The goal of the Space Science Enterprise's Structure and Evolution of the Universe (SEU) Theme is to seek the answer to three fundamental questions:

1. What is the structure of the universe and what is our cosmic destiny?
2. What are the cycles of matter and energy in the evolving universe?
3. What are the ultimate limits of gravity and energy in the universe?

SEU's strategy for understanding this interactive system is organized around four fundamental Quests, designed to answer the following questions:

1. Identify dark matter and learn how it shapes galaxies and systems of galaxies,
2. Explore where and when chemical elements were made,
3. Understand the cycles in which matter, energy, and magnetic fields are exchanged between stars and the gas between stars,
4. Discover how gas flows in disks and how cosmic jets formed,
5. Identify the sources of gamma-ray bursts and high energy cosmic rays, and
6. Measure how strong gravity operates near black holes and how it affects the early universe.
Subtopics

S2.01 Sensors and Detectors for Astrophysics

Lead Center: JPL

Future NASA astrophysics missions like Sofia, Herschel, Planck, FAIR, MAXIM, EXIST, and ARISE (http://spacescience.nasa.gov/missions/index.htm) need improvements in sensors and detectors. Beyond 2007, expected advances in detectors and other technologies may allow the Filled Aperture Infrared instrument (FAIR) to extend HST observations into the mid- and far-infrared (40–500 micron) region; the Micro-Arcsecond X-ray Imaging Mission Pathfinder (MAXIM) will demonstrate the feasibility of x-ray interferometry with a resolution of 100 micro-arc seconds, which is 5000 times better than the Chandra observatory; the Energetic X-ray Imaging Telescope (EXIST) will conduct the first high sensitivity, all-sky imaging survey at the predominantly thermal (x-ray) and non-thermal (gamma-ray) universe requiring a wide-field coded aperture telescope array; and the Advanced Radio Interferometry between Space and Earth (ARISE) mission will create an interferometer including radio telescopes in space and on Earth.

Space science sensor and detector technology innovations are sought in the following areas:

**Mid/Infrared, Far Infrared and Submillimeter**

Future space-based observatories in the 10-40 micron spectral regime will be passively cooled to about 30 K. They will make use of large sensitive detector arrays with low-power dissipation array readout electronics. Improvements in sensitivity, stability, array size, and power consumption are sought. In particular, novel doping approaches to extend wavelength response, lower dark current and readout noise, novel energy discrimination approaches, and low noise superconducting electronics are applicable areas. Future space observatories in the 40 micron to 1 mm spectral regime will be cooled to even lower temperatures, frequently 20 W Hz^{-1/2} over most of the spectral range in a 100x100 pixel detector array, with low-power dissipation array readout electronics. The ideal detector element would count individual photons and provide some energy discrimination. For detailed line mapping (e.g., C+ at 158 micron), heterodyne receiver arrays are desirable, operating in the same frequency range near the quantum limit.

**Space Very Long Baseline Interferometry (VLBI)**

The next generations of Very Long Baseline Interferometry (VLBI) missions in space will demand greatly improved sensitivity over current missions. These new missions will also operate at much higher frequencies (at first to 86 GHz and eventually to 600 GHz). These thrusts will require development of improved space-borne low-power ultra-low-noise amplifiers and mixers to serve as primary receiving instruments.

S2.02 Terrestrial and Extra-Terrestrial Balloons and Aerobots
Innovations in materials, structures, and systems concepts have enabled buoyant vehicles to play an expanding role in NASA's Space and Earth Science Enterprises. A new generation of large, stratospheric balloons based on advanced balloon envelope technologies will be able to deliver payloads of several thousand kilograms to above 99.9% of the Earth’s absorbing atmosphere and maintain them there for months of continuous observation. Smaller scale, but similarly designed, balloons and airships will also carry scientific payloads on Mars, Venus, Titan, and the outer planets in order to investigate their atmospheres in situ and their surfaces from close proximity. Their envelopes will be subject to extreme environments and must support missions with a range of durations. Robotic balloons, known as aerobots, have a wide range of potential applications both on Earth and on other solar system bodies. NASA is seeking innovative and cost-effective solutions in support of terrestrial and extraterrestrial balloons and aerobots in the following areas.

