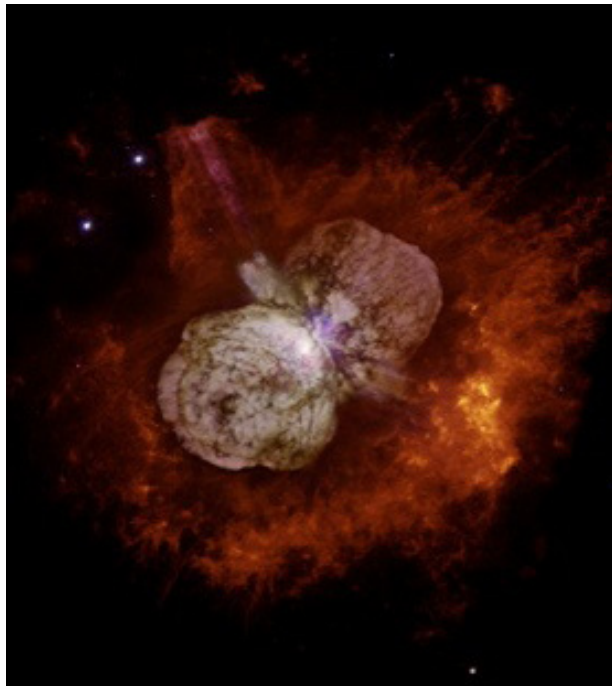
MWC 419, also known as V594 Cas, is a young, blue variable star located 2,100 light years away in the constellation Cassiopeia. The Keck Interferometer probed the temperature and density of the dust disk around MWC 419 to within a fraction of an astronomical unit from the star. *DSS/STScI/AURUA*

genitors of sun-like stars, to their more massive counterparts, like MWC 419.

Our team plans to study the range of developing stars because their mass, size, and luminosity might affect the composition and physical characteristics of the surrounding disk. The team is continuing to collect data on young stars and will combine their infrared observations with data from the Keck Interferometer's "nulling" mode, which blocks out the light from the central star in a young planetary system.

### **Eta Carinae: A Rosetta Stone or an Exception?**

Massive stars play key roles in both our Milky Way and in the distant reaches of our universe. The first ones, which formed out of pristine, unprocessed material from the big bang, were composed of hydrogen and helium. The first heavy elements formed in their cores and were soon ejected into the interstellar medium, eventually leading to chemically enriched gas and dust that led to generations of later star formation. What is the composition of this gas and dust? Some massive binaries are thought to lead to progenitors of distant gamma-ray bursts (GRBs) that satellites, such



Direct Hubble image of the Homunculus, an hourglass-shaped nebula ejected by the Eta Carinae binary during the 1840s outburst. The massive binary is beginning its final stages before becoming two supernovae. At least 12 solar masses were ejected in the 1840s, yet the two stars survived. Studies of this massive system gives astronomers insight on how massive stars evolve.

as Swift and Fermi, detect daily. What leads some massive binary members to become GRBs?

Astronomers do not have the luxury of studying the first stars in detail, but we can study massive stars in our own and nearby galaxies. Eta Carinae is a massive binary star system that is nearing the end of its life cycle. It is sufficiently close—only about 7,400 light years away—that with the power of the Hubble Space Telescope, astronomers can study this binary star as it undergoes changes on timescales within our historical records. At least one of the system's stars has run out of hydrogen fuel and has attempted to consume helium.

In the 1840s, astronomers saw Eta Carinae brighten to rival Sirius, the brightest star in the night sky. Today we see an expanding hourglass-shaped structure, known as the Homunculus, composed of material thrown out during this brightening. The Homunculus contains at least 12 solar masses of material that were

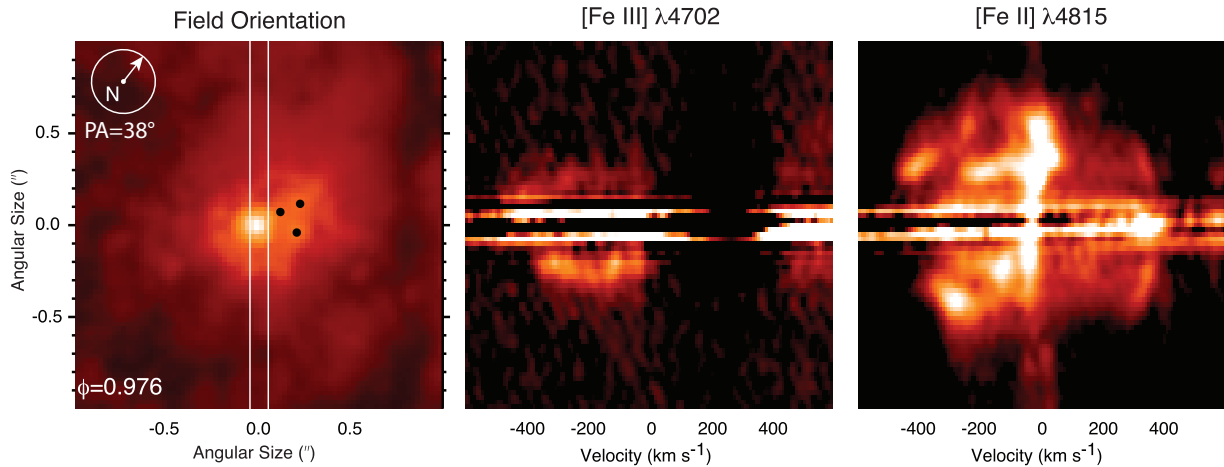
ejected in that major event, yet Eta Carinae survived. How?

Ground-based studies and monitoring of the X-ray flux by the Rossi X-ray Telescope Explorer (RXTE) reveal that Eta Carinae has a 5.5-year period, likely caused by a massive binary companion. Detailed spectroscopic studies with the Chandra X-ray Observatory fitted by models by Julian Pittard (University of Leeds) and Michael Corcoran (USRA/GSFC) indicate that the X-rays originate from massive stellar winds colliding at high velocities. A cavity is carved out of the primary's massive wind by a faster, less massive secondary wind. At the apex of their collisions, the gas is heated to X-ray-emitting temperatures.

The binary orbit of Eta Carinae is very elliptical in shape. For most of its 5.5-year period, the secondary star lies far from the primary. Then, for a few months, it plunges toward the larger star and passes deep into the primary wind. X-rays and far-ultraviolet radiation from the secondary star become trapped and the binary system goes through a low state as seen by astronomers.

**In the 1840s, astronomers saw Eta Carinae brighten to rival Sirius, the brightest star in the night sky. At least 12 solar masses of material were ejected in that major event, yet Eta Carinae survived. How?**

These massive winds of Eta Carinae are resolved by the high angular resolution of Hubble Space Telescope, permitting spectroscopic studies of the extended wind structures throughout the binary orbit. Recently, Ted Gull and a team of scientists used the Space Telescope Imaging Spectrograph to study the variations of these winds as the massive binary went through its 5.5-year orbit. Tom Madura, a graduate student from University of Delaware working with Stan Owocki, led the development of a three-dimensional model of the interacting winds. Merging of the model with the observations now provides astronomers with information on the orientation of the binary orbit and allows them to test their knowledge about how massive winds interact.



A slice of the winds of Eta Carinae. *Left:* A direct image of Eta Carinae, the star buried within the Homunculus. *Middle:* A portion of a long-slit spectrum centered on doubly-ionized iron ([Fe III] 4703Å) that reveals the boundary of the colliding winds. *Right:* A similar spectral portion centered on singly-ionized iron ([Fe II] 4814 Å) that shows the extent of the massive primary wind. Buried deep within the central core are two massive stars that total over 100 times the mass of our sun.

Eta Carinae, although it has a 5.5-year period, is gradually changing. Likely, the system is still settling down from the 1840s event (indeed, there was a lesser event in the 1890s that astronomers also observed), but it continues to evolve. Both stars are massive enough that each will evolve to become a supernova and eventually a black hole. The likelihood that either star will become a GRB is remote. Even in the early universe, few massive stars became GRBs, and as more and more heavy elements were produced, the stars that formed are thought to be less massive. Still, characterizing what the binary members of Eta Carinae are today will provide astronomers with a picture of potential GRB progenitors.

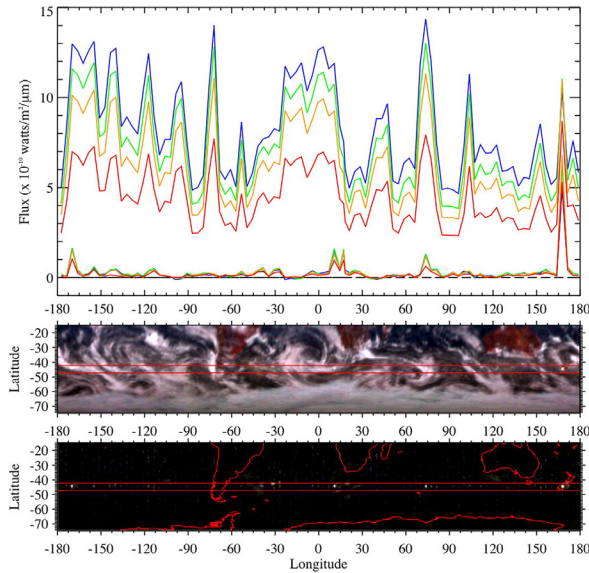
### Earth as an Extrasolar Planet

By the close of 2009, astronomers had catalogued more than 400 extrasolar planets. These have been identified using radial velocity, gravitational microlensing, and transit techniques. In most cases, little is known about these worlds other than their orbital period and inclination and some bulk properties, such as approximate mass, radius, and density. Using these aforementioned techniques, we are also sometimes able to determine an average orbital radius and eccentricity. These are important findings and establish a strong observational record for exoplanetary science.

The detection of such a trove of new planets within the past 15 years—beginning with the discovery of 51 Pegasi in 1995—indicates that there may be many such bodies. It provides a strong motivation to learn more about their individual characteristics, together with that of their host stellar systems. Using advanced techniques such as transit spectroscopy, nulling interferometry, and stellar coronagraphy, we are entering an epoch when we may progress past merely identifying and counting exoplanets and start to characterize their surfaces, atmospheres, and the exozodiacal dust disks theorized to frequently accompany planetary systems.

In our efforts to understand observations of extrasolar planets, and, in particular, to characterize exoplanets orbiting within the habitable zone of their host star—roughly defined as the range of distances from the host for which liquid water may exist on the surface—we have but one reliable example: Earth. We are strongly motivated to study our home world as if it were an exoplanet to establish an understanding of chemical abundances in the atmosphere and, in particular, that of biomarkers—molecular bands associated with an active biosphere. We also wish to comprehend the phenomenological evidence for a liquid-water hydro-sphere with implications to geomorphology.





Photometry of an 8-pixel-diameter patch centered on the calculated sun-Earth-observer specular reflection point, corrected for the solar spectrum. The upper four traces indicate the total flux. The lower four traces show the total flux minus the flux contributed from other sources, such as clouds. Center wavelengths of the four 100 nm filters segmenting the observed spectral range are  $0.35\ \mu\text{m}$  (blue),  $0.55\ \mu\text{m}$  (green),  $0.75\ \mu\text{m}$  (yellow),  $0.95\ \mu\text{m}$  (red). This analysis will be useful in understanding future observations of exoplanets and confirming models of Earth's atmosphere.

Scientists within the ASD are vigorously active in this area of research. For example, we have recently obtained Earth observations from a range of about 11 million miles using the High Resolution Instrument on the Deep Impact spacecraft. These observations,

conducted under the Extrasolar Planet Observation and Characterization (EPOCh) mission, for which Dr. Drake Deming of the Planetary Systems Laboratory (GSFC) is Co-PI, have provided us with low-resolution spectra of Earth's atmosphere, images of Earth in various phases, and spatially resolved images of Earth's surface. From these observations, we are able to describe our home planet in an abstract way that may be useful for exoplanet researchers.

One such study, led by Dr. Richard K. Barry of the Laboratory for Exoplanets and Stellar Astrophysics, seeks to characterize bright patches or "glints" noted in many of the individual Earth images. Calculations and analysis of the data show these glints are likely specular reflection of sunlight from the surfaces of bodies of water (see figure). The team has analyzed the photometry of these glints to characterize the reflecting surface and the layers of atmosphere traversed and to catalog the specific bodies of water associated with the glints. This allows the team to see geomorphological trends in the strength of the reflections, which appear to be a weak function of the isolation of the body of water. Additionally, the team is working closely with co-investigators at several universities to simulate these observations using the NASA Astrobiology Institute's Virtual Planetary Laboratory 3-D spectral Earth model and have matched visible, multi-wavelength 24-hour light curves of Earth to within three percent at most wavelengths.

These observations of Earth and the advanced models used to simulate them will be important not only in assisting our understanding of new exoplanet data but will prove crucial in feasibility studies for future space missions to detect and characterize earth-like planets.



### III. 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. See the 2008 report for awards extending back to approximately 2006.



Dr. Peter Serlemitsos

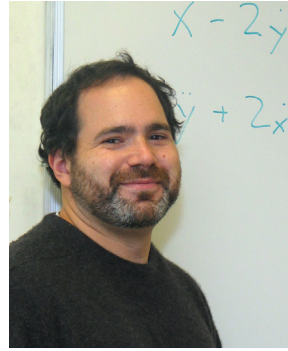
In January 2009, two ASD scientists were recognized. Dr. Peter Serlemitsos of the X-ray Astrophysics Laboratory was awarded the American Astronomical Society's Joseph Weber Award for Astronomical Instrumentation. The award recognizes the design, invention or significant improvement of instrumentation leading to advances in astronomy. The contributions of Serlemitsos led to major advances in both X-ray optics and multiwire proportional counters. These advances enabled many ground-breaking missions, including OSO-8, HEAO-1, RXTE, BBXRT, ASCA, Suzaku, as well as the upcoming Astro-H mission.

In the same month, Neil Gehrels, who heads the Astroparticle Physics Laboratory, was awarded the 2009 Henry Draper medal by the National Academy of Sciences. The citation reads: "For his pioneering contributions to gamma-ray astronomy. His leadership of the Compton Gamma Ray Observatory and the Swift Mission has led to new insights into the extreme physics of active galactic nuclei and gamma ray bursts." The National Academy of Science only presents this award every four years.



Dr. Neil Gehrels

In February 2009, Dr. Marc Kuchner, a member of the Exoplanets and Stellar Astrophysics Lab, was a recipient of an SPIE Early Career Achievement Award



Dr. Mark Kuchner

"in recognition of his outstanding achievements that have greatly facilitated the detection and characterization of extra-solar planets. His invention and refinement of new telescope coronagraph masks provide astronomers with innovative tools needed to detect planets directly around bright stars." The award is given annually to an early career professional in recognition of significant and innovative technical contributions to a field of science and/or engineering.

In March 2009, we learned that Dr. David Leckrone was awarded NASA's Distinguished Service Medal. This award is "the highest honor that NASA confers. It may be awarded to any person in the Federal service who, by distinguished service, ability, or courage, has personally made a contribution representing substantial progress to the NASA mission. The contribution must be so extraordinary that other forms of recognition would be inadequate." The award was bestowed for his leadership, through many servicing missions, of the Hubble Space Telescope. The medal was awarded in a ceremony at NASA HQ on April 16, 2009.



Dr. David Leckrone



Dr. Steven Ritz

Dr. Steven Ritz, previously a member of the Astroparticle Physics Lab and now at the University of California, Santa Cruz, was awarded the NASA Outstanding Leadership Medal for his leadership as NASA Project Scientist for the Fermi Gamma-ray Space Telescope. The fabulous success of this mis-

sion, as described elsewhere in this report, is due in no small part to his expert guidance and hard work.

Two groups in ASD also brought home NASA Achievement Awards in 2009—the BESS Polar Team (a large team of scientists from universities and institutions in Japan and the U.S.), for a record-setting circumpolar flight of the BESS balloon to search for cosmic antimatter, and the “Afterschool Universe Team” for Public Service in Education and Outreach. The Afterschool Universe program is intended for middle school students (grades 6–8). The Team includes Anita Krishnamurthi (now at the AAS), Sarah Eyerhmann, Sara Mitchell, George Gliba, Pat Tyler, Jim Lochner, and Chris Reynolds (at University of Maryland). The Afterschool Universe website is [universe.nasa.gov/au](http://universe.nasa.gov/au).



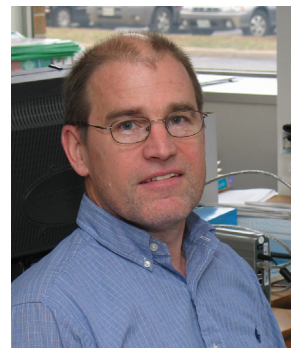
Dr. Kimberly Weaver

Dr. Kimberly Weaver, Associate Director for Science in ASD, received the Distinguished Alumna award from the University of Maryland Astronomy Department for her efforts in promoting science. Kim has an exceptional ability to convey the excitement of scientific discovery to the community, and we

thank our colleagues at the University of Maryland for their recognition.

The Swift Mission Team received the Maria and Eric Muhlmann Award from the Astronomical Society of the Pacific. The award is given for recent significant observational results made possible by innovative advances in astronomical instrumentation, software, or observational infrastructure.

Dr. Harvey Moseley received the Distinguished Presidential Rank Award for 2009. Quoting from the U.S. Office of Personnel Management web site: “Each year, the President recognizes and celebrates a small group of career Senior Executives and senior career employees with the Presidential Rank Award.



Dr. Harvey Moseley

Recipients of this prestigious award are strong leaders, professionals, and scientists who achieve results and consistently demonstrate strength, integrity, industry and a relentless commitment to excellence in public service.” The award for Harvey was in recognition of his decades of service to NASA in developing innovative new instrumentation and detectors to explore the universe (COBE, X-ray calorimeters, IRAC, detectors for HAWC, TES arrays, and microshutters). Harvey is only the third scientist in NASA to win this award—another was John Mather—so this is something special indeed. As is customary, Harvey will receive his award in a ceremony at the White House early in 2010.

## IV. Research and Development

### *Suborbital Projects*

#### **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 and provides 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). Hams and Sasaki are co-investigators. 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 collaboration carried out nine conventional northern-latitude flights between 1993 and 2002, recording 2,237 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. This may suggest a contribution from an exotic primary source, such as the evaporation of small primordial black holes (PBH) with initial mass around  $5 \times 10^{14}$  g, or the annihilation of candidate dark matter particles.

The BESS-Polar instrument was developed to greatly increase sensitivity using long-duration balloon flights over Antarctica. The BESS-Polar magnetic-rigidity spectrometer uses a unique 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 ac-

ceptances of  $\sim 0.3$  m<sup>2</sup> sr, 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 takes place at GSFC and GSFC co-leads launch and flight operations. GSFC has principal responsibility for instrument performance analysis.

**No antinucleus heavier than an antiproton has been detected in BESS flights through BESS-Polar I. These data have provided the most stringent reported test of the presence of heavier antinuclei in the current universe.**

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 8,000–10,000 antiprotons. Depending on the antiproton energy, this is 10–20 times the combined BESS 1995/97 statistics. The instrument performed very well, and analysis of 13.5 terabytes of data obtained on 4.7 billion cosmic-ray events is nearing completion.

No antinucleus heavier than an antiproton has been detected in BESS flights through BESS-Polar I. These data have provided the most stringent reported test of the presence of heavier antinuclei in the current universe, with a 95% confidence upper limit of  $2.7 \times 10^{-7}$  for antihelium/helium. If no antihelium is detected in BESS-Polar II data, this will be lowered by about a factor of  $\sim 3$ .

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 supersymmetric particle annihilation—and has reported an upper flux limit of  $3 \times 10^{-4}$  (m<sup>2</sup> s sr GeV/nucleon)<sup>-1</sup>.

The BESS-Polar II instrument could not be recovered in 2008 because its flight was terminated late in the



season and in a remote location. BESS-Polar II was successfully recovered in 2009/10, and the instrument is returning to GSFC for evaluation and refurbishment.

### 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), Caltech, GSFC, and JPL. John Mitchell leads the Super-TIGER effort at GSFC and co-investigators are Christian, De Nolfo, Hams, Link, Sasaki, and Barbier (now at NASA HQ).

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  $Z = 56$ . 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 permit 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  $^{31}\text{Ga}$ ,  $^{32}\text{Ge}$ , and  $^{34}\text{Se}$ . Super-TIGER measures the charge and energy of incident nuclei using three layers of plastic scintillator, together with Cherenkov detectors employing both acrylic and silica aerogel radiators. Scintillating optical fiber hodoscopes give the trajectories of individual particles to enable corrections for pathlength through the detectors, detector response maps, and interactions in the atmosphere and in the instrument.

GSFC is responsible for both the acrylic and aerogel Cherenkov detectors, the scintillators, the mechanical structure of the instrument and payload, and the high-voltage system. In addition, instrument and payload integration will be carried out at GSFC.

Super-TIGER has a total area of  $5.6 \text{ m}^2$  and is only 60 cm thick to maximize its geometric acceptance. The detector layout and minimal column density give an effective geometry factor of  $2.5 \text{ m}^2 \text{ sr}$  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.

**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.**

Super-TIGER is a forerunner of the ENTICE (Energetic Trans-Iron Composition Experiment) instrument on the OASIS (Orbiting Astrophysical Spectrometer in Space) mission. OASIS has been studied with NASA funding as an Astrophysics Strategic Mission Concept and was presented for consideration by the Astro2010 Decadal Survey. 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, Ohio State University, Ewha Woman's University (Korea), Kyung Pook National University (Korea), KAIST (Korea), LPSC Grenoble (France), CESR Toulouse (France), and UNAM (Mexico). John Mitchell is the GSFC Institutional PI and Link is a co-investigator.

In a series of long-duration balloon flights, CREAM will accumulate the large exposure needed to measure the energy spectra of the most common 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 will provide invaluable information on cosmic-ray composition, as well as the calibration data required to interpret airshower results.

The combined CREAM and airshower data will test models of Fermi shock acceleration of cosmic rays in supernova remnants. Standard models for this mechanism predict that a rigidity-dependent acceleration limit should be reached, resulting in a progressive composition change with increasing energy from dominance by light elements to dominance by heavier elements. 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), a transition radiation detector (CREAM-I), or a tungsten-scintillating optical-fiber calorimeter (all versions). The geometric acceptance of the TRD is  $\sim 1.3$  m<sup>2</sup>sr and the effective geometric acceptance (including interactions) for the calorimeter is about  $\sim 0.3$  m<sup>2</sup>sr for protons and greater for higher Z nuclei. A new TRD is being prepared by CERN (Switzerland) and JINR (Russia) to facilitate improved measurements of secondary-to-primary ratios.

GSFC responsibilities are to provide an acrylic Cherenkov detector for rapid particle identification—to preferentially 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 also supports integration and test of CREAM as well as launch and flight operations.