**Stratospheric Long Duration Balloon (LDB) Support**

**Materials**

- Innovative membranes for terrestrial applications to support the Long Duration Balloon (LDB) and Ultra-Long Duration Balloon (ULDB) development efforts. The material of interest shall meet all environmental, design, fabrication, and operational requirements and must be producible in large quantities in a lay-flat width of at least 1.6 m.
- Innovative concepts for reducing the UV degradation of flight components including balloon membranes, load carrying members, and parachute components.

**Support Systems**

- Innovative concepts for trajectory control and/or station-keeping for effectively maneuvering large terrestrial and small extraterrestrial aerobots in either the horizontal latitude or vertical altitude plane or both.
- Innovative low mass, high density, and high efficiency power systems for terrestrial balloons that produce 2 kW or more continuously.
- Innovative power systems that enable long duration, sunlight independent missions for a duration of 30 days or more.
- Innovative, low cost, low power, low mass, precision instrument pointing systems that permit arcsecond or better accuracy.
- Innovative sensor concepts for balloon gas or skin temperature measurements.
- Innovative floatation systems for water recovery of payloads.

**Design and Fabrication**
• Innovative, efficient, reliable and cost-effective balloon fabrication and inspection techniques to support the current ULDB development efforts.

• Innovative balloon design concepts for long duration missions which can provide any or all of the following:
  
  ◦ Reduced material strength requirements;
  ◦ Increased reliability;
  ◦ Enhanced performance;
  ◦ Reduced manufacturing time;
  ◦ Reduced manufacturing cost; and
  ◦ Improved mission flexibility.

Titan Missions Support

Titan is the second largest moon in the solar system and the only one that features a sufficiently dense atmosphere for buoyant vehicle flight. Targeted for exploration by Cassini-Huygens in 2004 and beyond, Titan is expected to be a geologically and chemically diverse world containing important clues on the nature of prebiotic chemistry. NASA is starting to lay the ground work for post-Cassini-Huygens exploration of Titan using highly autonomous, self-propelled aerobots capable of surveying many widely separated locations on the world and potentially including surface sampling and composition analysis. Innovative technologies are sought in the following areas:

• Concepts, devices and materials for sealing (repairing) of small holes in the balloon envelope material during flight at Titan. Repair of these holes may be required to enable the long mission lifetimes (6–12 months) desired at Titan. Although the balloon envelope material for Titan has not yet been specified, repair strategies should be generally compatible with polymer materials and the 90 K environment. It is imperative that proposed solutions be low mass (on the order of a few kilograms) and low power (a few Watts).

• Concepts and devices for the processing of atmospheric methane into hydrogen gas and its use as a makeup gas to compensate for leakage during operational flight at Titan. It is imperative that proposed solutions be low mass (on the order of a few kilograms) and low power (a few Watts).

Venus Missions Support

Venus is the second planet from the Sun and features a dense, CO₂ atmosphere completely covered by clouds. Although already explored by various orbiters and short-lived atmospheric probes and landers, Venus retains many secrets pertaining to its formation and evolution. One of NASA’s long-term objectives is to develop the technologies required for a surface sample return mission. A high temperature balloon is one key element that will be needed to loft the sample from the surface to a high altitude for launching a return rocket back to Earth. Innovative technologies are, therefore, sought in the following area:

• Designs, materials, and prototypes for surface-launched Venus balloons. Balloon volumes in the range of 0.5–5 m³ are required when fully inflated. The balloon must be storable in a packaged condition for up to 1 year and have an areal density of less than 1000 g/m². Proposed concepts must include an automatic
surface launch that will work in the Venus environment consisting of 460°C temperature, 90 atmosphere pressure, and surface winds of up to 1 m/s.