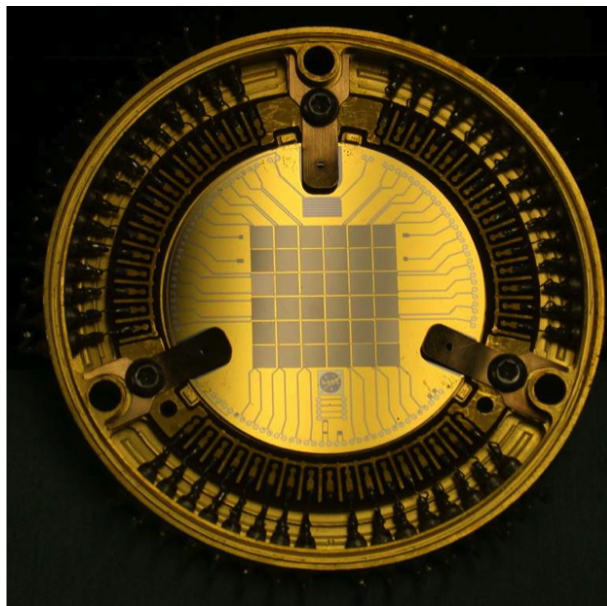
Originally designed for the anticipated ultra-long-duration balloon capability, CREAM has flown five times over Antarctica in long-duration flights, accumulating 159.5 days of exposure: 2004–2005, 42

days; 2005–2006, 28 days; 2007–2008, 29 days; 2008–2009, 19.5 days; and 2009–2010, 41 days. The flight of CREAM-VI is planned for the 2010–2011 austral summer.

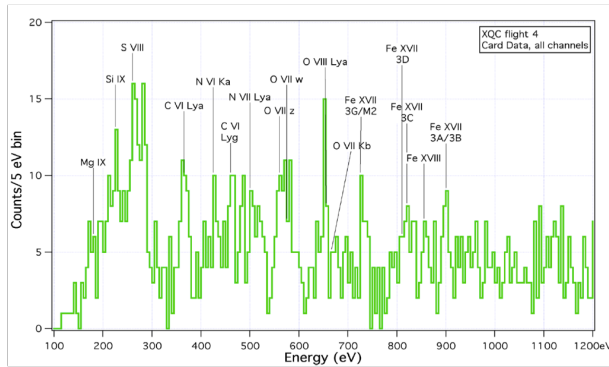
### X-ray Quantum Calorimeter (XQC) and Micro-X

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 Scott Porter, Richard Kelley, Caroline Kilbourne, and Megan Eckart. Collaborating institutions include the University of Wisconsin (Madison) and the University of Miami.

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 he-



The XQC payload uses a  $6 \times 6$  pixel X-ray calorimeter array developed and produced at GSFC. Each pixel in the array is  $2 \text{ mm} \times 2 \text{ mm}$ , and utilizes a  $0.8\text{-}\mu\text{m}$ -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. *NASA/XQC*



Preliminary spectrum of the soft X-ray background centered at galactic coordinates  $30^\circ$ ,  $+60^\circ$  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. *NASA/XQC*

liosphere. 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—spaceflight implementation of an X-ray calorimeter array.

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 x 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 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 5 of the XQC is planned for late 2010 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 X-ray absorber testing is currently underway.

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, Simon Bandler, Joseph Adams, Eckart, Stephen Smith, Peter Serlemitsos, and Yang 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 ( $11 \times 11$ ) 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 during 2011 to observe the bright eastern knot of the Puppis-A supernova remnant. The detector array will be 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<sup>2</sup> 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, and spatial-spectral imaging, and will provide a glimpse of what we can expect from Astro-H and then IXO in the future.

### Proto-EXIST

EXIST is a concept for an all-sky hard-X-ray imaging mission (see the mission concept section of this document for more information). ASD team members include Neil Gehrels, Scott Barthelmy, Jack Tueller, and Gerald Skinner.

Proto-EXIST1 is the first of a three-phase, balloon-based instrument to develop and prove the technology for the EXIST mission. Proto-EXIST1 successfully flew in October 2009 from Ft. Sumner, New Mexico



Proto-EXIST1 payload carried by the Columbia Scientific Balloon Facility launch vehicle “Big Bill” at Ft. Sumner, New Mexico, 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.

(6.5 hours at float altitude with a landing in western Kansas). It is lead by Josh Grindlay (CfA), with significant contributions from Goddard.

Goddard continues the development of the Command and Data Handling (C&DH) electronics in the front-end detector-array electronics (i.e., everything after the detector ASIC). The balloon flight raised the TRL from 5 to 6 for the entire end-to-end detector, to front-end electronics (ASIC and ADC), to the data-handling electronics, and the command and control system. It also tested the stacked-sheet design of the coded-aperture tungsten mask. During the flight, Cygnus X-1 was successfully imaged and a spectrum obtained.

Proto-EXIST2 will incorporate a new ASIC that (a) direct bonds to the CZT detector crystals (i.e., 2D stud-bump bonding), and (b) has half the pitch (i.e., 0.6mm pitch, four times as many pixels). Proto-EXIST2 will fly in the fall of 2010 from Ft. Sumner, New Mexico.

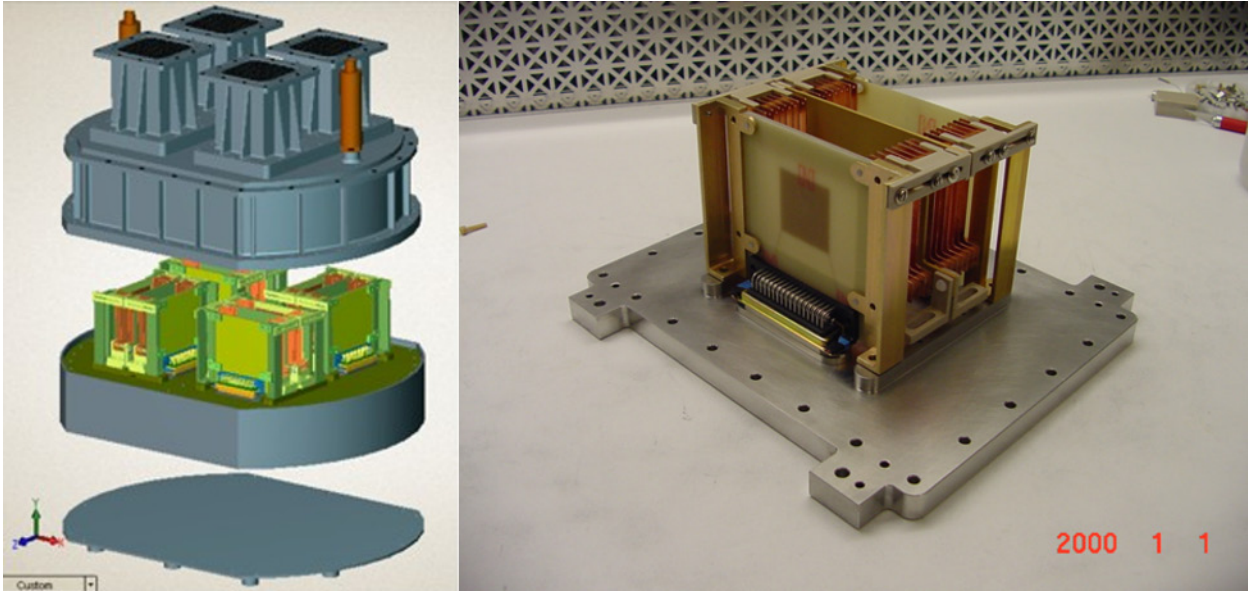
Proto-EXIST3 will incorporate a slightly revised version of the direct-bond ASIC to allow four-sided close-packing (instead of the three-sided, close-packing of the direct-bond ASIC). It will fly in 2011.

### Gamma-Ray Burst Polarimeter

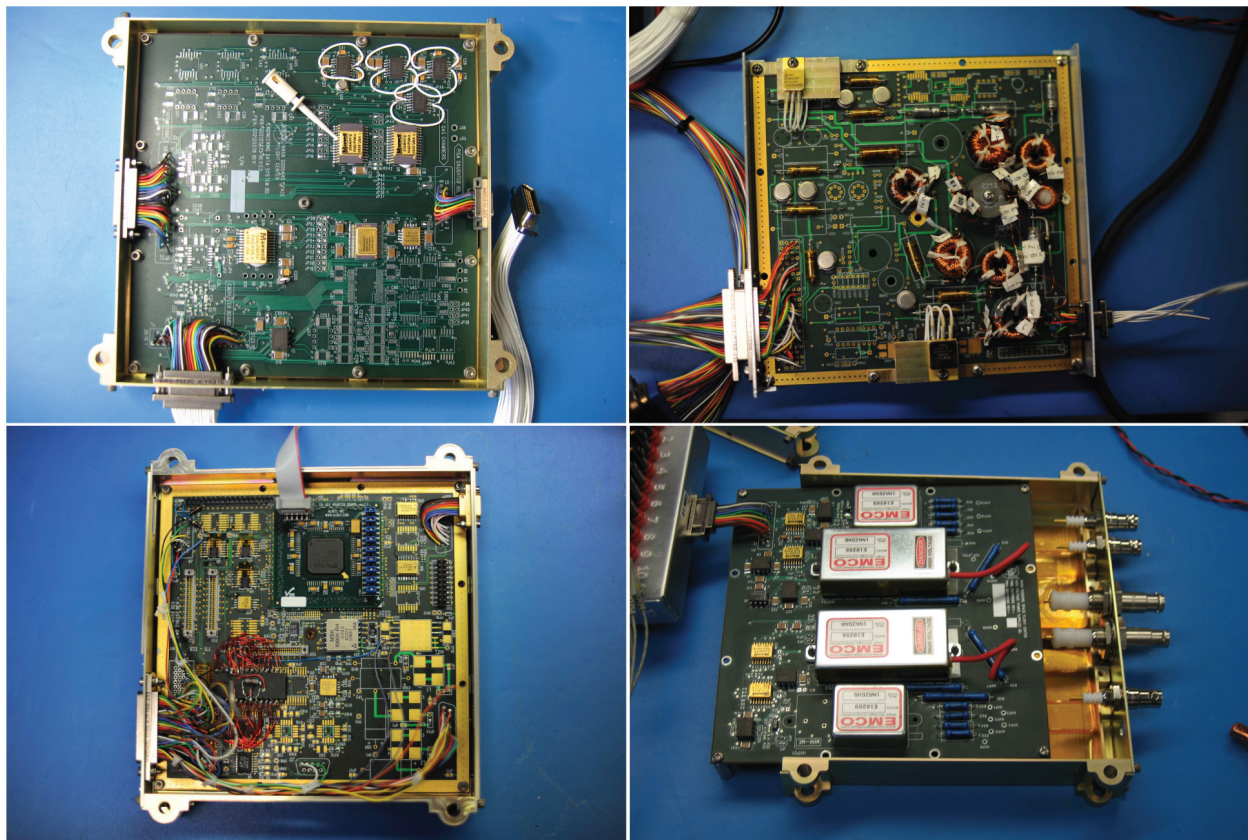
The Gamma-Ray Burst Polarimeter (GRBP) is an instrument originally designed for a small U.S. Naval Academy (USNA) satellite called MidSTAR-2 (Joe Hill, PI, and K. Jahoda, co-I). USNA funding for MidSTAR-2 has diminished, but the design and fabrication of GRBP continued through 2009, focused for a mission of opportunity (MoO) on another small satellite or for a sounding rocket.

The GRBP utilizes Time-Projection Chamber (TPC) technology in a new way to make polarization measurements of X-rays in the 2–10 keV energy band. The TPC polarimeter enables the design of a much higher sensitivity and wider field-of-view instrument. GRBP is designed to satisfy three requirements:

- To demonstrate a new technology in a space environment for the first time.



*Left:* GRBP flight design containing four  $6 \times 6 \times 5 \text{ cm}^3$  detector modules. Two detector units occupy a single gas enclosure. The frontend electronics will be mounted on the outside of the gas volume on the far side. *Right:* GRBP prototype detector module identical to the flight design.



GRBP flight electronics boards. *Top left:* Engineering data system. *Top right:* Low-voltage power supply. *Bottom left:* Engineering command and data handling board. *Bottom right:* High-voltage power supply.



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

This year, the design of the flight detectors and polarimeter enclosure have been completed. They will not be fabricated until a launch platform is identified and the interface finalized. A single detector unit and enclosure has been fabricated and is currently being tested in the lab with polarized and unpolarized X-rays. In April 2010, the detector will be tested at Brookhaven National Laboratory National Synchrotron Light Source. The supporting electronics, low-voltage power supply, high-voltage power supply, and housekeeping flight boards have been designed, built, and tested.

An engineering version of the command and data handling board has been built and tested, but the flight design cannot be finalized until a launch platform is finalized. An electronics box enclosure has been designed and fabricated to accommodate these four boards. The front-end electronics consists of a preamp board and a SIDECAR ASIC board for analog to digital conversion. The preamp board has been designed, fabricated, and tested; slight modifications are necessary prior to flight. The software for the SIDECAR has been written and tested with the detector and the C&DH board. A few minor changes are being implemented.

The team has been 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.

### **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 enable future missions (Gendreau, PI). The scientific objective of XACT is to measure the X-ray polarization properties of the Crab Nebula, the Crab 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.**

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.

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.

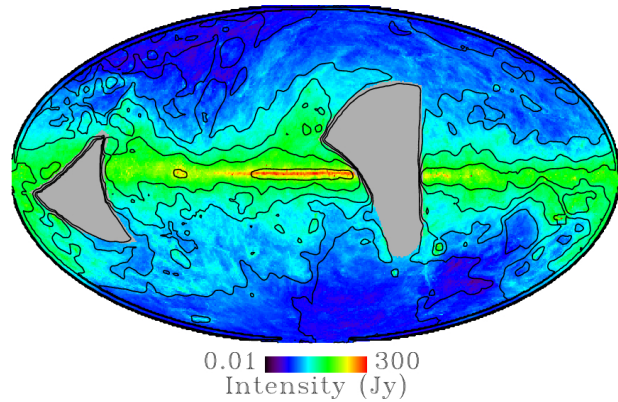
XACT will demonstrate in-flight calibration using a modulated electronic X-ray source that can be pulsed for arbitrary and commandable intervals. Such a source can be used to provide calibration information on demand. This minimizes the associated background and results both in higher sensitivity and observatory-scheduling freedom for future missions.

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 Dominic Benford, David Chuss, Dale Fixsen, James Hinderks, Gary Hinshaw, Harvey Moseley, Johannes Staguhn, and Edward 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 infla-



Expected sky coverage and signal-to-noise ratio for PIPER observations of polarized Galactic dust emission (Mollweide projection in Galactic coordinates). Contours are at S/N=3, 10, 30, 100, and 300 per 15 arcminute beam spot at 500  $\mu\text{m}$  wavelength. PIPER’s combination of high sensitivity and nearly full sky coverage are a powerful tool for both astrophysics and cosmology.

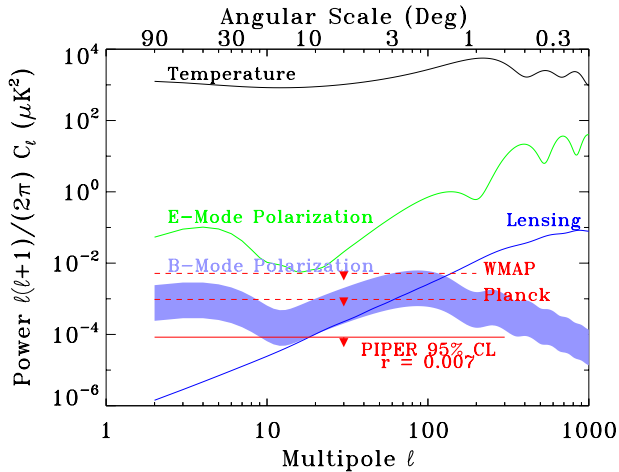
tionary epoch. Such a signal is expected to exist, with observable amplitude and a unique spatial signature.

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.

- 1) 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.
- 2) A Variable-Delay Polarization Modulator (VPM) injects a time-dependent phase delay between orthogonal linear polarizations to cleanly separate polarized





PIPER sensitivity (red) compared to the gravitational wave signal predicted by WMAP (blue band). PIPER is an order of magnitude more sensitive than the European Space Agency's Planck mission.

from unpolarized radiation. The fast (3 Hz) modulation allows full characterization of the incident radiation into Stokes I, Q, U, and V parameters on time scales that are fast compared to instrument drifts or beam motion on the sky.

3) 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,

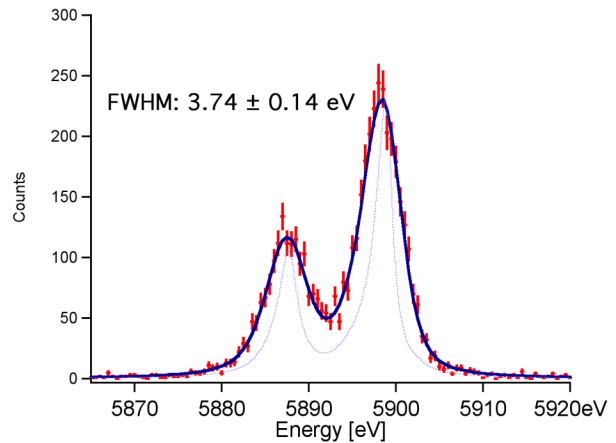
PIPER will map the sky in both linear and circular polarization, at wavelengths of 1500, 1100, 850, and 500  $\mu\text{m}$  (frequencies 200, 270, 350, and 600 GHz). It will detect the signature of inflationary gravity waves to a factor of three fainter than the lowest value predicted by inflationary models. The unbiased survey of sub-millimeter 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.

### Technology Development

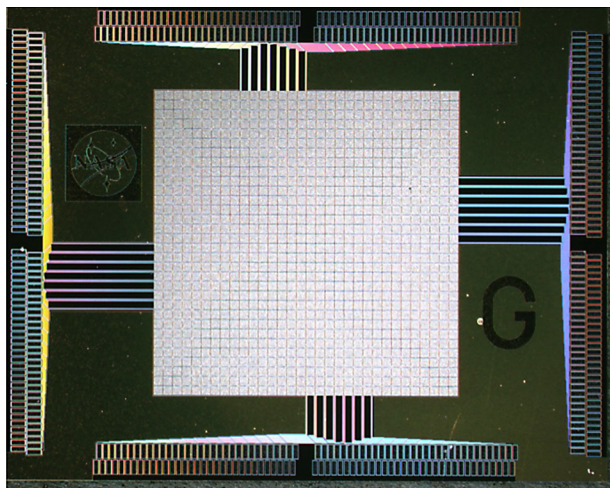
#### High-energy Laboratory Astrophysics Using an X-Ray Microcalorimeter with an Electron Beam Ion Trap

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 X-ray astrophysics begins to use high-resolution spectroscopy as 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, where every observation will produce a detailed, high-spectral-resolution image. Our program is designed to validate and



Mn Ka spectrum measured with a silicon-based calorimeter using improved HgTe X-ray absorber material. More than twenty such absorber samples have been tested on pixels compatible with the design of the SXS of Astro-H, with the results clustered tightly around a resolution of 4 eV.



Photograph of 32 x 32 array of TES pixels on 0.3 mm pitch. The absorbers are composed of electroplated Au and Bi.

correct the accuracy of the spectral synthesis models in controlled ground-based experiments that will give 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 Scott Porter, Richard Kelley, Caroline Kilbourne, Joseph Adams, Stephen Smith, Demitra Koutroumpa, and Maurice 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.

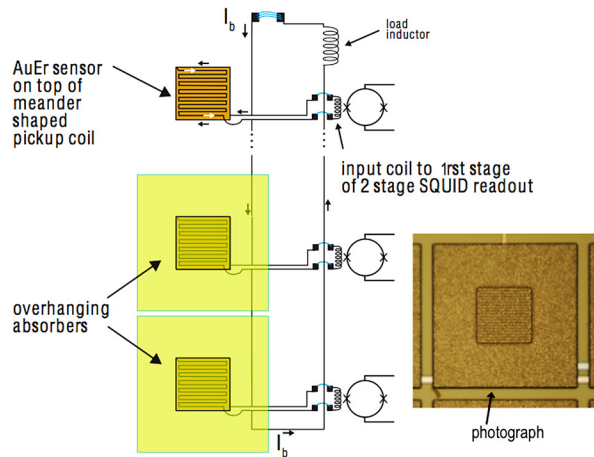
Non-equilibrium ionization conditions can also be produced with almost any astrophysically interesting ionization parameter. Typical measurements in our program include spectral-line identification, absolute cross sections, recombination, charge-exchange recombination, and cross sections in thermal and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

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 broad-band, 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 ongoing.

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 300 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 un-



Schematic of the read-out circuit for meander-based magnetic calorimeters. As shown in the illustration and photograph, an X-ray absorber can be affixed to each meander, making possible very large, close-packed arrays. Calorimeters of this design have achieved 3.3 eV resolution.

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 2011.

### 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 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 just now 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 includes 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.

The main development in the silicon-thermistor calorimeters since XRS/Suzaku has been in their X-ray absorbers. GSFC has been working closely with EPIR, a company that was awarded an SBIR contract to develop HgCdTe and 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. After extended process refinement and performance evaluation, EPIR's HgTe was selected for the SXS flight absorbers. Better than 4 eV resolution at 6 keV has been achieved using samples of EPIR HgTe in the size needed for SXS (0.83 mm wide). The SXS thermistor array itself is based heavily on the XRS design, but will include better heatsinking to reduce the impact of cosmic-ray heating.

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 not electrically short out the sensor, results in an unusual T-shaped geometry for the contact.

These devices consistently achieve energy resolutions of 2–3 eV FWHM at 6 keV. The pixels are sufficiently uniform that a  $2 \times 8$  SQUID multiplexer read-out demonstration, done in 2008 in collaboration with colleagues at the National Institute of Standards and Technology, achieved better than 3 eV resolution in all 16 pixels using the common biasing inherent to the design of the electronics. Work towards a  $3 \times 32$  SQUID MUX read-out demo is in progress, in order to demonstrate technology needed for the Interna-

tional X-ray Observatory. Arrays in a  $32 \times 32$  format have been completed, and process refinement for integrating high-density microstrip wiring with such arrays is nearly complete.

Goddard has also developed position-sensitive TES calorimeters. These devices join multiple absorbers to a single TES via different thermal links, and the pulse shape is used to determine which absorber received the X-ray photon. Four-absorber versions have demonstrated an energy resolution of 6 eV at 6 keV, and variations with larger absorbers and with more absorbers are being studied.

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. The change in inductance of the meander changes the current both through the meander and through the input coil of the SQUID.

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. Position-sensitive magnetic calorimeters analogous to the TES-based version are also under development.

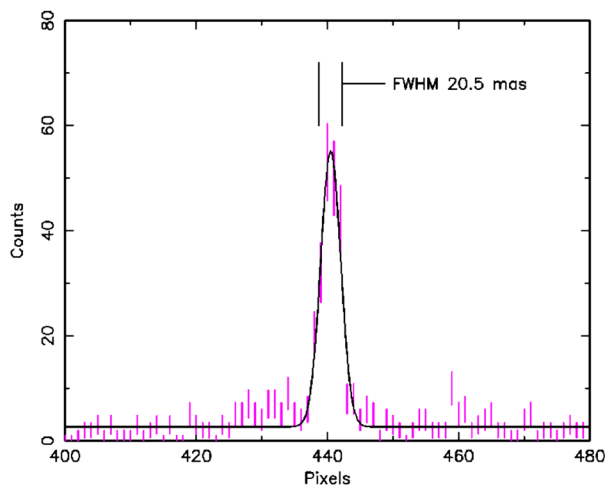
### X-ray Mirror Development: IXO and NuSTAR

Mirror technology development for the International X-ray Observatory (IXO), formerly known as Constellation-X, continues at GSFC and is led by Will Zhang. Zhang and his team are well on their way toward meeting the IXO requirement of 5". As of this writing, they have been able to consistently make mirror segments that, when properly aligned and integrated, will produce 7.5" X-ray images—within a factor of two of meeting the IXO requirement—by using a glass-forming technique.

They continued a collaborative effort with Goddard's Applied Engineering and Technology Directorate (AETD). They have completed two pairs of mandrels that meet IXO forming-mandrel figure requirements. 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.

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. They expect to complete a mini-module with at least two pairs of mirrors by 2010. 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



Projection of the image of a 5-mm slit formed in Cu Ka X-rays (8.04 keV) with a 3-mm diameter PFL. The focus has been trimmed with a refractive corrector lens. For comparison, the diffraction-limited response would correspond to 16.7 milliarcseconds, which includes slit-magnification and detector-resolution effects.



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 2008. It has been on schedule and on budget. The last batch of flight substrates will be delivered by March 31, 2010, helping the NuSTAR project to make its August 2011 launch.

### Coded-Mask and CdZnTe Detector Development

It is not possible to focus gamma rays with current technology, so the wide-field Burst Alert Telescope (BAT) on Swift uses a technique called coded-aperture imaging to image and localize incoming gamma rays. Gamma rays are detected at the focal plane by 32,768 pieces of CZT.

ASD (Barthelmy, Tueller, Okajima) has three development efforts to improve CZT detectors for new mission applications:

- the electronics and packaging for the Proto-EXIST and EXIST missions;
- a strip detector for the InFOCuS balloon instrument;
- a pixelated detector for homeland security uses.

The proto-EXIST and EXIST effort are described in the Suborbital section.

The CZT strip detector for InFOCuS is a 20-micron 2-D pattern of strips on 2mm CZT. ASD is working with Goddard's Engineering Directorate on this effort for the actual electrode fabrication on the CZT

material. This InFOCuS detector is  $26 \times 26 \times 2$ mm and uses the XA1 ASIC that we have previously used in the pixelated InFOCuS detector and for the Swift-BAT detector array. There is also a parallel effort to use the newer VATAGP7 ASIC from Gamma Medical-IDEAS, Inc.

The homeland security effort involves a  $20 \times 20 \times 5$ mm CZT crystal with an  $11 \times 11$  pattern of pixelated electrodes. Takashi Okajima (code 662) is working with the Engineering Directorate on this effort.

### Phase Fresnel Lens Development for X-ray & Gamma-ray Astronomy

Diffractive optics, specifically Phase Fresnel Lenses (PFLs), offer a mechanism to perform astronomical observations in the X-ray and gamma-ray energy regimes with diffraction-limited angular resolution. This translates to performing high-energy astronomy with milliarcsecond to microarcsecond angular resolution in the X-ray and gamma-ray bands. Furthermore, PFLs have high throughput at these high photonic energies and are capable of being scaled to large, meter-size dimensions, which would also lead to dramatic improvements in source sensitivity.

**These encouraging first results are a major step towards demonstrating that the superior imaging potential of PFL-based optics can be performed in a wide X-ray/gamma-ray energy band in a format that is scalable for astronomical applications.**

A group at NASA GSFC, in collaboration with the University of Maryland, has fabricated PFLs designed toward astronomical applications and characterized their imaging performance in an X-ray test-beam. The University of Maryland employed gray-scale Micro-Electrical-Mechanical System (MEMS) technology to fabricate two different PFL designs in silicon, one designed to image at 8 keV and the other at 17.4 keV. These PFLs were characterized in the GSFC 600-meter Interferometry Testbed. They demonstrated near diffraction-limited performance—corresponding to ~20 milliarcsecond angular resolution at 8 keV—with

an efficiency 76 percent of the theoretical maximum (limited by an observed and understood interference effect induced by the specific PFL implementation).

Initial imaging measurements on the PFLs designed for 17.4 keV have demonstrated imaging corresponding to ~25 milliarcsecond angular resolution; further development and experimentation is in progress. The group includes Drs. John Krizmanic, Gerald Skinner, Zaven Arzoumanian, Keith Gendreau, and Neil Gehrels at GSFC, and Prof. Reza Ghodsssi and his group at the University of Maryland. Additionally, an effort to fabricate binary PFLs at GSFC has been funded under a GSFC IRAD award to develop optics for solar imaging applications, in collaboration with Dr. Brian Dennis in the Heliophysics Science Division.

A key development has been overcoming one of the main limitations of purely diffractive optics—the narrow bandwidth in which superb angular resolution is obtained. The solution to this chromaticity problem is obtained by including a refractive component along with a PFL to construct an achromat. Refractive components have been fabricated at GSFC using diamond turning and a refractive lens was employed to “trim” the focal length of the 8 keV PFL, bringing the performance closer to the diffraction limit. Employing an inherent feature of PFLs—that the focal length is energy dependent—a proof-of-principle achromat was fabricated using the 17.4 keV PFL design for the diffractive component matched to an appropriate power refractive component. Initial test beam measurements determined a point-spread-function that was nearly flat over an energy range from 8–11.3 keV, validating that the chromaticity of a pure diffractive PFL can be overcome with a diffractive-refractive achromat. These encouraging first results are a major step towards demonstrating that the superior imaging potential of PFL-based optics can be performed in a wide X-ray/gamma-ray energy band in a format that is scalable for astronomical applications.

Advances in formation-flying spacecraft systems make an eventual mission feasible, and a team of scientists from ASD/GSFC are collaborating with the GSFC Guidance, Navigation, and Control (GN&C) Systems Engineering Branch, under a GSFC IRAD award (Shah, PI), to further develop the formation-flying aspects. The team had developed a flight dynamics tool

set to quantify the formation-flying requirements and analyze the performance of current attitude-sensor technologies, employing a milliarcsecond PFL-based X-ray imaging mission as a baseline. The team includes Krizmanic and Skinner from ASD, and Shah and Calhoun from GN&C.

### 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. The James Webb Space Telescope, scheduled to be launched in 2014, will provide a window into the epoch of galaxy formation to clarify the processes that produced the present universe.

**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 these systems.**

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 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 open-door flights, will be a key facility for imaging and spectroscopic follow-up of Spitzer and Herschel discover-

ies. 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.

The far-IR instrument development group in ASD (Benford, Chuss, Fixsen, Kogut, Moseley, Staguhn, Voellmer, Wollack) have 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, has recently been started and will use both the modulator and the large-format arrays.

One recent success has been the completion of a 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. This instrument, named GISMO, has been in use for astronomical observations at the IRAM

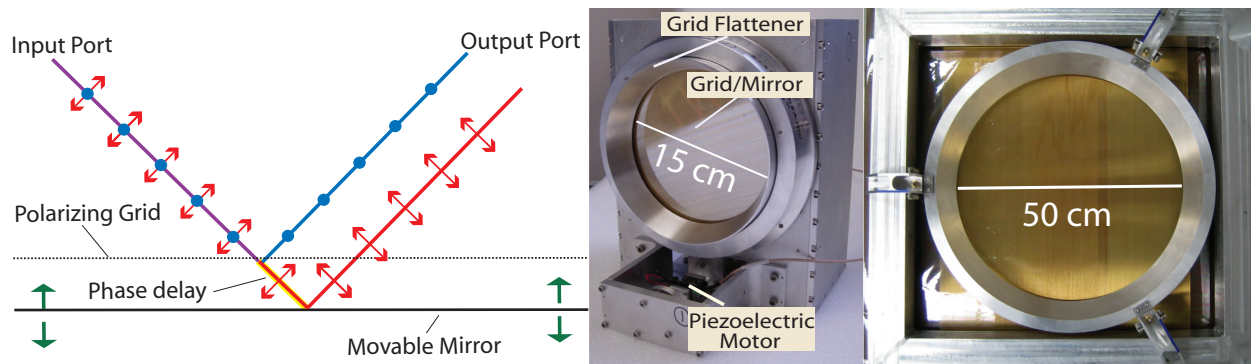
30m radio telescope in Pico Veleta, Spain, where it has already provided a great advance in our understanding of the technology and produced new astronomical measurements. This instrument is in the process of being made available to the worldwide astronomical community.

We have also produced the detector subsystem for the ZEUS spectrometer, an experimental instrument at the Caltech Submillimeter Observatory. Its relatively modest detector array (only 32 pixels) has nonetheless been able to make the first detections of redshifted line emission from galaxies halfway across the universe, near the epoch of peak star formation.

Recently, work has begun on a new generation of detector technology and instrument concepts. Based on superconducting resonators and kinetic inductance detection, this technology may enable entire instruments to be built on a single silicon wafer.

### Variable-delay Polarization Modulators for Exploring Inflation

The study of the cosmic microwave background (CMB) with missions such as COBE and WMAP has proven to be one of the most valuable tools in decoding the physics of the early universe. To explain the observed flatness and the origin of structure, it has been hypothesized that the universe underwent an early epoch of exponential expansion known as infla-



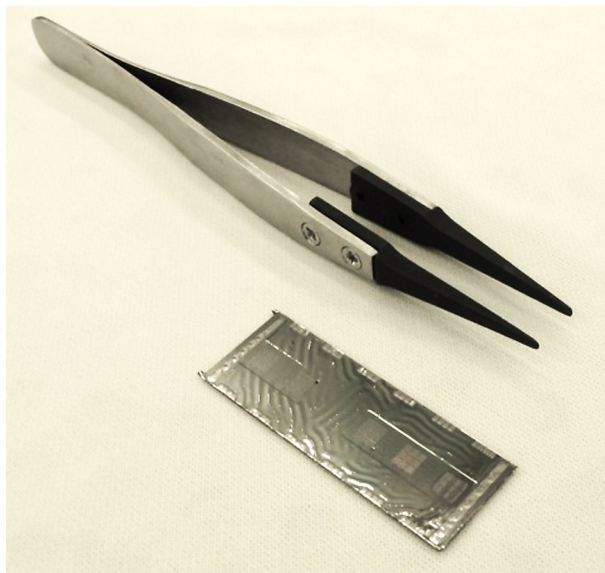
*Left:* A VPM consists of a polarizing grid placed parallel to and in front of a moving mirror. By varying the grid-mirror separation, a variable phase delay between two orthogonal polarizations is introduced. This delay sets the mapping between the output and input polarization states. *Center:* The Hertz VPM. This VPM provided a demonstration of the technology in the submillimeter regime. *Right:* A prototype large polarizing grid is shown, a required milestone on the path to constructing VPMs large enough to position at the front of CMB polarimeters.

tion. If inflation occurred, it is expected to have left a small, polarized signature on the CMB. Measurement of such a signal would provide direct evidence for this inflationary epoch, along with a means by which to measure the physics of the first  $10^{-32}$  second of the universe.

Polarization modulation provides a means for extracting the small polarized signal from inflation from the large unpolarized CMB. To this end, variable-delay polarization modulators (VPMs) are being developed for a space-based instrument to measure the polarization of the CMB by David Chuss, Edward Wollack, Harvey Moseley, Gary Hinshaw, and George Voellmer in the ASD Observational Cosmology Lab. These modulators consist of a polarizing grid placed parallel to and in front of a movable mirror. By varying the grid-mirror separation, the phase between two orthogonal linear polarizations is also varied. This leads to a modulation of a single linear Stokes parameter with little contamination from the instrument.

VPMs are potentially well-suited for a space mission because they avoid the use of dielectrics that require complex antireflection coatings. The modulation motion can be accomplished using small linear motions that can be done with reliable frictionless flexures. In addition, VPMs can be constructed large enough to cover the primary aperture of a telescope. This is advantageous in that it allows the modulation to be encoded on the signal before it can be contaminated by the instrument. In addition, the symmetry of the VPM modulation can be employed to reduce systematic errors, another key property of an eventual successful CMB polarimeter.

Prototype VPMs have been constructed for use with the Hertz submillimeter polarimeter. These have been demonstrated at the Submillimeter Telescope Observatory in Arizona. The team is currently working on second generation VPMs for use in the Primordial Inflation Polarization Explorer (PIPER), a balloon-borne CMB polarization experiment (PI, Kogut). The VPMs for PIPER will operate at 1.5 K, and therefore much of the current effort in design and fabrication involves challenges associated with these low operating temperatures that are similar to those for a space mission. The VPMs, along with detectors being developed



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

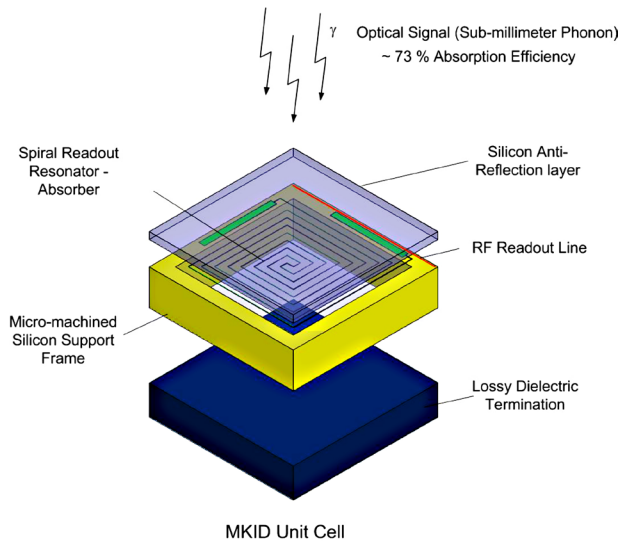
in the Laboratory, are a key technology on the path to an eventual CMBpol Inflation Probe mission.

### 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  $\mu\text{m}$  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 ( $\sim 10^5$  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—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 ultraluminous 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





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.

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 which 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 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 metalization 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 micro-wave transmission line.

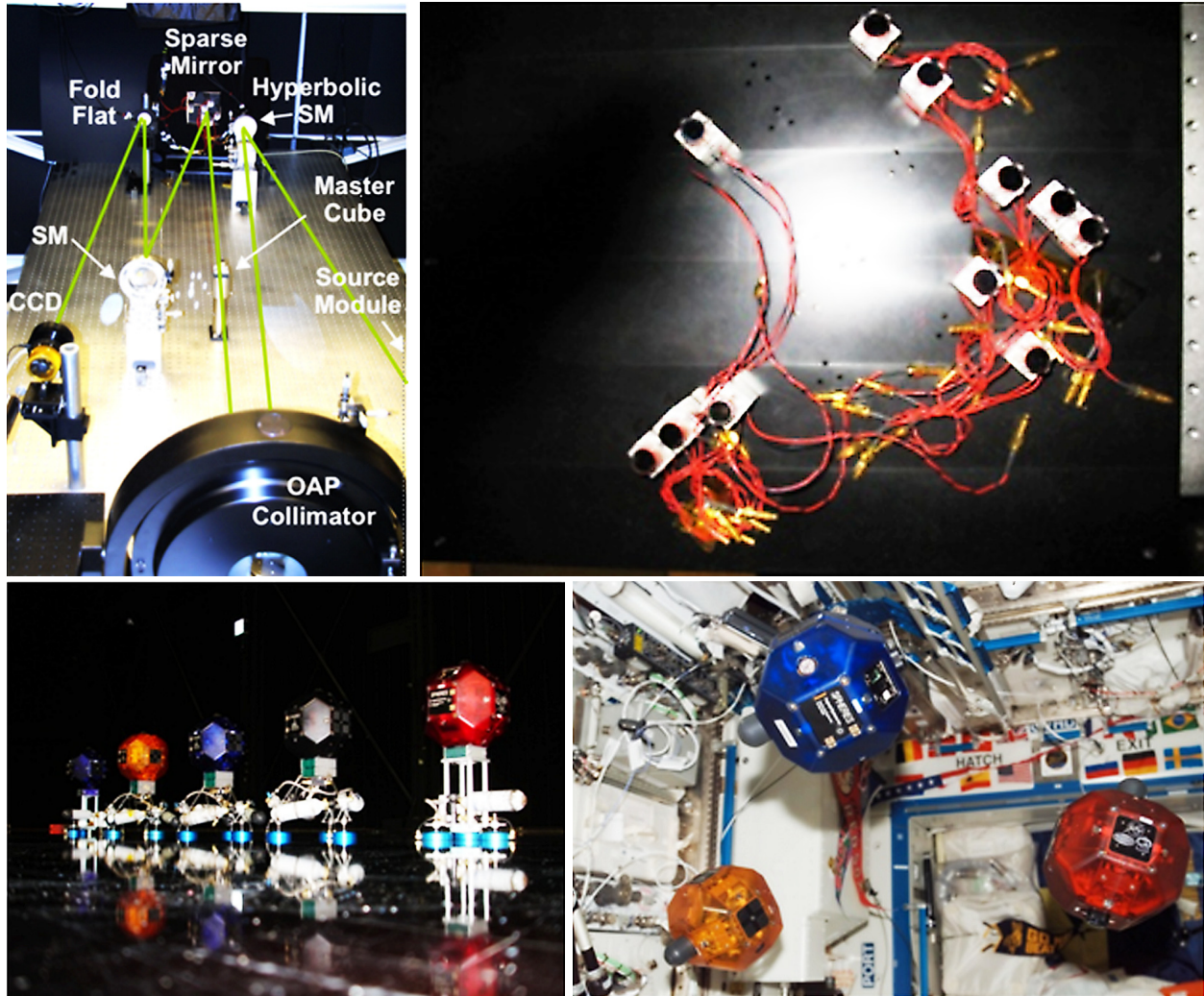
In the approach under development, the meander is chosen to have a surface-impedance and filling factor such that it presents the optimal matching impedance to the incoming wave, about  $157 \Omega$  per square. When the optical power is absorbed, it excites quasiparticles in the superconducting spiral, 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  $\sim 1$  GHz. The  $Q$  of the unilluminated 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  $350\mu\text{m}$  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

Dr. Kenneth Carpenter is coordinating the development of various technologies needed to enable large baseline, space-based imaging interferometers. These include:

- 1) the GSFC Fizeau Interferometer Testbed (FIT), a ground-based experiment to develop closed-loop, nanometer-level optical control of a many-element sparse array;



*Top left:* FIT Phase 1 at GSFC, 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 flying inside the International Space Station.

2) the MIT Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) experiment, which uses hardware on ground-based flat-floor facilities (2-D) and in space (3-D) inside the International Space Station (ISS), to test centimeter-level Precision Formation Flying (PFF) algorithms; and

3) the GSFC Formation Flying Testbed (FFTB), a hardware-in-the-loop simulation facility that includes a simulated deployment of array spacecraft and the multi-stage acquisition of target light the individual mirrors by the beam-combiner.

GSFC is also supporting an MIT SBIR Program utilizing the SPHERES to further develop formation-flying

and synthetic-imaging maneuvers for sparse arrays. The primary goals of these programs are to mature the command and control algorithms required to enable formation-flying sparse-aperture/interferometric imaging missions. These systems must collectively operate over  $\sim 12$  orders of magnitude, from the nanometer to the kilometer scale, and will therefore consist of “staged-control” algorithms operating in smaller, overlapping regimes but operating cooperatively over the full dynamic range.

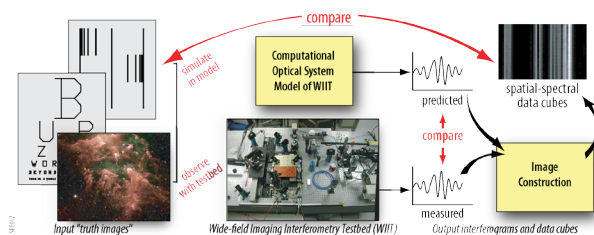
Kenneth Carpenter is the PI of the FIT effort and key Co-I’s include Richard Lyon (GSFC), and David Mozurkewich (Seabrook Engineering). The GSFC-located FIT is developing and demonstrating closed-



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 the MIT 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.

Eric Stoneking (GSFC/Engineering) has performed the most recent FFTB experiments. The end goal of all 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 numerous additional missions being considered by NASA for flight, including the Space Infrared Interferometric Telescope (SPIRIT), Sub-Millimeter 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 Exo-Planet Probes, and ESA's Pegase. Please see [hires.gsfc.nasa.gov/si](http://hires.gsfc.nasa.gov/si) for additional information.

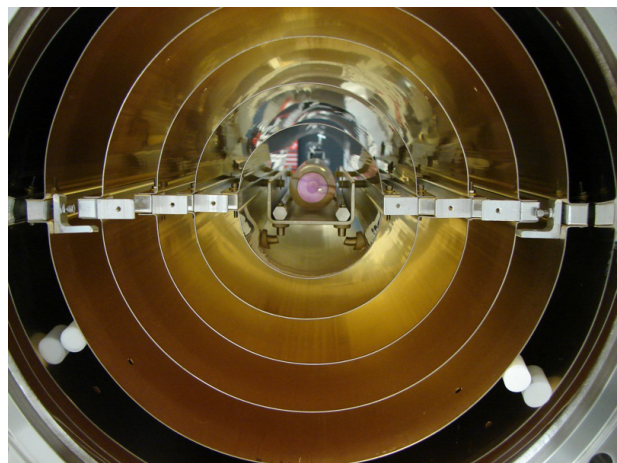


The Wide-field Imaging Interferometry Testbed is functionally equivalent to the Space Infrared Interferometric Telescope, SPIRIT. The testbed, a high-fidelity model of the testbed, and new algorithms for spatial-spectral image construction, provide vital practical experience with the wide-field double-Fourier interferometric technique to be used on SPIRIT

## Wide-field Imaging Interferometry Testbed

Leisawitz and Rinehart are developing a broadly-applicable technique for wide field-of-view “double Fourier” (spatial and spectral) interferometry and evaluating its practical limitations. The Space Infrared Interferometric Telescope (SPIRIT; see the Mission Concepts section) could employ this technique—an analog to integral field spectroscopy—to image stars, planetary systems, and galaxies in the far-IR at 100x better angular resolution than the Spitzer Space Telescope while simultaneously providing information-rich spectra.