S2.03 Cryogenic Systems

Lead Center: GSFC
Participating Center(s): ARC, JPL, MSFC

Cryogenic systems have long been used to perform cutting edge space science, but at high cost and with limited lifetime. Improvements in cryogenic system technology enable further scientific advancement at lower cost and/or lower risk. Lifetime, reliability, mass, and power requirements of the cryogenic systems are critical performance concerns. Of interest are cryogenic coolers for cooling detectors, telescopes, and instruments. In addition, cryogenic coolers for lunar and interplanetary exploration are of interest. The coolers should have long life, low vibration, low mass, low cost, and high efficiency. Specific areas of interest include the following:

- Highly efficient coolers in the range of 4–10 K as well as 50 mK and below, and cryogen-free systems that integrate these coolers together;
- Low-mass, highly efficient coolers for gas sample collection and liquefaction of gases for use in propulsion systems;
- Essentially vibration-free cooling systems, such as reverse Brayton cycle cooler technologies;
- Highly reliable, efficient, low-cost Stirling and pulse tube cooler technologies in the 10 K, 15 K, and 35 K regions;
- Highly efficient magnetic and dilution cooling technologies, particularly at very low temperatures;
- Hybrid cooling systems that make optimal use of radiative coolers; and
- Miniature, MEMS, and solid-state cooler systems.

S2.04 Optical Technologies

Lead Center: GSFC
Participating Center(s): JPL

The NASA Space Science Enterprise is studying future missions to explore the Structure and Evolution of the Universe (SEU). To understand the structure and evolution of the universe, a variety of large space-based observatories are necessary to observe cosmic phenomena from radio waves to the highest energy cosmic rays. It will be necessary to operate some of these observatories at cryogenic temperatures (to 4 K) beyond
geosynchronous orbits. Apertures for normal incidence telescope optics are required up to 40 m in diameter, while grazing incidence optics are required to support apertures up to 10 m in diameter. For some missions, these apertures will form a constellation of telescopes operating as interferometers. These interferometric observatories may have effective apertures up to 1000 m diameter. Low mass of critical components such as the primary mirror, its support and/or deployment structure, is extremely important. In order to meet the stringent optical alignment and tolerances necessary for a high quality telescope and to provide a robust design, there are significant benefits possible from employing systems that can adaptively correct for image degrading sources from inside and outside the spacecraft. This includes correction systems for large aperture space telescopes that require control across the entire wavefront, typically at low temporal bandwidth. The following technologies are sought:

- Grazing incidence focusing mirrors with response up to 150 keV.
- Large, ultra-lightweight grazing incidence optics for x-ray mirrors with angular resolutions less than 5 arcsec.
- Wide field-of-view optics using square pore slumped microchannel plates or equivalent.
- Develop fabrication techniques for ultra-thin-flat silicon (or like material) for grating substrates for x-ray energies
- Large area thin blocking filters with high efficiency at low energy x-ray energies
- Ultraviolet filters with deep blocking
- Develop novel materials and fabrication techniques for producing ultra-lightweight mirrors, high-performance diamond turned optics (including freeform optical surfaces), and ultra-smooth (2–3 angstroms rms) replicated optics that are both rigid and lightweight. Lightweight high modulus (e.g., silicon carbide) optics and structures are also desired.
- High-performance (e.g., high modulus, low density, high thermal conductivity) materials and fabrication processes for ultra-lightweight, high precision (e.g., subarcsecond resolution or
- Advanced, low-cost, high quality large optics fabrication processes and test methods including active metrology feedback systems during fabrication, and artificial intelligence controlled systems.
- Large, ultra-lightweight optical mirrors including membrane optics for very large aperture space telescopes and interferometers.
- Cryogenic optics, structures, and mechanisms for space telescopes and interferometers.
- Ultra-precise, low mass deployable structures to reduce launch volume for large-aperture space telescopes and interferometers.
- Segmented optical systems with high-precision controls; active and/or adaptive mirrors; shape control of deformable telescope mirrors; and image stabilization systems.
- Advanced, wavefront sensing and control systems including image based wavefront sensors.
- Wavefront correction techniques and optics for large aperture membrane mirrors and refractors (curved lenses, Fresnel lenses, diffractive lenses).
- Nanometer to sub-picometer metrology for space telescopes and interferometers.
- Develop ultra-stable optics over time periods from minutes to hours.
- Advanced analytical models, simulations, and evaluation techniques, and new integrations of suites of existing software tools allowing a broader and more in-depth evaluation of design alternatives and identification of optimum system parameters including optical, thermal, structural, and dynamic performance of large space telescopes and interferometers.
• Develop portable and miniaturized state-of-the-art optical characterization instrumentation and rapid, large-area surface-roughness characterization techniques are needed. In addition, develop calibrated processes for determination of surface roughness using replicas made from the actual surface. Traceable surface roughness standards suitable for calibrating profilometers over sub-micron to millimeter wavelength ranges are needed.