In 2009, the Wide-field Imaging Interferometry Testbed was used to collect a vast amount of high-quality interferometric data, an optical model of the testbed was refined and used to generate representative synthetic interferograms, and a wide-field spatial-spectral image-construction algorithm was further developed. A variety of spatial-spectral test scenes were observed in the lab, in most cases with the full u-v plane coverage required for high-fidelity image reconstruction. A new GSFC IRAD project will enable the replication of a NIST prototype hyperspectral scene generator. When ready, this device will produce complex, astrophysically realistic test scenes for observation in the lab. Co-op student Evan Sinukoff (McMaster University) gained proficiency in tuning and running the optical model, and model interferograms were found to be in excellent agreement with those observed.



A new support structure for the optical cavity and thermal shields was designed by students and installed in late 2009 after the move to the Exploration Sciences Building.

Funding support for this research comes from the ROSES APRA program. The period of performance runs through FY11, by which time wide-field imaging interferometry will have matured to TRL 6.

### Technology Development for LISA

Demonstrating technology readiness is critical to the success of the LISA mission. Scientists in the Gravitational Wave Astrophysics Laboratory, including Tuck Stebbins, Jeff Livas, Stephen Merkowitz, Jordan Camp, Kenji Numata, Felipe Guzman, and Ira Thorpe, are leading efforts to develop a number of technologies critical to LISA.

In addition to mitigating risks for LISA, these activities provided an opportunity for students to do cutting edge research. In 2009, several undergraduate students were involved in these activities including Chad Healy (USNA), Jeremiah Noordhoek (MIT), Kyle Norman (CU Boulder), Scott Smedile (VA Tech), and Wataru Kokuyama (U. Tokyo).

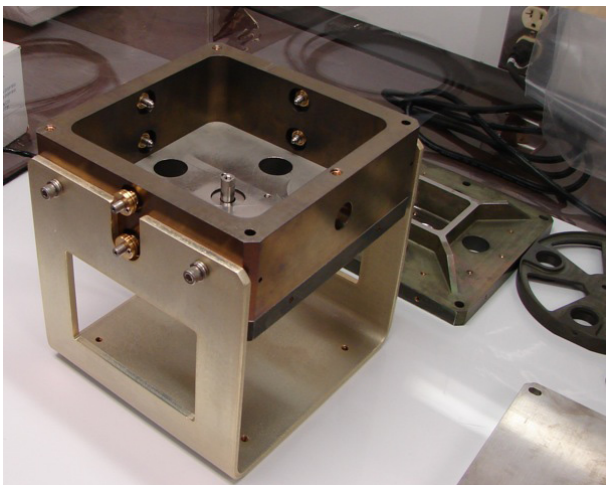
**Laser Frequency Stabilization.** LISA will use laser interferometry to monitor the distance between freely-floating test masses on spacecraft that are separated by five million kilometers. This measurement must be made with a precision on the order of 10pm (1pm =  $10^{-12}$  m) so that the effects of gravitational waves can be measured. A stable laser wavelength (or frequency) is critical to achieving this accuracy. Although LISA will employ a sophisticated post-processing technique

known as Time Delay Interferometry (TDI) to reduce the effects of laser frequency noise, it will still be necessary to actively stabilize the laser frequency.

One option for stabilizing the LISA lasers is to use the long arms of the constellation as a frequency reference, a technique known as arm-locking. Together with controls engineer Peiman Maghami (Code 591), Thorpe and Livas are studying arm-locking through frequency and time-domain simulations. By applying the techniques of optimal control theory to the problem of arm-locking, they have developed an approach that is less complex than the current baseline technique but with similar performance.

Another technique for stabilizing the LISA lasers is to use resonant optical cavities, a method commonly used in ground-based laboratories. The GSFC group has been developing optical-cavity-based stabilization systems for LISA for several years and has demonstrated that their performance exceeds the LISA requirements. Recently Livas, Numata, and Thorpe developed a modification to the standard optical-cavity technique that allows the stabilized laser to be tuned to any desired frequency without significantly degrading the stability. This work, which is the subject of a patent application, allows cavity stabilization to be combined with arm-locking, further increasing the performance margin for LISA.

**Optical Assembly Articulation Mechanism (OATM) Testing.** The LISA mission consists of a triangular



The inch-worm actuator was installed into the custom test apparatus in late 2009.



Summer student Kyle Norman uses a camera to inspect a bond during construction of the silicon carbide telescope structure.

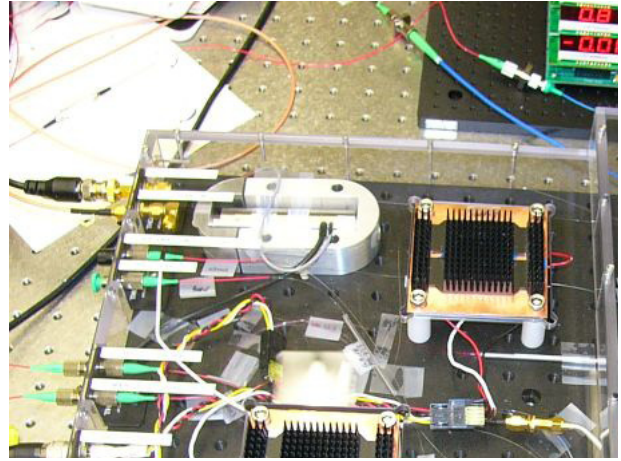




The completed silicon carbide telescope structure. A white cloth visible on the primary plate protect the optics mounting pads from scratches and dust.

constellation of three spacecraft, with interferometric links along each side of the triangle. As the spacecraft evolve in their orbits, the angles between pairs of arms vary slightly. A mechanism is needed to compensate for this variation and ensure that the LISA optical assembly is properly pointed at its distant target. The combination of high precision and large dynamic range is challenging for typical actuators. However, a device known as a piezoelectric inch-worm is well-suited for such an application. GSFC has identified and procured an inch-worm that could meet the LISA requirements. Merkowitz and Thorpe, together with contract and civil-servant engineering support, are developing a test apparatus to evaluate the inch-worm. Using capacitive and interferometric sensing, the precision and stability of the inch-worm will be evaluated over its entire dynamic range. The test bed construction is nearly complete and a test campaign is expected to begin in early 2010.

**Telescope Structure Stability:** The LISA telescope is used to increase the light-transfer efficiency between distant spacecraft. Since it lies in the interferometric

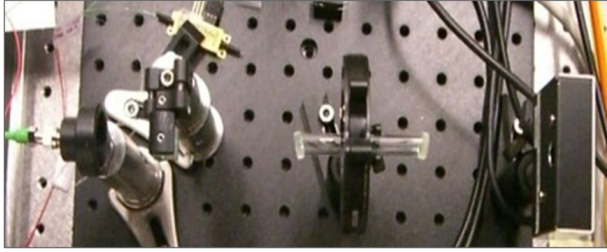


Fiber lasers such as this one developed at GSFC could be an alternative to commercial NPROs for the LISA seed lasers.

path, it is critical that the optical path length through the telescope remain stable at the picometer level. Standard athermal design methods must be modified due to the presence of a large axial temperature gradient, since the secondary mirror looks at cold space while the primary is near the main optical bench, which is at room temperature. There is a smaller transverse temperature gradient as well.

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 then bonded together using hydroxide-catalysis bonding. The structure will be tested in a thermal vacuum chamber 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. Testing is expected to begin in the spring of 2010.

**Fiber laser development.** The LISA laser requires a single-longitudinal-mode output with high intensity



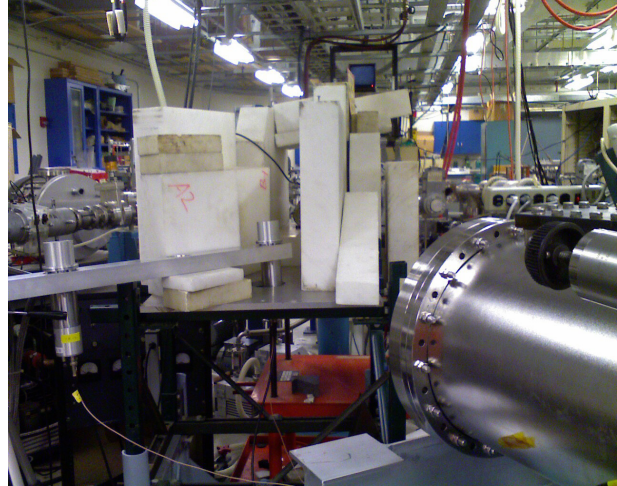
A simple iodine wavemeter based on a frequency-doubling waveguide and a fixed-pressure short iodine cell aids in heterodyne acquisition.

and frequency stability. Fiber laser/amplifier technologies have made great advances over the last decades and have some advantages over traditional bulk-optics-based lasers and amplifiers.

Numata and Camp, together with technical support from the GSFC laser and electro-optics branch, have developed a ytterbium-fiber-ring laser. The performance of the fiber laser is comparable to commercial Non-Planar Ring Oscillator (NPRO), which has been traditionally used in low-noise applications. The fiber laser offers alignment- and magnet-free operations, rapid coupling into a fiber amplifier, and a spatially cleaned output.

Space qualification testing of the fiber components is expected to begin in the spring of 2010. It will include radiation hardness, outgas, thermal cycling, and vibration tests. This work is in cooperation with Lucent Government Solutions (LGS), which is performing thermal cycling tests of fiber amplifiers for LISA. In addition, Numata and Camp are investigating alternative oscillator configurations at several industrial vendors. These include the use of lasers based on short, high-gain phosphate glass fibers, and external cavity waveguides.

**Absolute frequency reference.** The heterodyne interferometry employed by LISA relies on the ability to match the absolute frequencies of the lasers on each spacecraft to within tens of megahertz. Numata, Camp, and Kokuyama have developed a reliable heterodyne acquisition system based on an iodine cell. They have demonstrated that two lasers can be tuned to a known absolute frequency within  $\sim 10$  MHz accuracy using a very simple setup.



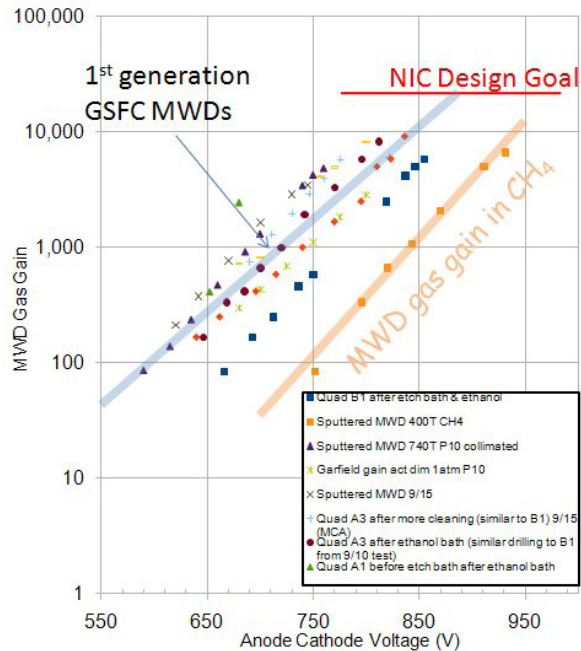
The  $10 \times 10 \times 15$  cm<sup>3</sup> NIC prototype and liquid scintillator neutron monitor at the NSWC Positive Ion Accelerator Facility. Neutrons were symmetrically scattered from the first scintillator into the second scintillator and the NIC.

### 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 that will provide optimum angular resolution over the energy range from  $\sim 5$ –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 by-products.

Stanley Hunter, with Georgia de Nolfo, 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  $\mu\text{m}$  diameter on 400  $\mu\text{m}$  centers, is a gas proportional counter which allows gas gain in excess of  $10^4$ . Negative ion drift is utilized to reduce the drift





Gas gain vs. anode/cathode voltage performance of second-generation GSFC MWDs produced in 2009 is similar, and in some cases, exceeds the performance of the first-generation MWDs (blue line). The gain measurement was done using a collimated  $^{55}\text{Fe}$  source, in P-10 (90% Ar, 10%  $\text{CH}_4$ ) gas at 1 atmosphere. The maximum gain is limited by breakdown. Orange data points are in pure  $\text{CH}_4$  gas.

velocity and diffusion allowing for the large TPC volume. This team's accomplishments this year include:

1) Complete analysis of the Neutron Imaging Camera (NIC) data taken at the NSWC Positive Ion Accelerator Facility (PIAF). This analysis, including measured neutron angular resolution,  $\theta_{68} \sim 8$  deg at 2 MeV, were presented by Dr. Son at the APS meeting in Denver and by Dr. de Nolfo at the IEEE meeting in Massachusetts.

These NIC results were obtained using helium-3, the traditional neutron-detection gas. The availability of helium-3, however, has recently become very limited with little or no improvement foreseen. This forced us to re-examine the operation of the NIC. Extensive calculations, corroborated with GEANT4 by Dr. de Nolfo and GARFIELD simulations by Dr. Dion, indicate that the NIC performance can be realized

using multiple proton scattering in a proton rich gas such as methane or ethane. Michael Shields, a summer intern, contributed to these calculations. Ongoing MWD testing has demonstrated viable operation in methane. This work was summarized in an internal report and included in a detailed brief to DTRA in September 2009.

2) The in-house laser micro-machining facility was re-established, including upgrades to the computer interface and control software, and addition of Lab-View image processing software. Improvements in our micro-machining techniques have resulted in fabrication of high-gain  $10 \times 10 \text{ cm}^2$  MWDs to track minimum ionizing electrons resulting from photon interactions in the TPC gas. The next goal is to produce  $30 \times 30 \text{ cm}^2$  MWDs.

3) The electrical and mechanical design of a  $30 \times 30 \times 30 \text{ cm}^3$  3-DTI prototype has been completed. This prototype will require 1,536 channels of charge amplifier and transient digitizer. Two versions of an ASIC with sixteen channels of charge and shaping amplifiers, optimized for negative and positive signals, have been fabricated and are being tested. A new readout method has been devised and incorporated into the design of the transient digitizers. This "streaming mode readout" eliminates essentially all dead-time in the 3-DTI by continuously sampling the output and sending only those samples above threshold to the next level of data processing, i.e., hardware zero-suppression. The front-end ASIC board, TD concentrator board, and the power distribution board make up the remainder of the electronics. The design of these boards has started.

4) A second  $10 \times 10 \text{ cm}^2$  test chamber was built. This chamber also provide a means of testing MWDs up to  $30 \times 30 \text{ cm}^2$  using the existing 10 cm electronics.

S. Hunter and collaborators submitted the White Paper "Medium Energy Gamma-Ray Astrophysics" for consideration to the Astro2010, Astronomy and Astrophysics Decadal Survey.

### Photon Counter Detector Development

Work is ongoing in the Exoplanets and Stellar Astrophysics Lab to develop photon-counting detectors for

space in the UV, visible and near-IR by Woodgate, Kimble, Rauscher, Norton, and Hilton.

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 AlGa<sub>N</sub> and MgZnO, in both planar and nano-wire forms. By cesiating GaN, QEs of 50–60% at 180 nm, a factor ~6 higher than flown on HST/STIS, and 65–68% 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 AlGa<sub>N</sub> photocathodes. Woodgate, along with GSFC engineering, university, NIST, and commercial partners, plans to build these photocathodes into EBCCD and 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 will use 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.

In the Near-IR the use of InGaAs photocathodes in EBCCD detectors are being investigated, including the extension of useful external QE at cold temperatures for long exposures via an SBIR program.



## V. Projects

### *Projects in Operation*

#### **The Fermi Gamma-ray Space Telescope**

GSFC personnel are extremely active in all aspects of Fermi (formerly the Gamma-ray Large Area Space Telescope, GLAST), both at the mission level and within the instrument teams. Highlighted here is GSFC's role in Fermi's Large Area telescope (LAT), some of the current LAT activities, and some of the mission-level work, including the Science Support Center.

#### *Fermi-LAT First Year Science*

**Current Fermi LAT Activities.** The LAT Principal Investigator is P. F. Michelson (Stanford). Within the LAT team, GSFC members played key roles throughout the first year of science observations. Presently, the major roles include the following: N. Gehrels (Senior Scientist Advisory Committee [SSAC] chair and Publication Board [PB] member); A. Harding (Galactic Sources Group coordinator), E. Hays (Spectral Analysis Study group lead), J. McEnery (SSAC, PB, GRB commissioner); A. Moiseev (active in electron analysis); D. J. Thompson (Multiwavelength Coordinator, Catalog Group coordinator, SSAC). Bonnell, Corbet, Davis, Ferrara, Hirayama, Hunter, Sambruna, Shrader, and Stecker are affiliated-scientist members of the LAT team.

GSFC scientists have made major contributions to the first year of LAT science results. McEnery focuses on the study of high-energy gamma-ray emission from gamma-ray bursts, especially the temporally extended component recently discovered by Fermi to be present in all high-energy-emitting GRBs. Alice Harding plays a key role in data analysis and theoretical interpretation of the growing Fermi pulsar populations. Hays, in collaboration with C. C. Cheung (former GSFC postdoc) conducts searches for unassociated gamma-ray transients near the Galactic Plane and pursues multiwavelength follow-up to determine their origin. J. Racusin is pursuing Fermi-Swift overlap studies of GRBs. Corbet has played a key role in the detection of periodicity in gamma-ray binaries such as LS +61 303, LS 5039, and Cygnus X-3. Ferrara participates in the identification of pulsar candidates and is leading work

to characterize the current unassociated gamma-ray source population.

Goddard plays an important role in a very broad variety of LAT activities through a number of students and postdocs that collaborate with the international team. The current PhD students are T. Johnson, W. McConville, E. Winter, M. DeCesar, S. Zhu, and J. Cohen (all at University of Maryland), and the post-docs are O. Celik, and V. Vasileiou. McConville has served as both a data quality monitor and a gamma-ray skywatcher/flare advocate. Vasileiou and Winter contribute burst advocate shifts and the analysis of GRBs with the LAT data. In addition, Vasileiou has developed an innovative method for characterizing LAT background rates during gamma-ray burst observations. Zhu is studying possible improvements to onboard gamma-ray burst detection that may enhance the ability of the LAT to respond to high-energy activity and trigger critical multiwavelength follow-up observations. McConville analyzes the temporal and spatial properties of gamma-ray emission of radio galaxies, such as NGC 1275 and Cen A. Johnson and Celik have conducted high-precision studies of the dependence of gamma-ray emission from bright pulsars, such as Vela, Crab, and Geminga, depends on rotational phase. Johnson is also active in characterizing the spectra of gamma-ray millisecond pulsars for use in deciphering the underlying emission mechanism of this growing gamma-ray source class. DeCesar explores the pulsar lightcurves from gamma rays to radio as a tool for probing emission zones. Cohen is beginning work to characterize the morphology and spectra of the unpulsed, nebular component present in some gamma-ray pulsars.

**Fermi Mission and SSC.** The Fermi mission is managed at Goddard, and the Mission Operations Center (MOC) is located here. The MOC is staffed by an outstanding Flight Operations Team and is supported by a small sustaining engineering group. McEnery is the Project Scientist, and Hays, Thompson, and Gehrels are Deputy Project Scientists. The Fermi Science Support Center (FSSC) is also located at Goddard and is led by Chris Shrader. The FSSC functions can be divided into three main roles.

- 1) The mission planning and operations branch compiles and optimizes the Fermi observation plan (including responding to and evaluating Target of Op-

portunity requests). This branch runs weekly planning meetings to coordinate observatory operations across all mission elements.

2) The analysis software and databases branch developed the high-level analysis software in partnership with the LAT and Gamma-ray Burst Monitor (GBM) instrument teams. The FSSC serves data to the community, working with the HEASARC to ensure that the analysis tools and data formats conform to standards in high-energy astrophysics. High-level LAT data and all GBM data have been hosted since the beginning of science operations; the portal to the low-level LAT came online in August 2009; and the first catalog provided by the LAT is hosted by the FSSC.

3) The user-support branch of the FSSC is responsible for running the Fermi guest investigator program, developing proposal preparation tools, providing documentation, running workshops, and answering questions via an electronic helpdesk. Cycles 1 and 2 were both very successful, and the Cycle 3 proposal deadline is February 5, 2010. The FSSC hosted a series of highly successful data analysis workshops during late 2009 to aid guest investigators in using the tools and developing proposals.

Supporting all three branches of the FSSC is a group of talented programmers and software engineers who build and maintain the software infrastructure and web pages. All the mission elements are functioning together efficiently and seamlessly.

### The Rossi X-ray Timing Explorer

The Rossi X-ray Timing Explorer (RXTE) celebrated its 14th birthday on Dec. 30, 2009, and began its 14th cycle of observations. Of currently operating NASA missions, only Hubble has been in orbit longer. Jean Swank is the Project Scientist and Tod Strohmayer became the Deputy Project Scientist in 2006. In its long and productive history, RXTE is responsible for numerous discoveries resulting in three Rossi Prizes—to Strohmayer and Chakrabarty (2006), Kouveliotou and Thompson (2003), and Bradt and Swank (1999)—more than 90 PhD 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 (including Keith Jahoda, Craig Markwardt, and Nikolai Shaposhnikov at Goddard). Improvements in background determination and response matrices continue to be made.

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 personnel Evan Smith and Divya Pereira). RXTE's most-used follow-up capability is currently for time-scales 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.

**RXTE is the only current X-ray observatory with the capability to routinely measure the millisecond spin periods of accreting neutron stars.**

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, are allowing the mission to operate through September 2010. The possibility of extension of RXTE's mission for an additional

year or two beyond that will be addressed by NASA's 2010 Senior Review, to which RXTE has been invited to submit a proposal. This will allow the torch of X-ray coverage of variable sources to be passed to other missions, such as the recently launched MAXI and the yet to be launched Astrosat.

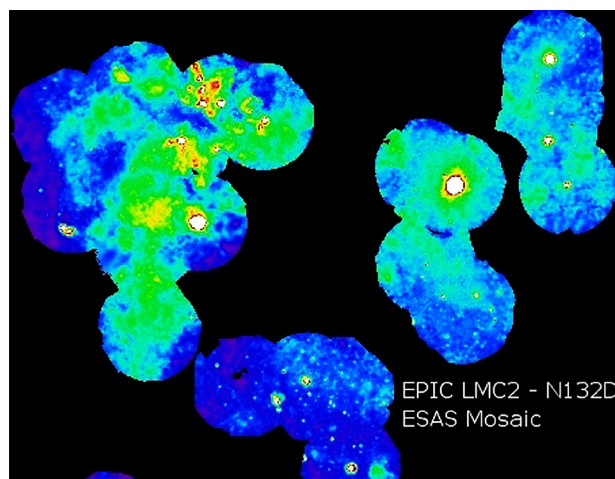
RXTE is the only current X-ray observatory with the capability to routinely measure the millisecond spin periods of accreting neutron stars. Recent observations have led to the discovery of two more of these objects, including one, NGC 6440 X-2, that shows unusually short, faint, and frequent outbursts that are easily missed with current X-ray monitoring capabilities, suggesting that a sizeable population of similar objects may await discovery. A program of monitoring pulsar spin histories of magnetars has recently found sudden increases or glitches in their spin rates with exotic properties. In several cases, the frequency jumps up, but then more slowly recovers to a value less than the pre-glitch frequency. This is the first time such "negative recovery" glitches have been seen in magnetars (postdoctoral researcher Fotis Gavriil is involved with this work). Coverage of the QPO and spectra of multiple Galactic black holes—including the newly discovered sources XTE J1652-453 and XTE J1752-223—allow the correlations to be related to fundamental properties of mass and spin (as by postdoctoral researcher Nikolai Shaposhnikov). RXTE's observing flexibility is enabling it to support Fermi monitoring observations of blazars, such as the recent observing campaign studying active flaring in Mrk 421.

### XMM-Newton Guest Observer Facility

ASD operates the U.S. XMM-Newton Guest Observer Facility (GOF). ESA allocates resources to support European XMM-Newton users, but looks to the U.S. GOF to provide support to the large U.S. community. GOF activities include facilitating the submission of GO proposals to ESA and the supplying of expertise, analysis software, documentation, new data products, and access to the data, including both the distribution of proprietary data to PIs and to the full public science archive. The GOF organizes the GO budget submission and review process and manages the distribution of awarded funds.

A U.S. XMM-Newton Users Group under the chairmanship of Prof. Craig Sarazin (U. Virginia) provides community oversight of GOF activities. Steve Snowden is the NASA Project Scientist. The XMM-Newton GOF works in conjunction with the GSFC 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 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-Newton and include (besides the activities mentioned above) development of software tools (ESAS, QuickSim, Xsim) and the updating of HEASARC multi-mission software (Browse, PIMMs, etc.). The GOF created and maintains the extensively used "ABC Guide" and "D Guide" for the analysis of XMM-Newton science data. The GOF has also supported the HEASARC HERA project which will provide an online multimission (including XMM-Newton) data analysis capability.

The GOF remains involved in the particle background calibration of the X-ray imagers and the cross-calibration between the XMM-Newton instruments and other X-ray observatories (e.g., Chandra, Suzaku, ASCA,



XMM-Newton European Photon Imaging Camera (EPIC) image of the LMC2 – N132D region of the Large Magellanic Cloud. This background-subtracted, exposure-corrected image was made possible by software developed by the GOF.

and ROSAT), which enhances the utility of multi-observatory data analysis. This has been a major activity over the last three years, with major XMM-Newton GOF participation in the International Astronomical Consortium for High Energy Calibration (IACHEC). It became clear, thanks to the efforts of the XMM-Newton SOC at the European Space Astronomy Center (ESAC) and the GOF, that the XMM-Newton calibration has become very reliable and that direct comparison of Chandra and XMM-Newton results on clusters of galaxies revealed a previously unknown error in the Chandra calibration which has major implications for cosmology.

The GOF prepared and maintains 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. The GOF worked with the 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.

The XMM-Newton archive at the GSFC GOF 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.

The GOF consists of Project Scientist Snowden, GOF scientists Lynne Valencic and Kip Kuntz, and about four other support personnel and programmers. The scientific return to the community is exceptionally high for such a lean staff.

## 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.

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 afterward—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 1600 and 6000 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.

**By the end of 2009, more than 800 refereed papers have been published that are based on Swift results. These Swift papers have a very high citation rate of around 19 per paper on average (more than 15,000 total).**

In the five years since launch, Swift has detected and localized approximately 500 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 45 short and hard GRBs, about half with likely host identifications and/or redshift estimates. These observations provided





Ultraviolet mosaic image of M31 taken with Swift's UVOT in filters uvw1 (192.8 nm), uvm2 (224.6 nm), and uvw2 (250 nm). The image shows a field of  $\sim 100 \times 50$  arcminutes.

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 from the shock breakout from the surface of a star 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 1,400 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 after being requested.

By the end of 2009, more than 800 refereed papers have been published that are based on Swift results. These Swift papers have a very high citation rate of around 19 per paper on average (more than 15,000 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 100 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 ground-breaking mission. It was ranked first in the 2008 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-GRB science. During the 2009 Cycle 6, 169 proposals were received, requesting \$4.8M in funds and 16.7 Ms total exposure time for 1,244 targets. The oversubscription rate has grown to a factor of 4.4 for non-TOO proposals and the TOO category had an oversubscription factor of 6.1.

### **Suzaku (Astro-E2)**

Suzaku (Astro-E2) 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, 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. In the third observing cycle (April 2008–March 2009), Long Proposals (observing time > 300 ks) were introduced to the program. In the fourth observing cycle (April 2009–March 2010), key projects (observing time > 1Ms) were introduced. Four key projects were selected: extensive mapping of the Galactic center region; a comprehensive study of anomalous X-ray pulsars; a deep observation of Kepler's SNR to characterize the explosion mechanism through measurements of modest-abundance metals; and a census of broad Fe lines in AGN. Also, joint Suzaku-Chandra

observations are now available through the Chandra GO program.

Suzaku received a high ranking (fourth of nine missions) by the 2008 NASA Senior Review of operating missions. Funding is secure through FY 2011, and the opportunity exists to extend U.S. participation beyond that through a proposal to the 2010 Senior Review.

The Suzaku GOF 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 GOF staff consists of three full-time scientists (Koji Mukai, Kenji Hamaguchi, Katja Pottschmidt) and one programmer, plus part-time support from HEASARC staff.

## INTEGRAL

INTEGRAL, the INTErnational Gamma-Ray Astrophysics Laboratory, is an ESA mission with which NASA has partnered since its selection in 1995. It was launched in October 2002 and has now completed more than seven years of successful scientific operations.

INTEGRAL carries two main instruments—the high-resolution gamma-ray spectrometer, SPI, and the high-angular-resolution gamma-ray imager, IBIS—as well as X-ray and optical monitors. Together, these instruments provide unprecedented spectral coverage from the optical to gamma-ray energies up to 10 MeV, as well as excellent imaging capabilities at hard X-ray and gamma-ray energies.

The scientific goals of the INTEGRAL mission are varied and far-reaching. The SPI instrument is a coded-mask germanium spectrometer with excellent energy resolution in the low-energy gamma-ray regime, from 20 keV to 8 MeV. It was designed to study, in detail, gamma-ray lines produced through a variety of processes. These include the decay of radioactive isotopes produced in supernovae and novae as well as the annihilation of positrons near the center of our Gal-

axy. SPI can trace the production of these radioactive isotopes and positrons by mapping the locations and intensities of the resulting gamma-rays. These studies lead to a better understanding of the chemical evolution of the Galaxy, Galactic star-formation rates, and the inner workings of supernovae and novae.

The IBIS imager is a coded-mask gamma-ray telescope that operates between 15 keV and 10 MeV. The sensitivity and angular resolution of this telescope make it extremely useful for observing Galactic black hole and neutron-star binary systems as well as active galactic nuclei (AGN). To this end, a significant portion of the INTEGRAL observing time has been spent scanning the Galactic disk and Galactic Center region in an effort to monitor the known Galactic X-ray binary population and discover new sources. Studies of these binary systems give us a better understanding of the end products of stellar evolution.

In the seven years since launch, there have been numerous notable discoveries, including:

- Discovery that the hard x-ray/soft-gamma-ray emission from the Crab nebula/pulsar is highly polarized, suggesting that the high-energy electrons producing this emission are in a highly ordered structure near the pulsar.
- Discovery that the Galactic 511 keV emission due to positron annihilation is not symmetric about the Galactic Center. This has significant implications for determining which source(s) are producing these positrons.
- Observations of the gamma-ray lines from the decay of both  $^{26}\text{Al}$  and  $^{60}\text{Fe}$  in the Galaxy suggest that much of the  $^{26}\text{Al}$  is produced in core-collapse supernovae.
- Discovery of a large number of X-ray binary systems containing a supergiant companion. Among this class of objects, two subclasses have been identified: Systems with highly absorbed soft X-ray spectra and systems that exhibit very fast transient behavior. The hard X-ray sensitivity of IBIS and its monitoring observing program were instrumental for these discoveries.

Since launch, INTEGRAL has operated as an international observatory with observing time available to U.S. scientists. NASA has an INTEGRAL Guest

Investigator Program that provides funding for U.S. scientists who were successful in obtaining observing time. In 2009, the INTEGRAL Guest Investigator Program has funded 12 observing programs for a total of \$350,000.

The U.S. INTEGRAL Guest Observer Facility maintains a copy of the full INTEGRAL public data archive and supports U.S. scientists with their data analysis. Neil Gehrels is the NASA INTEGRAL Project Scientist and Steve Sturmer is the GOF Lead Scientist.

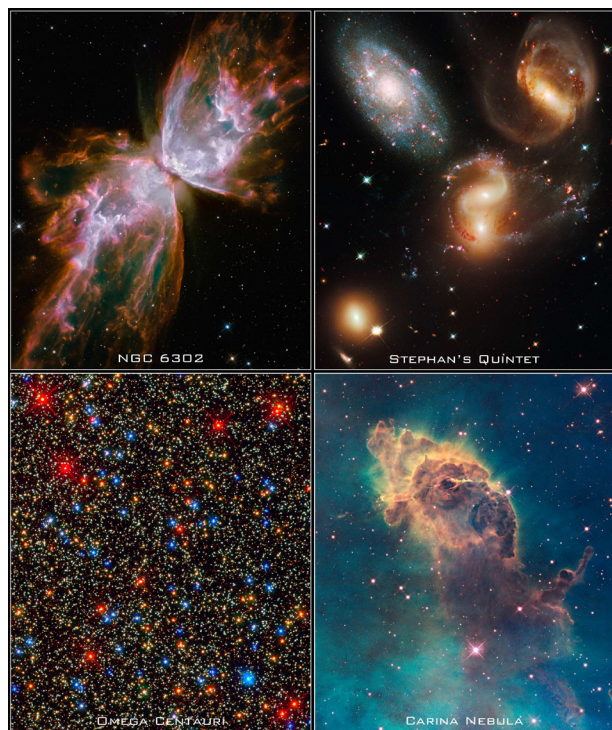
### **Hubble Space Telescope: SM4 and Wide Field Camera 3**

#### *SM4 a complete success, the long-awaited science begins*

The year 2009 was utterly spectacular for Hubble. Servicing Mission 4 (SM4), the mission originally planned for 2002 but long delayed, finally got off the ground with the May 11 launch of Space Shuttle Atlantis and the STS-125 mission. The manifest was so densely packed with replacement and repair hardware that the official EVA timeline did not accommodate all the tasks. In a servicing *tour de force* made possible not only by the astronauts but also by the work of more than a thousand people at GSFC, JSC, STScI, and various contractor sites, Atlantis's crew accomplished *all* tasks. The mission was jointly run out of JSC—responsible for the shuttle and its astronauts—and GSFC, which controlled and operated Hubble during the mission. The result is a new telescope, one with scientific capabilities far beyond what it has ever possessed. The final chapter of Hubble science—the next five-plus years—promises to be truly remarkable.

Before SM4 there was only one working science instrument (two, if the astrometer Fine Guidance Sensor [FGS] is counted): the venerable Wide Field and Planetary Camera 2 (WFPC2). Now the Hubble science community has at least four (five with FGS) to utilize in their research: Wide Field Camera 3 (WFC3) and Cosmic Origins Spectrograph (COS)—both new—and Space Telescope Imaging Spectrograph (STIS) and Advanced Camera for Surveys (ACS)—both repaired during SM4 in the first successful instrument surgeries in space. The Near Infrared and Multi-Object Spectrometer (NICMOS), which was not serviced





WFC3 produced these four stunning images as part of the SM4 Early Release Observation (ERO) program. *Clockwise from upper left:* the “Butterfly,” a planetary nebula also known as NGC 6302; the “Stephan’s Quintet” compact group of galaxies; a portion of the Carina nebula showing a pillar of gas and dust in which stars are forming; and the heart of the globular cluster Omega Centauri, showing through their colors the broad range of stellar types present in the cluster.

in SM4, is at the time of this writing being prepared for a restart of its cryocooler. Because NICMOS only receives 1.4 percent of HST’s total observing time, failure to restart the instrument will not compromise the telescope’s output or long-term scientific legacy.

ASD’s role in Hubble is substantial, as its personnel continue to play a vital role in servicing, operating, and using Hubble. In 2009, five scientists from ASD served as full-time HST Project Scientists: Dave Leckrone (Senior Project Scientist), Mal Niedner (Deputy Senior Project Scientist), Randy Kimble (Development Project Scientist and WFC3 Instrument Scientist), Ken Carpenter (Operations Project Scientist), and Stephen Rinehart (Associate Project Scientist).

All in the Hubble Project Science Office had important, well-defined roles in the run-up to and execution of SM4, with special emphasis on the instrument and instrument-repair development efforts, the prioritization of tasks (both scientific and engineering) for the mission, overall mission operations, and the development and interpretation of on-orbit functional tests (FT) of the new and repaired science instruments. In addition, ASD scientists Bruce Woodgate and Ted Gull—STIS PI and Deputy PI, respectively—contributed oversight to that instrument’s repair effort and were on shift during the STIS repair EVA, helping interpret the FT data. In October 2009, Dave Leckrone retired from the civil service and his post as Senior Project Scientist. George Sonneborn is serving as the Acting HST Senior Project Scientist until a replacement for Leckrone is found. Niedner currently serves as HST Observatory Project Scientist and Carpenter as its Operations Project Scientist.

After SM4 was completed, the telescope went through a ~4-month-long Servicing Mission Observatory Verification (SMOV) program, during which the new and repaired instruments were focused, aligned, characterized, and preliminarily calibrated, and the observatory as a whole was put through a battery of check-out and performance testing. Certainly the highlight of SMOV was the Early Release Observation (ERO) press conference on September 9, which proved both how spectacularly powerful the new WFC3 and COS are, and that STIS and ACS are back in operation after several years of being down. The only post-SM4 downside to report is that in the eight months since SM4, the replacement Science Instrument Command & Data Handling (SI C&DH) unit has experienced three lock-ups in one of the internal Science Data Formatters (SDF). These are easily cleared by power-cycling the entire SI C&DH, and there is no evidence that this is anything but a rare and subtle microcircuit timing hiccup, as opposed to degrading components. The telescope is scientifically non-operational only for about a day after each lock-up, and at the apparent modest rate of occurrence there is not a significant risk to HST productivity.

The “SM4 instruments”—WFC3, COS, STIS, and ACS—are working spectacularly. The remainder of



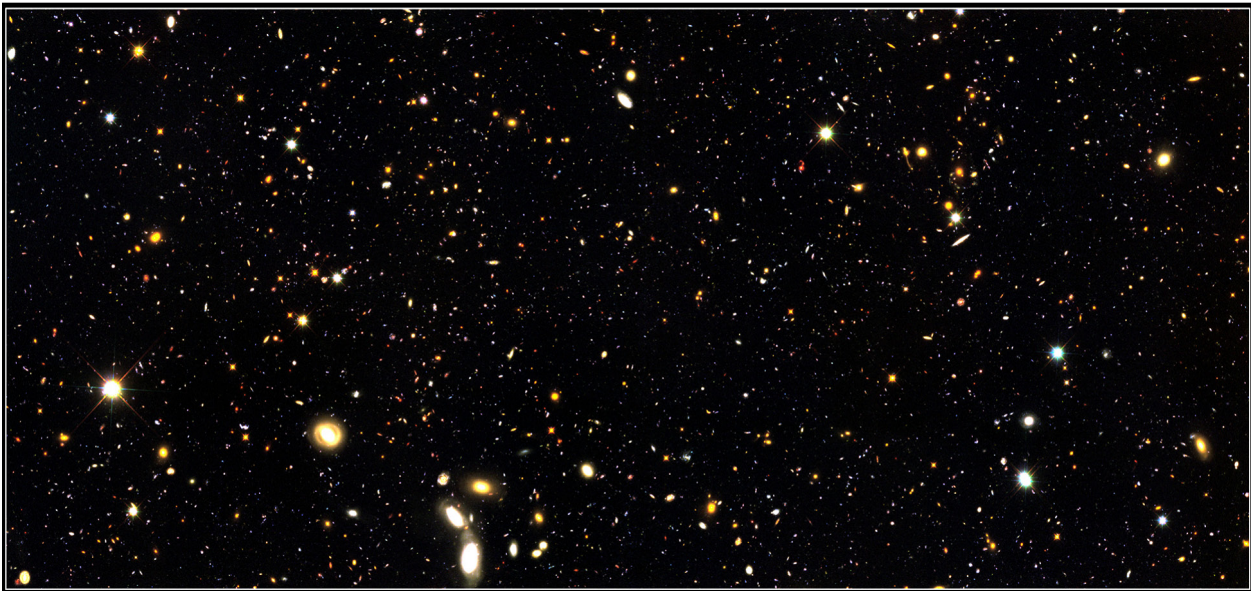
this report describes some early post-SM4 science with the new instruments, starting with WFC3, the facility instrument whose development was managed and largely carried out by GSFC.

**WFC3.** Although the WFC3 ERO images clearly showed the instrument's power, two scientific observing programs in particular are quantifying that power. The instrument's infrared channel (0.8–1.7 $\mu$ ) is being used in a 2009–2010 repeat of the seminal 2004 “Hubble Ultra Deep Field” (HUDF) carried out with ACS in the visible-red. At this point, although the 192-orbit program (G. Illingworth, PI) has not yet completed its data-taking, the results are spectacular. Due to the non-proprietary status of the new HUDF data, multiple research teams are writing papers on them, and while the teams' results are different in the details, one thing all scientists agree on is that the Hubble Program has delivered a superb camera to HST that is substantially exceeding expectations. The speed with which WFC3/IR is picking up  $z \sim 7$  galaxies exceeds that of the earlier NICMOS efforts by factors of 40 to 50 times, a performance metric that exceeds pre-flight calculations. The WFC3/IR HUDF has gone *deeper than that*, however, having crossed into the  $z = 8-9$  range, with some indication of a few  $z \sim 10$  objects being detected as well. Translated into cosmic

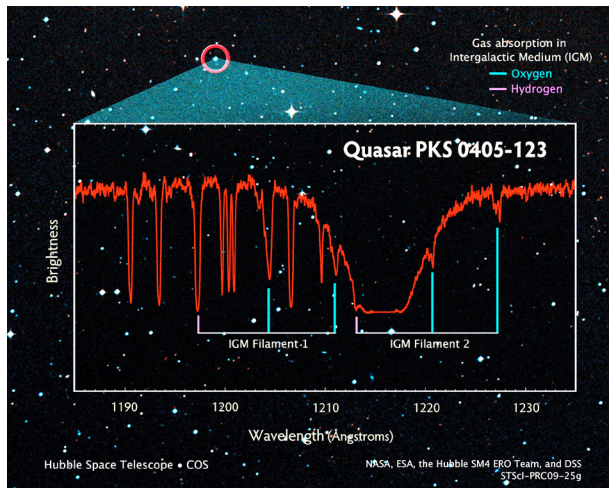
time, WFC3/IR is probing the zoo of early galaxies to within  $\sim 500$  million years of the Big Bang. Data such as these clearly serve as a bridge to JWST.

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The second program mentioned above is that designed by the WFC3 Science Oversight Committee (SOC), called “Early Release Science” (ERS). ERS utilizes 214 orbits of non-proprietary Hubble time and exercises both the WFC3 IR and UVIS (200–1000 nm) channels to address two themes: star formation in nearby resolved galaxies, and star formation/galaxy assembly at half the Hubble time. As opposed to going ultra-deep in the near-IR along three boresights (the HUDF/IR), the second (distant) ERS theme tiles (in a  $2 \times 4$  pattern) a portion of the large GOODS south field in UV and IR filters, which with pre-existing



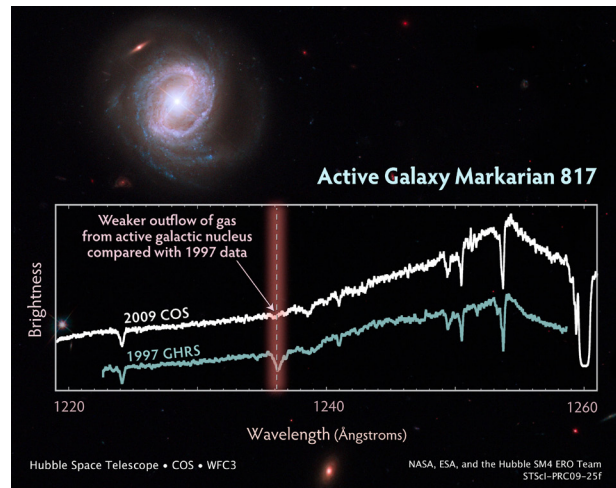
The deep WFC3/ERS Theme 2 (“Star Formation at half the Hubble Time”) field, a  $2 \times 4$  tiled mosaic of  $\sim 40$  sq. arcmin of the GOODS-South field. Deeply panchromatic, the image contains 10 passbands of imaging, including several from ACS, extending from 225nm to 1600nm.



COS observed a long sightline to a quasar at between 7 and 8 billion years of look-back time in this ERO observation, detecting the absorption lines of many elements. Five times as many hydrogen lines were seen as with previous instruments, and in only one quarter the observing time. This is an indication of COS's extreme ultraviolet sensitivity.

ACS visible-light images represents a panchromatic range of total spectral coverage. In spite of its somewhat shallower depth, ERS/Theme 2 is reaching redshifts of  $z \sim 7-8$ , and use of the photometric drop-out technique in the UV is revealing star formation and other properties important to galaxy assembly at  $z = 1-3$ , the redshift interval during which universal star formation and galaxy assembly processes were peaking. Theme 1 takes a massively multi-filter, panchromatic approach to address star formation in nearby, resolved galaxies such as the spiral M83. The early results from this theme are equally spectacular, showing among other things the power of WFC3's very full and diverse set of filters, its exquisite angular resolution over a wide field, and its unmatched ability to "go deep" on objects with crowded point sources. The M83 images show hundreds of young super star clusters of various ages, and scores of supernova remnants.

**COS.** While not a facility instrument like WFC3, the Cosmic Origins Spectrograph (James Green, PI, University of Colorado/Boulder) is an instrument that in the design, development, and testing phases benefited from extensive involvement of the ASD-staffed Hubble Project Science Office.



Comparative spectra—from COS and the first-generation Goddard High Resolution Spectrograph (GHRs)—of the active galactic nucleus of Markarian 817. Powered by a central supermassive black hole, Mrk 817 expels large amounts of matter outward in time-variable winds. The upper COS spectrum, taken in less than nine percent of the time GHRs needed, shows that a hydrogen cloud seen in absorption in 1997 has disappeared by 2009.

Early results from the COS Instrument Development Team (IDT; Green et al.), as well as those from General Observers (GOs) whose programs are executing early, demonstrate that COS is more than living up to its promise. COS is a purely UV spectrograph (115-320 nm) *designed for high sensitivity*, enabling many high-impact programs to execute relatively quickly, programs of the sort that, if possible at all with STIS (many were/are not), only executed with a much larger investment of observing time and with substantially lower signal-to-noise.