• Develop instruments capable of rapidly determining the approximate surface roughness of an optical surface, allowing modification of process parameters to improve finish, without the need to remove the optics from the polishing machine. Techniques are needed for testing the figure of large, convex aspheric surfaces to fractional wave tolerances in the visible.

S2.05 Advanced Photon Detectors
Lead Center: GSFC
Participating Center(s): MSFC

The next generation of astrophysics observatories for the infrared, ultraviolet (UV), x-ray, and gamma-ray bands require order-of-magnitude performance advances in detectors, detector arrays, readout electronics, and other supporting and enabling technologies. Although the relative value of the improvements may differ among the four energy regions, many of the parameters where improvements are needed are present in all four bands. In particular, all bands need improvements in spatial and spectral resolutions, in the ability to cover large areas, and in the ability to support the readout of the thousands to millions of resultant spatial resolution elements.

Innovative technologies are sought to enhance the scope, efficiency, and resolution of instrument systems at all energies and wavelengths:

• The next generation of gravitational missions will require greatly improved inertial sensors. Such an inertial sensor must provide a carefully fabricated test mass which has interactions with external forces (i.e., low magnetic susceptibility, high degree of symmetry, low variation in electrostatic surface potential, etc.) below 10–16 of the Earth’s gravity, over time scales from several seconds to several hours. The inertial sensor must also provide a housing for containing the proof mass in a suitable environment (i.e., high vacuum, low magnetic and electrostatic potentials, etc.).

• Advanced charged couple device (CCD) detectors, including improvements in UV quantum efficiency and read noise, to increase the limiting sensitivity in long exposures and improved radiation tolerance. Electron-bombarded CCD detectors, including improvements in efficiency, resolution, and global and local count rate capability. In the x-ray, we seek to extend the response to lower energies in some CCDs, and to higher, perhaps up to 50 keV, in others.

• Significant improvements in wide band gap (such as GaN and AlGaN) materials, individual detectors, and arrays for UV applications.

• Improved microchannel plate detectors, including improvements to the plates themselves (smaller pores, greater lifetimes, alternative fabrication technologies, e.g., silicon), as well as improvements to the associated electronic readout systems (spatial resolution, signal-to-noise capability, dynamic range), and in
sealed tube fabrication yield.

- Imaging from low-Earth orbit of air fluorescence UV light generated by giant airshowers by ultra-high energy (E > 1019 eV) cosmic rays require the development of high sensitivity and efficiency detection of 300–400 nm UV photons to measure signals at the few photon (single photo-electron) level. A secondary goal minimizes the sensitivity to photons with a wavelength greater than 400 nm. High electronic gain (~106), low noise, fast time response (2 to 10 x 10 mm². Focal plane mass must be minimized (2 g/cm² goal). Individual pixel readout. The entire focal plane detector can be formed from smaller, individual sub-arrays.

- For advanced x-ray calorimetry improvements in several areas are needed, including:
  
  - Superconducting electronics for cryogenic x-ray detectors such as SQUID-based amplifiers and their multiplexers for low impedance cryogenic sensors and superconducting single-electron transistors and their multiplexers for high impedance cryogenic sensors;
  
  - Micromachining techniques that enhance the fabrication, energy resolution, or count rate capability of closely-packed arrays of x-ray calorimeters operating in the energy range from 0.1–10 keV; and
  
  - Surface micromachining techniques for improving integration of x-ray calorimeters with read-out electronics in large scale arrays.

- Improvements in readout electronics, including low power ASICs and the associated high density interconnects and component arrays to interface them to detector arrays.

- Superconducting tunnel junction devices and transition edge sensors for the UV and x-ray regions. For the UV, these offer a promising path to having "three-dimensional" arrays (spatial plus energy). Improvements in energy resolution, pixel count, count rate capability, and long wavelength rejection are of particular interest. We seek techniques for fabrication of close packed arrays, with any requisite thermal isolation, and sensitive (SQUID or single electron transistor), fast, readout schemes and/or multiplexers.

- Arrays of CZT detectors of thickness 5–10 mm to cover the 10–500 keV range, and hybrid detector systems with a Si CCD over a CZT pixelated detector operating in the 2–150 keV range.