COS was designed and built with, among other things, detailed studies of the intergalactic medium, its relationship with galaxies and their growth, and the creation of heavy elements with cosmic time in mind. Early results are beginning to come in on all these themes as high-S/N absorption-line spectra along sightlines to distant quasars are probing in unprecedented detail the baryonic component of the "cosmic web." Some of those sightlines pass close enough to imaged galaxies to probe the chemical content and physical state of their halo gas. And observations of



supernova remnants are detecting the nucleosynthetic products of supernovae at levels of detail (high S/N at excellent spectral resolution) that were just not possible with STIS. Rounding out the early COS science results are programs characterizing exoplanetary atmospheric constituents and the time-variable kinematics of active galactic nuclei.

**STIS and ACS.** ASD was substantially involved in the repair efforts of STIS and ACS, and it is gratifying to see these two (still) immensely important instruments performing at the level we last knew (in 2004 and 2007, respectively), the one exception being the unsuccessful attempt to restore the ACS High Resolution Channel (HRC). Return of HRC operability was, however, not the reason for the ACS repair effort. It was known from the beginning to have no better than a 50-percent probability of success, given that the target of the repair was the much more highly used (and important) Wide Field Channel (WFC). WFC was restored, and with a reduction of the WFC/CCD read noise from the  $\sim 5$  to  $\sim 4$  electron level, WFC is in some ways *better* than in January 2007. This was a remarkable accomplishment directly attributable to the use of an ASIC (“Application Specific Integrated Circuit”) in the replacement CCD control electronics. Although they are both electronically “single string,” STIS and ACS offer outstanding promise to the rejuvenated Hubble and are key components in the deep “tool kit” now available to astronomers.

With its new breadth of capabilities—many never before present on the telescope—Hubble is now more scientifically powerful than ever. With five, and hopefully as many as 10, years ahead of it, this observatory’s best epoch of discovery may well lie ahead.

Mal Niedner, for the Hubble Project Science Office, January 19, 2010.

### The Galaxy Evolution Explorer (GALEX)

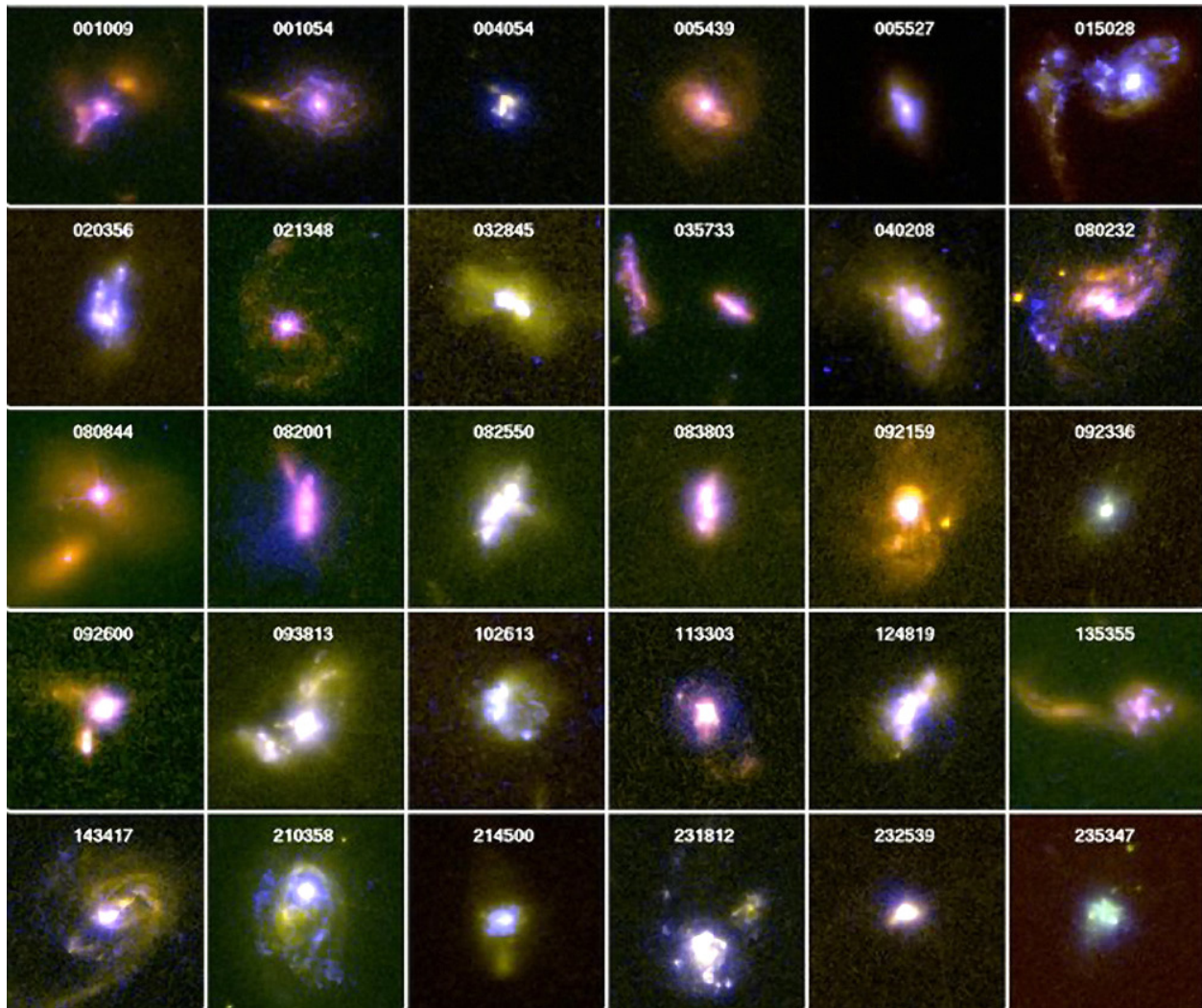
The Galaxy Evolution Explorer (GALEX), a Small Explorer (SMEX) ultraviolet survey mission, is in its sixth year of science operations. All flight and ground systems are currently healthy, with the exception of the Far-UV detector; recovery efforts for the FUV are in progress.

Most of the GALEX science operations are at Caltech. The core of the science team is also at Caltech, with smaller groups at Columbia, JHU, UCLA, Carnegie, and GSFC. Approximately one-third of GALEX observing time is dedicated to a robust Guest Investigator program, operated by GSFC (30 to 35 GI programs annually). Susan Neff (ASD) is the GALEX Mission Scientist.

GALEX is delivering its sixth (annual) GALEX Data Release (GR6) to MAST (Multi-Mission Archive at Space Telescope), which serves both GRs and GI data to the scientific community. 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; a particularly rich match is with the Sloan Digital Sky Survey. GALEX also can provide wide-field, low-resolution spectroscopy, useful, e.g., for identifying HST/COS targets or for variable objects in the Kepler field. Time-tag capabilities allow observers to determine a sampling time *post facto*, e.g., for identifying stellar pulsation modes.

The primary GALEX mission (completed in late 2007) had the goals: calibrate UV observables to star formation rate (SFR); measure star-formation history ( $0 < z < 1.5$ ); and explore the UV universe. The GALEX Extended Mission (EM), endorsed by the 2006 and 2008 Senior Reviews and up for review again in 2010, is carrying out 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; and determine the relative importance of the primary drivers of SF, such as galaxy assembly history, feedback from AGN, contributions from dust, or fractions of different gas phases.

GALEX observations have been used to determine the cosmic 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).



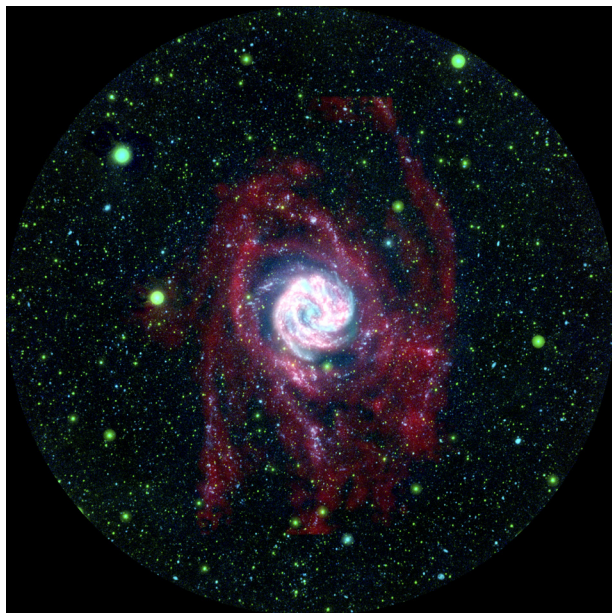
Lyman Break Analogs, as seen by HST (red) and GALEX (blue), from Overzier et al. (2008), showing that the LBAs often consist of multiple regions of intense star formation, indicative of merging activity.

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 (HR) 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, in prep).

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,





M83 shows an XUV disk (blue) and an HI extended disk (red), from Thilker et al. (2005). Star formation is occurring in regions where the gas density is below the previously suggested “threshold.” The star-forming regions in the extended disk may have an IMF that is relatively light on the most massive stars.

but seen in much more detail (Overzier et al. 2008; Basu-Zych et al. 2009).

GALEX has opened several new lines of investigation in the low-density regime. GALEX observations of Extended UV (XUV) disks has 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, in prep) has found that the 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.

### High Energy Astrophysics Science Archival Research Center (HEASARC)

Since 1990, the HEASARC has been an essential element of NASA’s astrophysics missions. The HEASARC’s 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 25 terabytes (TB), having grown by 7 TB in 2009, 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 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).

In 2009, the HEASARC began a major effort to renovate its underlying archive software, led by Dr. Tom McGlynn. The new system will be faster, more portable, and more capable. Initial alpha releases of the software were made in Fall 2009 and the HEASARC plans to make the first versions available to the public in Spring 2010. All tables and metadata have been ported to a free PostgreSQL database and new web technologies are being used to serve HEASARC data. In addition, the HEASARC archive and web site are currently transitioning into a virtualized computer en-

vironment that will allow more efficient use of computer resources. Other elements of the ASD are expected to follow the HEASARC along this path.

The HEASARC is a core partner in a joint NSF/NASA program to manage and operate the U.S. Virtual Astronomical Observatory. As part of this effort, McGlynn developed the first implementation of the new IVOA Table Access Protocol (TAP) to support both parameterized queries and generic SQL-like queries. TAP interfaces in astronomy archives will allow the HEASARC to send complex queries to remote sites, and conversely to allow other astronomical software to easily integrate HEASARC resources. The HEASARC has developed a database tracking the conformance of all registered VO services against VO standards and coordinates a world-wide effort to raise the quality of VO implementations.

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McGlynn also leads the development of the popular community resource, SkyView. In 2009, SkyView added all-sky surveys from the WMAP mission. While SkyView used data in the underlying HEALPix projection, it is the first site to treat HEALPix data as a straightforward two-dimensional projection rather than a complex linear pixelization. This makes WMAP data much more accessible to the community in general. Other new surveys include the Sloan DR7, GALEX GR4, and Mellinger medium-resolution optical surveys. Features for overlaying constellations were added to SkyView, and an image gallery established to allow users to save interesting images has been very popular.

During 2009, HEASARC programmers under the direction of Dr. Bill Pence coordinated five online public releases of the HEASOFT data analysis software package. This package contains about 2.5 million lines of code contained in over 500 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. There are about 1,000 registered individual or institutional users of the HEASOFT package, which is essential for deriving new scientific results from the HEASARC's large data archive. Notable new features provided in 2009 include major enhancements to the XSPEC multi-mission spectral fitting program, and support for a new, more efficient image-compression technique that can compress astronomical images up to a factor of 10 without loss of scientific information.

Dr. Steve Drake worked on the creation and/or updating of 57 Browse tables in 2009, of which 40 were brand new, bringing the total number of tables in Browse to just over 600 by the end of the year. Of the newly created tables, 20 were Chandra source lists, and the others included a broad range of missions including XMM-Newton, ROSAT, WMAP, SDSS, GALEX, CGRO, and INTEGRAL. Drake has also worked on 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. In 2009, three to four new items per week appeared in the HEASARC RSS/Latest News, providing an important and timely resource to the astronomical community.

A landmark event was the opening of the Fermi archive in August 2009. Dr. Mike Corcoran provided code to create transient and monitored-source light-curves and create a web page displaying these light-curves. The Fermi LAT Bright Source list was released by the Fermi project and implemented by Corcoran and programmer Ed Sabol as a searchable table within Browse. Corcoran and programmer Pan Chai worked with the Fermi project to implement the GBM response matrix generator in HERA, allowing users to access GBM spectra, and perform spectral analysis via the web without having to download and install any software. The Fermi calibration data for the GBM and LAT instruments were released by the Fermi project and implemented in the HEASARC calibration database (CalDB) by Corcoran. This in-

cluded definition of the CalDB index files for both instruments, documentation regarding keyword usage, and construction of an update pipeline. Corcoran also improved the remote retrieval software to provide more consistent usage for anyone using the remote data access facility to access calibration data. In 2009, there were a total of 44 updates of the Swift, Suzaku, Chandra, RXTE, and Fermi CalDB areas.

In 2009, Dr. Keith Arnaud participated in the releases of v6.6 and v6.7 of HEASOFT. This included a major new release of XSPEC (v12.5) that included many new models, support for algebraic models defined on-the-fly, improved estimation of uncertainties on fluxes, and a first step at parallelization for multi-core processors. This release also included a new version of EXTRACTOR with region-filtering now using (fast) internal CFITSIO code. Arnaud has continued to develop XSPEC with current emphasis on designing methods to allow parameterized modeling of the response, more flexible plotting, and preliminary work on a Python interface. In collaboration with Dr. John Baker (GSFC) and colleagues, Arnaud has continued work on using XSPEC for simulations of gravitational wave data analysis. This work included responding to the Mock LISA Data Challenge as well as writing the core of a new software system to tie together the different projects underway. Arnaud was a successful co-I with Goddard and UMD colleagues on a NASA theory proposal to assess the importance of recent numerical relativity results on the LISA data analysis.

Under the direction of Dr. James Lochner, the HEASARC E/PO program continues to fulfill its mission of bringing high-energy astrophysics and cosmology to teachers and students. In 2009, the Cosmic Times project was completed. This set of six posters and lesson plans describes how our knowledge of the universe has changed over the past hundred years. Each poster mimics the front page of a newspaper with articles about key discoveries in this history. The posters were printed mid-year and by end of the year more than 1,000 sets had already been distributed. The Cosmic Times web site provides resources for teachers, including the lessons and a teacher guide, and in 2009 was revised to include online versions of the posters. A third version of the poster articles was developed to make them more accessible to students in grades 7–9. We conducted five workshops on Cosmic Times,

including an NSTA webinar, and published an article about Cosmic Times in NSTA's *The Science Teacher* journal for high-school teachers.

The HEASARC continues to send out formal education materials to teachers and workshop providers; but in the past year, we branched out to supply our materials to the Night Sky Network, an organization run by the Astronomical Society of the Pacific consisting of more than 200 amateur astronomy clubs around the country. These clubs have used the Imagine the Universe CDs not only for their star parties and teacher workshops, but for other events and audiences such as the National Federation of the Blind, a city symphony, several senior citizen centers, a summer camp for children of incarcerated parents, a 4H group, the Science Olympiad training, and a dozen presentations at inner city libraries—all greatly expanding the audience for our materials.

In 2009, Lochner successfully obtained funding through the Education & Public Outreach for Earth and Space Sciences (EPOESS) Program to continue the HEASARC's production of the "Imagine the Universe!" DVD-ROM. The DVD-ROM captures the HEASARC's education web sites, as well as the previous year's Astronomy Picture of the Day pages. The grant will not only provide funding for production for three years, but also funding to determine more precisely the demographics of our audience and how they use the DVD-ROM.

Within the next four 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 from an archive that is projected to reach 40+ terabytes by 2012. Priorities within the 2010–2013 timeframe include the development and implementation of archival support for NuSTAR, Astro-H, and GEMS data under the direction of Dr. Lorella Angelini, and two ground-based CMB experiments ACT and SPT, under the direction of Dr. Gary Hinshaw; continuing support for the HEASARC's exponentially growing data holdings and retrievals; a closer integration of archive access and analysis tools; development of science-based topical archives; and enhanced interoperability with other archive centers and the Virtual Observatory.



## Wilkinson Microwave Anisotropy Probe (WMAP)

As of January 2010, WMAP had been in orbit for 8.5 years and is still taking data at the Sun-Earth second Lagrange point (SEL-2). Aside from a few minor hardware problems over the life of the mission, there has been no significant degradation anywhere on the observatory. The current plan is to continue operating the mission until the end of fiscal year 2010, and then spend several years performing the final data analysis and archiving.

The scientific results from the first seven years of operations were recently published, and included the following highlights:

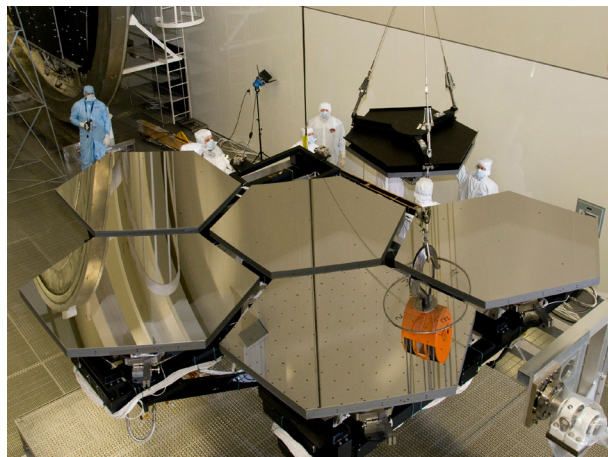
- Reported the first direct detection of pre-stellar helium, providing an important test of the Big Bang prediction.
- Placed 50% tighter limits on the standard model of cosmology (Cold Dark Matter and a Cosmological Constant in a flat universe), with no compelling sign of deviations from this model.
- Placed strong constraints on dark energy and the geometry of the universe.
- Placed new constraints on the number of neutrino-like species in the early universe.
- Detected, with very high significance, temperature shifts induced by hot gas in galaxy clusters.
- Produced a visual demonstration that the polarization pattern around hot and cold spots follows the pattern expected in the standard model of cosmology.

Further details on WMAP and its discoveries can be found at the WMAP website [map.gsfc.nasa.gov](http://map.gsfc.nasa.gov).

### Projects 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 in 2014. 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 observing objects in our solar



In early 2010, James Webb Space Telescope mirror segments were prepped to move into the X-ray and Cryogenic Facility, or XRCF, at NASA's Marshall Space Flight Center in Huntsville, Ala.  
*NASA/MSFC/Emmett Givens*

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 eight project scientists. The Senior Project Scientist is John Mather and his deputy is Jonathan Gardner. The other members of the team: Matthew Greenhouse (Instrumentation), Bernard Rauscher (deputy); Mark Clampin (Observatory), Charles Bowers (deputy); Randy Kimble (Integration and Test) and George Sonneborn (Operations). The ASD is currently seeking to hire a Deputy Project Scientist for Operations.

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 astrobio-





NASA engineers check out the unwrapped ISIM structure in the Goddard clean room. The ISIM Structure supports and holds four Webb telescope science instruments. *NASA/Chris Gunn*

ogy, exoplanet coronagraphy, exoplanet transits, first-light galaxies, resolved stellar population, and solar system observations. 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](http://jwst.gsfc.nasa.gov/scientists.html).

The JWST Project is now in phase C/D, and the project is working towards the Critical Design Review (CDR) in mid-2010. All four instruments have passed their CDRs. Engineering units of the instruments will arrive at Goddard in 2010, and the flight instruments will arrive in 2011. Most of the instrument flight hardware and all of the flight detectors are selected and are in the process of integration. The Integrated Science Instrument Module (ISIM) flight structure was delivered to Goddard in 2009, and development of ISIM-level test facilities is underway. The GSFC Space Environment Simulator (SES) cryogenic vacuum chamber was modified by the JWST project with a liquid helium shroud, the largest such shroud in the world. 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. Most of the segments have completed fine polishing

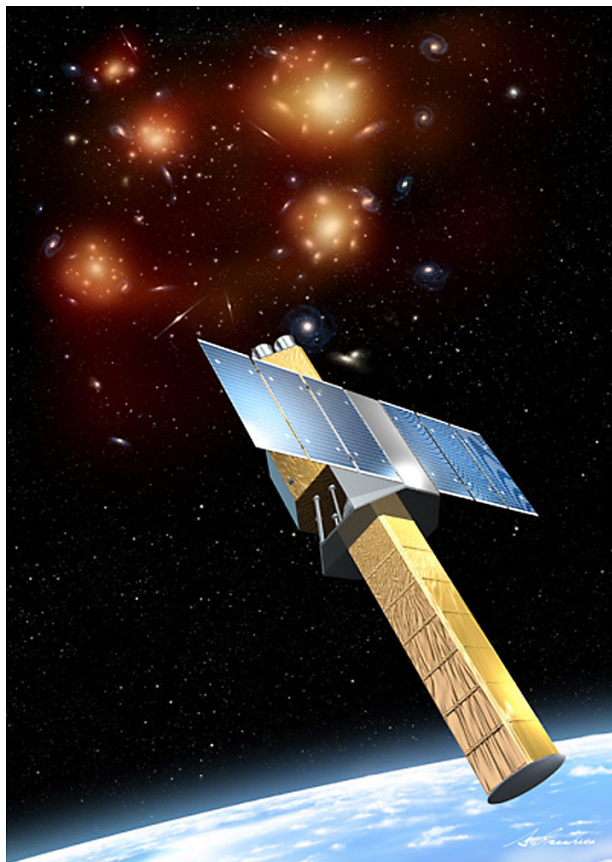
and are ready for the measurement of their cryogenic figure at Marshall Space Flight Center (MSFC), in preparation for the final stage, known as cryo-polishing. An engineering-demonstration segment has completed cryo-polishing and will be verified in a cryogenic vacuum test in January 2010. Following this final test, the segment will be ready for gold coating.

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 Robert Silverberg and 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 flight MSA is currently in test and will be delivered to ESA early in 2010. The detectors in the NIRSpec are also being built at Goddard, under the leadership of Bernard Rauscher, and will also be delivered in 2010. Both Rauscher and Moseley are members of the NIRSpec Science Teams 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. In response to the 2007 NASA Announcement of Opportunity soliciting investigations for Small Explorer (SMEX) missions and Missions of Opportunity (MO), a group headed by Richard Kelley of the X-Ray Astrophysics Laboratory was selected to provide key components of a high-resolution X-ray calorimeter spectrometer that will constitute one of the observatory's primary science instruments. Among Code 660 scientists, Caroline Kilbourne and Scott Porter are responsible for the detector subsystem and Peter Serlimitsos and his team of Takashi Okajima and Yang Soong are responsible for the X-ray mirror.



The Soft X-Ray Spectrometer (SXS) will consist of a 36-pixel X-ray calorimeter array with better than 7 eV resolution (and a goal of 4 eV) 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;
- 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 SNRs;
- And 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 proposed 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 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 also proposed 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.

This year saw two major accomplishments for the SXS. In June 2009, the project was successfully elevated to Phase B, the design phase, following an extensive review at NASA Headquarters (“Key Decision Point-B”). In November 2009, a revised plan for the SEO, including budget profile, was favorably received by NASA Headquarters.

### **Gravity and Extreme Magnetism SMEX (GEMS)**

The information contained in the polarization of X-ray fluxes has long been viewed as the unexplored handle on the geometrical and magnetic structures of X-ray-emitting regions. Sensitivity to the effects of strong gravity around black holes and the virtual pair creation of strong magnetic fields in neutron stars give

polarization a special place as a probe of fundamental physics.

In April 2009, the team for the Gravity and Extreme Magnetism SMEX (GEMS) held the site visit for the proposed SMEX mission for X-ray polarization measurements for a variety of black hole and neutron star X-ray sources. The review was held at the Orbital Sciences Corporation in Dulles, Virginia. At the end of June, we were delighted to learn that GEMS is one of the two selected SMEX missions from the 2007 SMEX AO and that GEMS will be the second of these to fly, after the solar mission IRIS from Lockheed Martin. The GEMS launch date is April 2014. In keeping with this date, the project has begun with a slow ramp-up. GEMS was proposed from the X-Ray Astrophysics Laboratory. Jean Swank is the Principle Investigator (PI), with Keith Jahoda Deputy PI. Timothy Kallman is the Chair of the Science Working Group.

**GEMS combines the X-Ray Astrophysics Laboratory's interests in instruments and in the physics of astrophysical sources.**

GEMS carries three telescopes, with each of the mirrors being a copy of the 4.5m-focal-length Suzaku mirror. The detectors behind the mirrors are Time Projection Chambers in which micropattern gas detectors record the tracks of photoelectrons as they lose energy. The mirrors and the polarimeters for GEMS are optimized for 2–10 keV. The spacecraft will rotate at 0.1 rpm to allow systematic affects to be detected and corrected. The rotation allows a student experiment from co-investigators at University of Iowa to measure the polarization at 0.5 keV by scattering these X-rays out of the beam from one of the mirrors into a small proportional counter.

The 1972 rocket flight detection of polarization of the Crab Nebula X-ray flux was followed by spacecraft efforts to detect polarization in bright sources using Bragg scattering instruments. These had good sensitivity to the polarization of an X-ray but very low sensitivities as instruments. The sensitivity of the photoelectric effect to the polarization of the X-ray raised the possibility of more efficient instruments. To use

this effect, it is necessary to track the ejected electrons whose distribution is peaked around the direction of the electric vector. In several early laboratory efforts to do this, the tracks were too short. It was achieved in a potentially practical way by Bellazzini at INFN, as reported in the paper by Costa et al. (2001).

The GEMS polarimeters use the same physical effect with a more efficient geometry and will make possible measurement of polarization to an accuracy of about 1% for representatives of stellar black holes, supermassive black holes, neutron star pulsars (including magnetars), and supernova remnants. The baseline science program can be carried out in nine months with 35 targets. In the balance of a two-year mission, a General Observer (GO) program could measure the polarizations of as many more targets. The Science Operations would be set up to support GOs as well as the baseline mission.

GEMS combines the X-Ray Astrophysics Laboratory's interests in instruments and in the physics of astrophysical sources. Polarization data, as well as timing and spectroscopy data, will provide a robust guide to resolving alternative interpretations of X-ray emission in various cosmic sources.

**Laboratory Development of X-ray Polarimetry.** The charge signal associated with the photoelectric absorption of X-rays has been exploited over many years for imaging, timing, and spectroscopy. It has long been recognized that a polarization signature is also present, as the photoelectron direction is correlated with the photon electric-field vector.

Work on micropattern gas detectors in ASD led to a 2003 SMEX proposal for the Advanced X-Ray Polarimeter (AXP), in collaboration with Palo Alto Research Center and the Italian INFN and IASF-CNR. While AXP was not selected, funding for detector development permitted continued laboratory work. The polarimeters proposed for GEMS are several times more efficient than the AXP polarimeters. This increase in sensitivity was enabled by adopting a Time Projection Chamber readout geometry. The TPC is widely used in particle physics. In 2009, most laboratory efforts supported developing the TPC readout specifically for GEMS.



Measuring the direction of the photoelectron track in a practical detector is complicated by the fact that the photoelectron track length is small ( $< 10^{-2}$ ) compared to the photon absorption depth. However, Costa et al. (2001) demonstrated that a gas proportional counter with a finely pixelated readout can make polarization measurements in the X-ray band. Careful choices of gas composition and pressure allow tuning of the photoelectric path length; current practical technologies require that the photoelectron track be between 100 and 1000 microns in the band of interest.

Over the last few years, members of the X-ray Astrophysics laboratory (Jahoda, Black, Hill, Deines-Jones, Swank) have concentrated on exploiting photoelectric polarimetry in geometries suitable for Explorer class missions. Recent efforts have centered on developing the Time Projection Chamber Readout as proposed for GEMS (Black et al. 2007). In this geometry, the track is drifted perpendicular to the photon direction of incidence to a readout plane. This innovation largely decouples detector depth (i.e., efficiency) from the ability to image the track (polarization sensitivity).

During 2009, we successfully demonstrated a TPC polarimeter that uses the ASIC-based readout required for GEMS, and demonstrated the efficiency of using rotation to remove instrumental signatures associated with the asymmetry of the TPC readout.

### *Mission Concepts*

#### **Absolute Spectrum Polarimeter (ASP)**

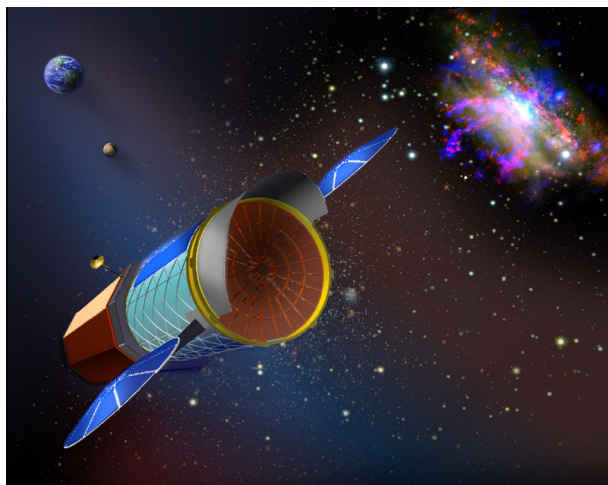
The Absolute Spectrum Polarimeter (ASP) is an Explorer-class mission concept to measure the polarization pattern and frequency spectrum of the cosmic microwave background. ASP will measure the linear polarization produced by gravity waves excited during an inflationary epoch shortly after the Big Bang. Such a signal is expected to exist; its detection would have profound consequences for both cosmology and particle physics. Not only would it establish inflation as a physical reality, but it would provide a model-independent determination of the relevant energy scale ( $\sim 10^{15}$  GeV) some 12 orders of magnitude beyond those accessible to particle accelerators.

ASP uses a cryogenic Michelson interferometer to measure the differential spectrum between two independent inputs in two orthogonal linear polarizations. ASP will measure the frequency spectrum of the Stokes I, Q, and U parameters from 1 cm through 60  $\mu\text{m}$  wavelength. Its high sensitivity and broad spectral coverage enable a range of science goals. The polarization on large angular scales encodes the ionization fraction as a function of redshift, providing critical inputs for models of reionization and structure formation.

Measurements of the CMB blackbody spectrum provide an independent determination of reionization through the Sunyaev-Zeldovich spectral distortion and will search for evidence of dark matter decay or annihilation in the very early universe ( $10^7 < z < 10^3$ ). ASP will measure the spectra of the temperature and polarization anisotropy to confirm their cosmological origin, and will measure both the far-infrared background and its power spectrum to test models of structure formation. Its measurements of the diffuse interstellar medium include full-sky maps of the major C+, N+, OI, and CO lines as well as thermal dust, free-free, and synchrotron emission.

#### **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 circa





2021 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 but have not been detected. IXO will detect these missing baryons and 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.

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, Webb, 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 and an extendible optical bench, with a focal length of 20m, 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 Observa-

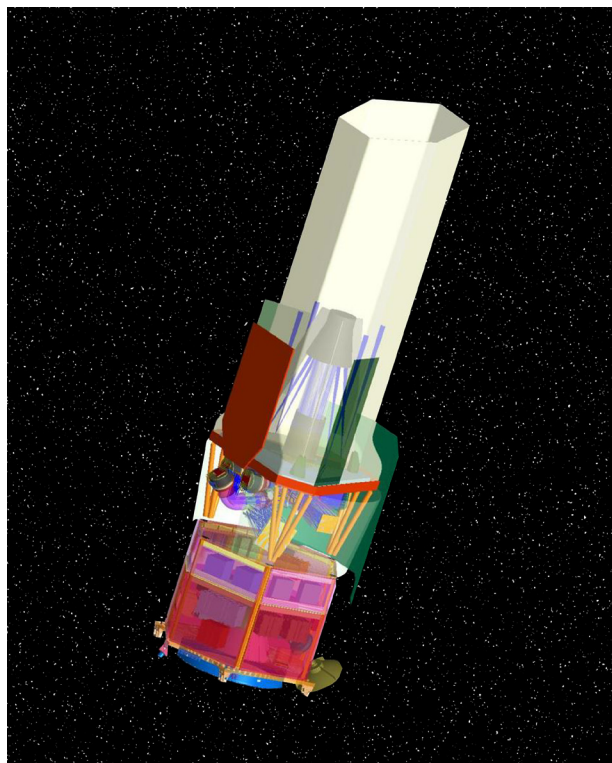
tory Project Scientist is Rob Petre. Project science support is provided by Steve Snowden, Tim Kallman, Tod Strohmayer, and Rita Sambruna. Will Zhang leads the mirror technology development; Richard Kelley, Caroline Kilbourne, and Scott Porter lead the calorimeter development.

Over the past year substantial effort has been devoted to providing input to the NAS Decadal Survey of Astronomy and Astrophysics. In early 2009, approximately 25 science white papers were submitted by scientists around the world, on topics that IXO is ideally suited to address. The mission team submitted a response to a request for information by the Decadal panel in April 2009, provided a written response to two sets of questions by the panel (June and July 2009), and made an invited presentation to the Electromagnetic Observations from Space Panel during the June 2009 AAS meeting. Project team efforts are currently focused on providing input to ESA’s Cosmic Visions process.

### Joint Dark Energy Mission (JDEM)

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.

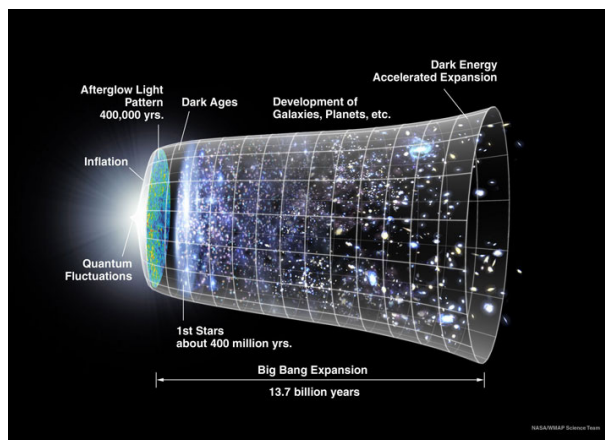
Prior to 2008, NASA and its partner, the U.S. Department of Energy (DOE), solicited concepts for a dark energy mission. Three concepts were submitted: DESTINY, ADEPT, and SNAP. ASD scientists were involved in each of the three funded mission concepts. Benford, Carpenter, and Sonneborn were on the DESTINY (supernovae and weak lensing) science team; Moseley, Hinshaw, Oegerle, and Bowers were on the ADEPT (baryon acoustic oscillations and supernovae) team; and Woodgate, Rauscher, Kimball, and Greenhouse were members of the SNAP (supernovae and weak lensing) team. At that time the mission was



Artist's view of one of the concepts (IDECS) for a JDEM observatory.

conceived to be PI-led. Programmatic changes were later made such that GSFC would be the lead NASA center for managing the project, working in collaboration with a DOE team at Lawrence Berkeley National Laboratory (LBNL). Science teams will be selected to participate in the mission at a later time.

The JDEM Project team at GSFC and the JDEM Project Scientist, Dr. Neil Gehrels, worked closely with a NASA and DOE selected Science Coordination Group (including ASD scientists Benford and Moseley) to develop a mission concept that was scientifically compelling and affordable. Many of the ASD scientists who supported the original three concepts now work as part of the JDEM team. In particular, K. Carpenter/667, G. Hinshaw/665, J. Kruk/JHU, Bernie Rauscher/665, and E. Wollack/665 are working as Deputy Project Scientists/Science Advisors to the GSFC management team. The team responded to the Astro2010 Decadal Survey RFI with concepts that utilized all three dark energy techniques. Recently, the team has been working closely with the DOE partners and the JDEM Interim Science Working Group



An illustration of how the universe's expansion rate is increasing in the current epoch. Astrophysicists have no understanding of what causes this acceleration. JDEM is designed to make the necessary measurements for a breakthrough in our knowledge of the "dark energy" that drives the acceleration.

(ISWG) to find a lower cost, yet scientifically worthwhile, "probe" concept. The scientists from ASD have been concentrating on the development of design specifications for each technique and optimal observing strategies.

Several studies are underway to reduce uncertainty and risk during the concept phase. A telescope study is being executed to develop detailed cost estimates and models for telescopes with primary mirrors having diameters in the 1.0- to 1.5-meter range. The telescope contractors are working closely with our team to ensure the cost estimates are reasonable and acceptable and the implementation straightforward. An Engineering Demonstration Unit (EDU) focal plane will be built in order to characterize the building, testing and use of HgTeCd detectors for dark energy studies. Our team is also working with Ames Research Center to test detectors for susceptibility to the effect of space-based radiation.

The GSFC JDEM Project utilizes the skills of a broad cross-section of GSFC personnel for project management, science, resource management, and engineering. It is a collaborative effort across multiple GSFC directorates, including the Science, Engineering, and Flight Projects Directorates.

### The Fourier-Kelvin Stellar Interferometer (FKSI)

The long-term focus of planet-finding efforts at NASA has been directed toward the search for extrasolar terrestrial planets, like those in our own solar system, within the habitable zone around stars similar to our own Sun, e.g., F, G, and K main sequence stars. Our present theoretical understanding is that all stellar systems, including those with planets, form out of material in primordial disks. Thus, the formation of planets is intimately linked to the evolution of circumstellar disks, which for mature stars like our own Sun, have optically thin “debris disks” in their habitable zones.

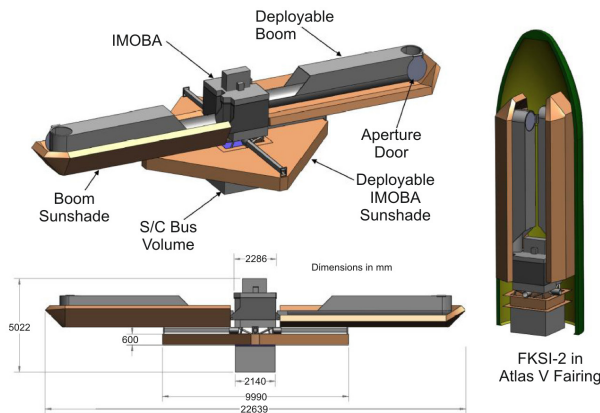
Recent studies of the requirements for planet-finding-and-characterization missions such as the Terrestrial Planet Finder (TPF) have shown that the amount of exozodiacal emission from warm and hot dust in the habitable zone is a crucial parameter. Observations of planets in stellar systems with more than about 10 times the zodiacal light as our solar system will be extremely difficult, as exozodiacal dust emission (and/or scattering) interferes with the observer’s ability to detect the faint emission from an earthlike planet.

Thus it is crucial to observe all of the likely targets for TPF to determine the amount of exozodiacal emission around nearby stars with sufficient accuracy for the flagship missions. In particular, we must answer the question: What is the star-to-star statistical distribution of exozodiacal material in the habitable zone around nearby stars? The need for this measurement is documented in the report from the ExoPlanetary Task

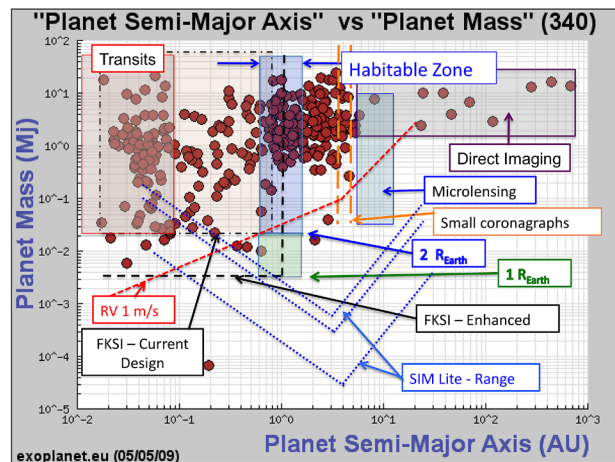
Force (Lunine et al., 2008). This measurement can be made with a small, spaceborne infrared interferometer having apertures ~0.5–1m in diameter and passively cooled to about 60 K.

One such implementation is the Fourier-Kelvin Stellar Interferometer (FKSI) mission, which is an infrared space interferometer composed of two 0.5m-aperture telescopes on a 12.5m baseline on a boom, operating in the spectral range 3 to 8 (or 10) microns, and passively cooled to about 60 K. Dr. William C. Danchi, senior scientist in the Laboratory for Exoplanets and Stellar Astrophysics, is the Principal Investigator for FKSI. The main goals for this mission are the measurement and characterization of the exozodiacal emission around nearby stars, debris disks, spectroscopic characterization of the atmospheres of known exoplanets, and the search for and characterization of super-Earths around nearby stars.

Last year, with efforts funded by a Goddard Internal Research and Development (IRAD) grant, the FKSI team investigated if an enhanced version of FKSI that could detect and characterize many super-Earths and a few Earth twins was feasible within the expected cost cap for a mid-sized strategic or “Probe” mission. The enhanced version of FKSI consists of two 1-m telescopes separated by a 20-m baseline, passively cooled to 40K, with a science wavelength band from 5 to 15 microns, and a Field-of-View of +/- 45 degrees from the ecliptic. Studies of the performance of the enhanced FKSI, using the TPF-I performance simula-



Engineering model of the enhanced FKSI design, called FKSI-2.



Comparison between the discovery space for exoplanets with FKSI and other mission concepts and techniques.



tor of Dubovitsky and Lay (2004), demonstrated that with these parameters, the enhanced FKSI, or FKSI-2, can detect and characterize one-Earth-radius planets around four nearby G and K stars, and detect 34 two-Earth-radius super-Earths and characterize 16 of them, in the habitable zones of these stars. An engineering realization of FKSI-2 is displayed below, as well as a chart that shows the unique discovery space available to this mission concept. Note that FKSI-2 is the only proposed mission concept in a Probe-class budget category that can detect and characterize Earth-twins and super-Earths in the habitable zone of nearby stars (see Danchi et al. 2009 for more information on FKSI-2).

The FKSI mission has been reviewed in the context of the Exoplanet Community Forum 2008 and has been included in the notional timeline developed for the area of “Direct Infrared Imaging of Exoplanets” as a candidate for a mid-sized or Probe-class strategic mission (see the Exoplanet Community Forum Report, Chapter 4). FKSI has also received international recognition and collaborators in Europe have been able to include FKSI as a “mission of opportunity” in the plans for the French space agency (CNES) and the European Space Agency (ESA). Most of the technical risks have been retired through technology investments for JWST, SIM, and TPF-I/Darwin, and most technologies are at a Technical Readiness Level (TRL) sufficient for advancement to Phase A. This mission could receive a Phase-A start in the next 2–5 years with only modest technology investments.

### Stellar Imager (SI)

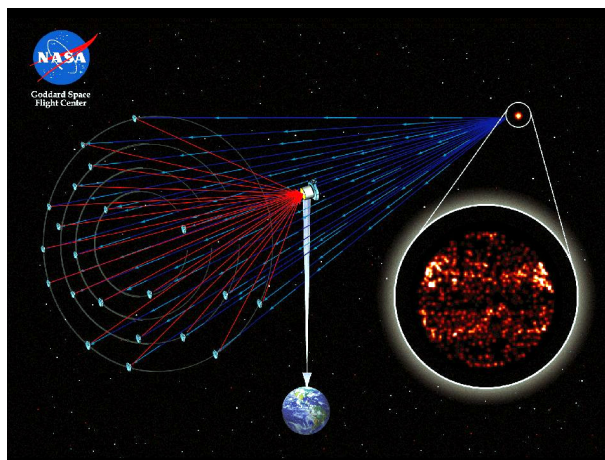
The Stellar Imager (SI) Vision Mission (see [hires.gsfc.nasa.gov/~si](http://hires.gsfc.nasa.gov/~si)) is a UV-optical aperture-synthesis spectral imager with some 30 apertures, each at least one meter in diameter, and spread over baselines up to a kilometer across. A central beam-combing hub with focal-plane instrumentation provides an angular resolution of 0.1 milliarcsecond, or *more than 200 times that of Hubble Space Telescope (HST)*. It will provide heretofore unattainable views of the surfaces and (via spatially-resolved asteroseismology) interiors of other solar-type stars, of 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 Flagship “Landmark Discovery” Mission in the 2005 Heliophysics Roadmap and a potential implementation of the UV/Optical Interferometer (UVOI) in the 2006 Science Program for NASA’s Astronomy & Physics Division.

The primary goal of this cross-theme mission 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
- Extrasolar planet transits and disks

The PI of the Stellar Imager concept development is Dr. Kenneth Carpenter (GSFC/667). He leads a large collaborative team of about a dozen GSFC personnel plus co-investigators at some 18 external institutions (academic, aerospace, and international) established for the Vision Mission Study and expanded, at low level of effort, in the following years. GSFC’s role is to continue to foster and coordinate the further development of the science program goals, and a mission architecture to satisfy those goals—and to pursue and



An array of thirty 1-m mirrors flies in precision formation to form a virtual parabola 500-m across. This structure would enable submilliarcsecond spectral imaging of many astronomical objects. Shown in the inset above is a solar-type star imaged in the light of CIV emission lines.

encourage the development of the technologies needed to enable the mission in the 2020s.

The primary activity of the SI Team (lead by K. Carpenter and R. Lyon/GSFC-667, K. Schrijver/LMATC, M. Karovska/CfA, D. Mozurkewich/Seabrook Engineering, and S. Kraemer/CUA) in 2009 has been to prepare and submit input to the 2010 Astrophysics Decadal Survey on the science goals of SI, its technology development needs, and a mission architecture that would achieve the science goals. The Team has also continued to describe to various committees and the astronomical community the value of the SI observatory for addressing both NASA Astrophysics and Heliophysics Division science goals and the ways in which the mission could potentially be enhanced by use of the Constellation Architecture to launch and/or service it.