- For improvements to detector systems for solar and night-time UV and EUV (approx. 20–300nm) observing the following areas are of interest: Large format (4 K x 4 K and larger); high quantum efficiency; small pixel size; large well depth; low read noise; fast readout; low power consumption (including readout); intrinsic energy and/or polarization discrimination (3d or 4d detector); active pixel sensors (back-illumination, UV sensitivity); and high-resolution image intensifiers, UV and EUV sensitive, insensitive to moisture.

- Space spectroscopic observations in the UV, visible and IR requiring long observations times would be much more sensitive with high quantum efficiency (QE) and zero read noise. Techniques are sought which improve the QE of photon counters, or eliminate the read noise of solid state detectors.

- X-ray and gamma-ray imaging with higher sensitivity, dynamic range, and angular resolution requires innovations in modulation collimators and detection devices. The energy range of interest is from a few kilo-electron Volts to hundreds of milli-electron Volts for observations of solar flares and cosmic sources. Collimators with size scales down to a few microns and thicknesses commensurate with photon absorption over a significant fraction of this energy range are required. Low-background detectors capable of
S2.06 Technologies for Gravity Wave Detection

Lead Center: JPL
Participating Center(s): GSFC

Instruments that detect low frequency gravity waves offer a new window on the universe, its origin, evolution and structure. Complementing ground-based experiments such as the Laser Interferometer Gravitational Wave Observatory (LIGO), the Laser Interferometer Space Antenna (LISA), and the follow on vision mission, Big Bang Observer, will implement ambitious systems to detect and characterize gravity waves associated with the Big Bang, mergers of black holes, and other significant astrophysical phenomena. The success of such investigations will largely depend on the technology building blocks that are needed to implement multiple spacecraft constellations with extremely precise laser interferometers and test masses which are actively decoupled from systematic and random disturbances.

The technology areas are organized into two subsystems, one dealing with the disturbance rejection subsystem, which houses the proof mass with active sensors and thrusters to cancel non-gravity wave disturbances, and the other implementing the network of laser interferometers with nanometer-level resolution of relative range between the test masses. Because the systems will be deployed in space, the technologies to be considered must be, or have, credible paths toward full space flight qualification, including thermal and radiation considerations. Background information on LISA, along with preliminary technology discussions, can be found in the proceedings of the 4th International LISA Symposium, Penn State University, 19–24 July 2002, published in the Classical and Quantum Gravity Journal, Volume 20, Number 10, 21 May 2003.

**Disturbance Reduction System (DRS)**

- Vacuum system – non-magnetic vacuum pump for reaching pressures of -6 Pa with a pumping volume of 1 liter; with associated valves and electronics
- Vacuum gauge – read pressure down to 10^{-6} Pa on orbit, must be non-magnetic
- Caging actuator – hold 2 kg mass ~4 cm^3 against launch loads of ~25 g rms, with the capability for moving caged test mass over ~10 micron range with ~1 nm precision during ground testing
- Test mass, ~4 cm^3, mass ~1–2 kg, magnetic susceptibility -6 (e.g., 73% gold/27% platinum)

**Laser Interferometer**

- Laser with exceptional power, frequency noise, amplitude noise, lifetime characteristics.
  - Fiber coupled output power (1 W) CW
  - A combination of a lower power master oscillator with suitable amplifier to yield 1 W of total fiber coupled output power may be acceptable
  - Frequency and amplitude noise characteristics: Frequency stability to (30 Hz/vHz at 1 mHz), and power stability to (2x10^{-4}/vHz at 1 mHz)
  - Lifetime of 10 years or more.
- Wavelength is nominally 1.064 micron, but +/- 20% of that value is acceptable.

- Semiconductor diode pump laser with outstanding reliability to operate with a suitable solid-state laser (e.g., non-planar ring oscillator laser) is required.

- Electro-optical modulator – produce phase modulation of continuous laser beam with 10% (power) modulation depth at frequencies from 1.9–2.1 GHz with fiber coupled input and output. Baseline operation will be at 1.064 microns. In addition to the space qualification requirements, the modulator must be able to handle optical power levels at ~ 1 W.

Research and technology development should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware demonstration, and when possible, deliver a demonstration unit to a participating NASA Center for testing at the completion of the Phase II contract.