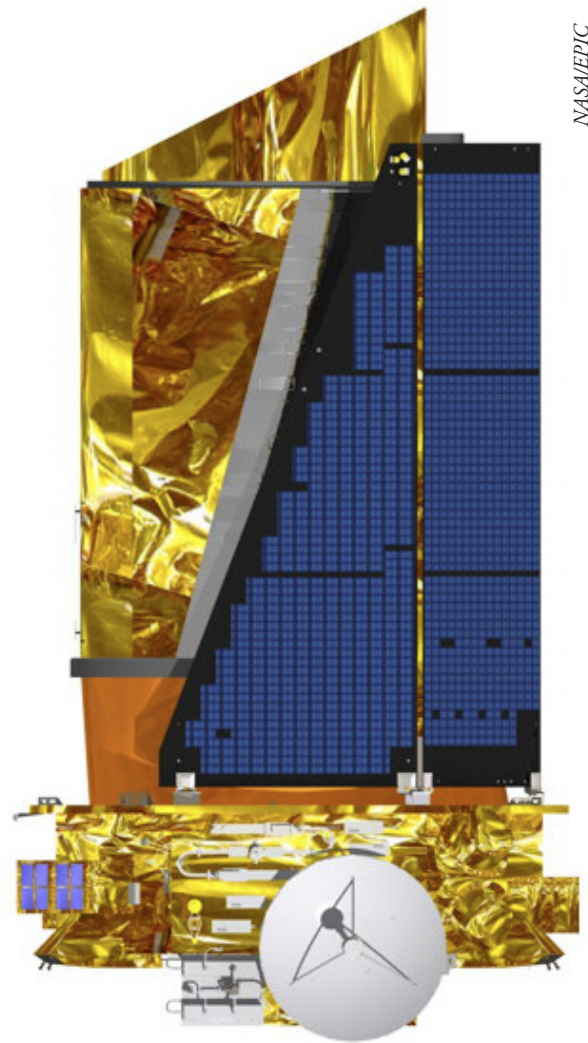
The whitepapers submitted to the Astrophysics Decadal Survey include: “Mass Transport Processes and their Roles in the Formation, Structure, and Evolution of Stars and Stellar Systems” (Carpenter, K. G. et al. 2009); “Dyamos and Magnetic Fields of the Sun and other Cool Stars, and their Role in the Formation and Evolution of Stars and the Habitability of Planets” (Schrijver, C. J. et al. 2009); “Active Galactic Nuclei and their Role in Galaxy Formation and Evolution” (Kraemer, S. et al. 2009); “Technology Development for Future Sparse Aperture Telescopes and Interferometers in Space” (Carpenter, K.G., et al. 2009); “Stellar Imager (SI) – A UV/Optical Interferometer (UVOI) Viewing the Universe in High Definition” (Carpenter, K. G., et al. 2009).

### Extrasolar Planetary Imaging Coronagraph (EPIC)

Direct imaging/characterization of extrasolar planets is predicated on the ability to unambiguously detect planets in the presence of diffracted/scattered light from the parent star, its exozodiacal light, and other objects in the field of view. Astrometric missions can detect Earth-mass planets and determine orbital parameters yet cannot determine the zodiacal light—crucial for a future exosolar terrestrial imaging mission.

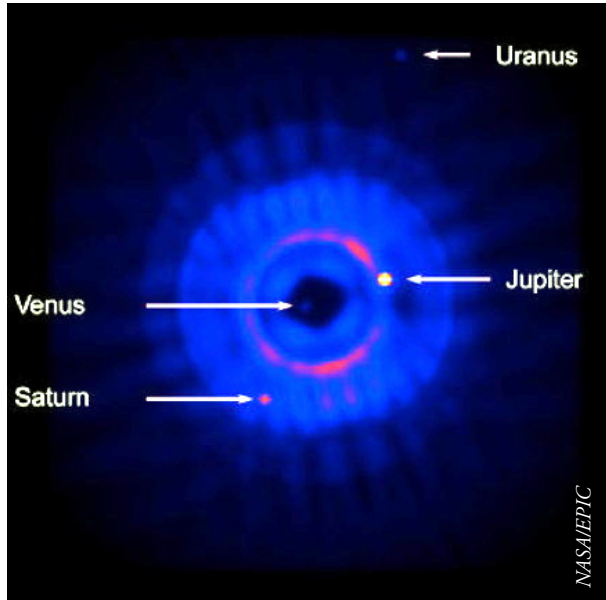
EPIC is an alternative approach which images and characterizes jovian planets and exozodi disks around single, binary and ternary stars. It would provide the first direct measurements of a range of fundamental physical characteristics of exosolar giant planets—a step toward the long-term goal of imaging exosolar terrestrial planets (Mark Clampin, PI; Gary Melnick/CfA, Deputy PI; Rick Lyon, Project Scientist).

Science goals are achieved by a 1.65-meter telescope coupled to a visible nulling coronagraph (VNC) delivering broadband starlight suppression ( $10^9$  @ 125 mas) and permitting direct observation and broadband (0.4–1.0  $\mu\text{m}$ ) spectral characterization. EPIC is aligned with the strategic objectives of NASA per



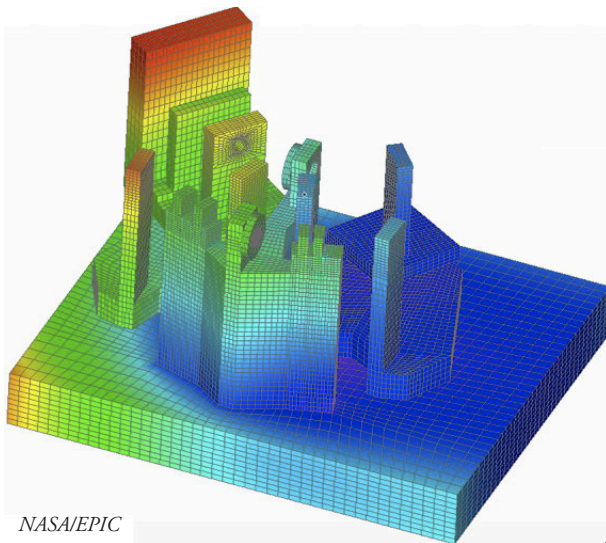
NASA/EPIC

Artist's concept of the EPIC spacecraft.



This simulated EPIC image shows our solar system as seen face-on from 10 parsecs away. Major planets and structure within zodiacal dust disk are evident.

“The New Age of Exploration” and fulfills the goal of “Vision for Space Exploration,” which calls for planet searches. EPIC meets the recommendations of the Exoplanetary Task Force (ExoPTF) to characterize exosolar disks and is a funded Astrophysics Strategic Mission Concept study (ASMC). The results of the study will be presented to the Decadal review.

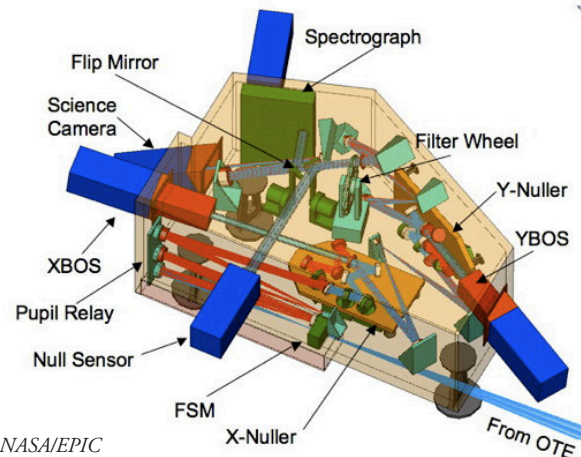


STOP analysis of Compact Nuller showing the effect of thermal gradients. The largest dimension is ~10 inches.

EPIC has been proposed as a NASA/Discovery mission. The EPIC team, including industrial partners Lockheed Martin (telescope & VNC), Ball Aerospace (spacecraft bus), and the GSFC Instrument Design Center, have conceived a mature design using heritage technology (Kepler, Deep Impact) for a Probe class mission (< \$800 million). The design includes extensive mission- and systems-level engineering down to the sub-system/component level, leading to a well-balanced error budget with a low-risk design and realizable mission. EPIC was selected as a NASA Astrophysics Strategic Mission Concept (ASMC) study (FY08/FY09) and as part of this effort was the only selected mission independently costed through both GSFC Integrated Design Center (ICD) and JPL’s Team-X, thereby achieving high reliability in the cost estimates.

GSFC FY09 IR&D funding enabled demonstration of the critical VNC technology to achieve  $\sim 10^8$  contrast in the core of the Airy disk (narrowband). NASA FY09 SBIR funding enabled development and delivery of critical component level technology including the highest quality MEMS deformable mirror ever manufactured, and a high-quality coherent fiber bundle matched to the deformable mirror. GSFC, with its industrial partners, developed an incremental suite of VNC testbeds, which include the Vacuum VNC, the Null Control Breadboard (NCB), and the Compact Nuller.

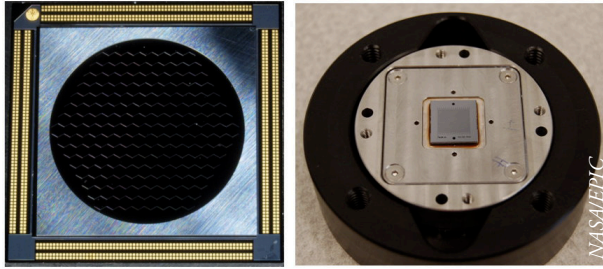
The Vacuum VNC allows successive validation of milestones through ever increasing contrast in succes-



NASA/EPIC

Schematic view of one design for the EPIC Visible Nulling Coronagraph.





The VNC deformable mirror and spatial filter array. *Left:* Photo of SBIR Phase-II developed MEMS deformable mirror (uncoated). Diameter of black circular region is ~9 mm. *Right:* Photo of custom coherent fiber bundle without lenslet arrays mounted.

sively broader bands through the use of the deformable mirror, achromatic phase shifter, coherent fiber bundle, and successively better null sensing and control. The NCB allows sensing and control algorithm development, and the Compact Nuller incorporates lessons learned into an athermal kinematic design that is cross-validated against a detailed structural, thermal, optical (STOP) model developed by Lockheed Martin. Recent selection of the VNC under a NASA TDEM (Technology Development for Exoplanet Missions, FY10/11) allows the EPIC team to advance the TRL from 3 to 4 and achieve  $10^9$  contrast in  $>15\%$  passband and hold it for  $> 1,000$  seconds.

### 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. Three spacecraft form an equilateral triangle with five-million-kilometer-long sides defined by six masses, located in pairs at the vertices. Changes in the separations are monitored interferometrically to achieve a usable sensitivity in the frequency band between  $1 \times 10^{-4}$  and 0.1 Hz

The science objectives of the missions are:

- 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 ( $10^2$ – $10^7$  solar masses,  $z < 20$ , tens to 100 per year)
- Stellar mass black hole inspirals ( $\sim 10/10^6$  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 data analysis.

**Goddard scientists support all aspects of project formulation, such as requirements development and flowdown, system analysis, system modeling, design of all mission elements, trade studies, and document preparation.**

Goddard scientists support all aspects of project formulation, such as requirements development and flowdown, system analysis, system modeling, design of all mission elements, trade studies, and document preparation. 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 larger 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 the first half of 2012. The Project has passed its mission CDR, the spacecraft is almost completely integrated and the propulsion module is complete.

In a new initiative, the Gravitational Astrophysics Lab hired James (Ira) Thorpe to support 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. Dr. Thorpe has participated in workshops preparing for the analysis of data from inflight tests.

### **Advanced Technology Large Aperture Space Telescope (ATLAST)**

ATLAST is a concept study consisting of three point designs for an 8- to 16-meter UV/optical/NIR observatory designed for operation in a halo orbit at the Sun-Earth second Lagrange point (SEL2). ATLAST would have an angular resolution 5–10 times better than the James Webb Space Telescope (JWST) and a sensitivity limit 40–300 times better than the Hubble Space Telescope (HST). This concept was selected for

study by NASA as one of the Astrophysics Strategic Mission Concept studies in preparation for the National Academy's Astro2010 Decadal Survey. Marc Postman (STScI) is the Principal Investigator and GSFC is the managing NASA Center. Team members include JPL, NGST, Ball Aerospace and scientists from the community. ASD scientists involved in the study include Mark Clampin, Ted Gull, Rick Lyon, Bill Oegerle, Jennifer Wiseman, and Bruce Woodgate, as well as a number of people from the GSFC Engineering Directorate.

The ATLAS Telescope is envisioned as a flagship mission of the 2025–2035 period designed to address one of the most compelling questions of our time: Is there life elsewhere in our Galaxy? It will have the capabilities required to explore the nearest ~1,000 stars capable of harboring life for Earth-size planets and characterize their spectra. ATLAST will also be a next generation UV/Optical Great Observatory—in the model established by HST—that is capable of achieving breakthroughs in a broad range of astrophysics and adaptable to addressing scientific investigations yet to be conceived. Indeed, such a telescope would revolutionize the study of galaxy evolution, enabling, for the first time, measurements of the kinematics of both the gaseous and stellar components of the smallest dwarf galaxies. It would yield such precise constraints on hierarchical-structure formation models that a new era of “precision galaxy evolution” would ensue. The superb spatial resolution would also allow unprecedented studies of resolved stellar populations in nearby galaxies.

**The ATLAS Telescope is envisioned as a flagship mission of the 2025–2035 period designed to address one of the most compelling questions of our time: Is there life elsewhere in our Galaxy?**

Two of the point designs (for an 8m monolithic mirror telescope and a 16m segmented, deployable-aperture telescope) are enabled by NASA's plans for a large Cargo Launch Vehicle (the Ares V), which will have a fairing size of 9–10 meters in diameter and the lift capacity to take 100 metric tons to SEL2. The 8-meter monolith telescope would fit into the Ares V fairing

with the secondary fully deployed in an upright position. This eliminates a lot of risk in deployment in orbit. The 16m segmented-aperture telescope builds on the JWST heritage in terms of its segmented design and folded packaging.

A third point design, being studied primarily at GSFC, is for a 9.2m segmented telescope that would fit into the fairing of an upgraded Evolved Expendable Launch Vehicle (EELV), such as the Delta IV heavy. All three point designs are identifying the technology

investments needed to enable these telescopes, such as lightweight mirrors with accurate figures, active wavefront sensing and control, and large-format detector technologies, to name just a few. The ATLAST study report was delivered to NASA in April 2009 and several reports were submitted to the Astro2010 Decadal Survey committee for consideration. Further details about the ATLAST mission can be obtained from the ATLAST public website [www.stsci.edu/institute/atlast](http://www.stsci.edu/institute/atlast).





## VI. Education and Public Outreach in NASA's Astrophysics Science Division

### E/PO within the Astrophysics Science Division

The Astrophysics Science Division supports a strong and vibrant Education and Public Outreach (E/PO) program. The E/PO team includes members who support various NASA astrophysics missions and programs, including ACE, HEASARC, Webb, GEMS, Suzaku, and RXTE. The team also supports a broader EPO effort that is not mission specific and covers ASD science and technology. The E/PO group was led by Dr. Anita Krishnamurthi (CRESST/USRA) until August 31, 2009, after which Dr. James Lochner (CRESST/USRA) assumed the duties as Acting E/PO Lead.

This past year saw a number of significant events, milestones and accomplishments.

The ASD E/PO group took a lead role in organizing Goddard's participation in the International Year Of Astronomy's 100 Hours of Astronomy from April 2–5. We piloted a number of ideas to reach new audiences and engage the local community. We also partnered with our Goddard Education colleagues in the Education office and in other divisions to hold these events. We invited area informal educators for a tour of Goddard facilities and provided a showcase of GSFC-wide products and programs for informal settings. We also provided a tour and a panel discussion for area guidance counselors, offering them a first-hand view into different NASA careers. We offered a "Teacher's Night at Goddard" at the Visitor Center, providing an informal setting for teachers to mingle with Goddard scientists, and education professionals, while learning about our formal education products and programs. We worked with the Friends of Ann Arundel County Trails to run a docent-hosted Planet Walk along the Baltimore-Annapolis Trail. *We provided volunteer scientists from GSFC to staff tables at each of the planets so that visitors may learn about the planets and about recent the NASA planetary missions. We also provided structured activities for families at the Visitor Center, arranging for Astrocappella to provide entertainment. Finally, the Astronomical Society of Greenbelt and the Goddard*

*Astronomy Club pitched in to provide a "Telescope Tune-up" workshop, and to hold star parties.* The 100 Hours project added to the ASD's existing efforts and EPO portfolio by bringing new community partners and audiences to the table.

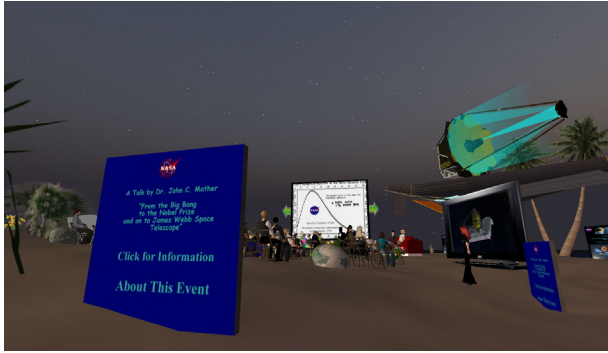
Afterschool Universe continues to expand its network of trained providers who run this 12-unit afterschool program in local communities. Anita Krishnamurthi, Sarah Eyermann (SP Systems), and Sara Mitchell (SP Systems) ran six training workshops around the country. The team won 2009 NASA Honor Award for Public Service Group Achievement for "dedication and innovation in bringing NASA into the lives of thousands of individuals who might not otherwise be engaged in space science." In addition, the team won an Education & Public Outreach for Earth and Space Sciences (EPOESS) grant to run a "train the trainer" workshop to continue program dissemination in 2010 and beyond.

Our Blueshift podcast, under the direction of Sara Mitchell, is now on a semimonthly release schedule. In 2009, we released 23 episodes, including a special video episode exploring the hidden corners of Building 2, with over 100,000 downloads. The podcasts have tackled a variety of topics, from exoplanets to cosmology to technology, while taking listeners behind the scenes in ASD.

The Big Explosions and Strong Gravity (BESG) program, directed by Ann Hornschemeier (GSFC) and Sarah Eyermann, targets Girl Scouts aged 11 to 13. This is a one-day event where girls meet real scientists



Families participated in ASD-led events at the Visitor Center for 100 Hours of Astronomy.



A crowd gathers to hear John Mather’s presentation in Second Life.

and join them for a day of hands-on exploration into supernovae and black holes. Girls whose interest in science is piqued by this event participate in a follow-on program, the A.C.E. of Space club (A.C.E. stands for Astronomical Cosmic Exploration). This is a girl-led club in which the members explore different parts of the universe during their meetings over the course of a year.

ASD E/PO, as well as a number of our mission E/PO programs, ventured into social media, establishing accounts on Twitter, Facebook, and for Webb a YouTube channel. Our NASAUniverseEdu Twitter feed, with tweets composed by Barbara Mattson (ADNET), provides information about upcoming workshops, facts about our missions, and updates to our web sites. We currently have 129 followers. In addition, John Mather gave a talk in Second Life on the NASA eEducation Island. It was well attended by avatars from around the world!

Using the five-year WMAP results, Britt Griswold (Maslow Media) and Gary Hinshaw (GSFC) created the second edition of the “WMAP Beach Ball.” More than 5,000 were distributed in 2009. (The first edition of the WMAP Beach Ball is part of the set for the CBS comedy “Big Bang Theory”.) Mike Greason (ADNET), Britt Griswold, and Gary Hinshaw also released “Build a Universe,” a Flash-based game to help the public understand how scientists figure out the age and content of the universe from the WMAP results.

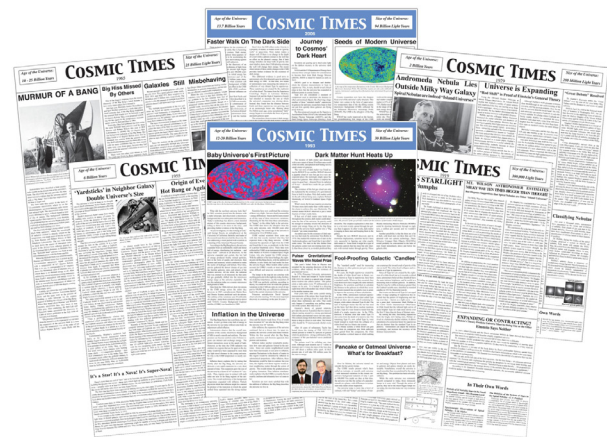
For the James Webb Space Telescope, Maggie Masetti (ADNET) completed two new levels of “Scope

It Out,” an online game about the development of telescopes and the design of Webb. Masetti also took Webb into the world of social media, with accounts on Twitter and Facebook, and a YouTube channel.

## HEASARC E/PO

The HEASARC E/PO program continues to fulfill its mission of bringing the science of high-energy astrophysics and cosmology to teachers and their students.

Dr. James Lochner (CRESST/USRA) and Dr. Barbara Mattson (ADNET) completed the HEASARC’s “Cosmic Times” project. This set of six posters with accompanying lesson plans describes how our knowledge of the universe has changed over the past 100 years. Each poster mimics the front page of a newspaper with articles about key discoveries in this history. The posters were printed mid-year and by end of the year more than 1,000 sets had already been distributed. The Cosmic Times web site provides resources for teachers, including the lessons and a teacher guide. This year, Dr. Lochner and Mattson also revised the Cosmic Times web site to include an on-line edition of the posters. They also developed a third differentiated version of the poster articles to make the material more accessible to students in grades 7–9. During the course of the year, they conducted five workshops on the Cosmic Times materials, including an NSTA webinar, as well as published an article about Cosmic Times in NSTA’s *The Science Teacher*, a journal for high school teachers.



The Cosmic Times posters



The HEASARC E/PO program continues to send out our formal education materials to teachers and workshop providers. But over the past year we branched out to supply our materials to the Night Sky Network, an organization run by the Astronomical Society of the Pacific consisting of more than 200 amateur astronomy clubs around the country. These clubs have used the *Imagine the Universe!* CDs not only for their star parties and teacher workshops, but for other events and audiences such as the National Federation of the Blind, a city symphony, more than a few senior citizen centers, a summer camp for children of incarcerated parents, a 4H group, the Science Olympiad training, and a dozen presentations at inner

city libraries. This has greatly expanded the audience for our materials.

The HEASARC E/PO program successfully obtained funding through the Education & Public Outreach for Earth and Space Sciences (EPOESS) Program to continue the production of the *Imagine the Universe!* CD-ROM. The CD-ROM captures the HEASARC's education web sites, as well as the previous year's Astronomy Picture of the Day pages. The grant will not only provide funding for production for three years, but also funding to determine more precisely the demographics of our audience and how they use the CD-ROM.







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<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b>  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.					
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