S4  Exploration of the Universe Beyond Our Solar System

The Universe division of the NASA/GSFC is charged with exploring the universe beyond the solar system - out to its very edges. To do this, requires ever more powerful missions (beyond Chandra, Spitzer, and Hubble) with larger and better optics and detector systems. Future mission may include optics that fold and deploy and can be assembled on orbit, as well as larger arrays of detectors, bolometers, microcalorimeters (superconducting), and room temperature semiconductors. Our missions cover the full range of the electromagnetic spectrum and gravitational waves. Some of our major science goals are to identify dark matter, to understand dark energy, to produce a census of black holes, to image material in the accretion disks around black holes, and to measure gravitational waves from a wide range of sources. In addition, we are exploring new technologies for sub-orbital platforms including long duration balloons, tethered balloons, and airships. We are soliciting ideas and concepts in six areas covering optical systems, UV, visible, IR and sub-mm detectors, X-ray and Gamma-ray detectors, lasers for gravitational wave measurements, and sub-orbital platforms. The subtopics in this area are described in detail in each subtopic section.

Subtopics

S4.01 Infrared & Sub-mm Sensors and Detectors

Lead Center: JPL
Participating Center(s): MSFC

NASA astrophysics missions currently under development, such as Sofia, Herschel, and Planck (http://science.hq.nasa.gov/missions/phase.html) have been enabled by improvements in sensors and detectors. Beyond 2007, expected advances in detectors, readout electronics, and other technologies, particularly those enabling polarimetry and large format imaging arrays for the far IR/submm and spectroscopy with unprecedented sensitivity. These advances may enable future mission concepts such as the Single Aperture Far Infrared (SAFIR) Observatory (http://safig.jpl.nasa.gov/technologies.shtml), SPICA (http://www.ir.isas.ac.jp/SPICA/), and CMBPOL.

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

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

The next generations of 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.

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### S4.02 Terrestrial and Extra-Terrestrial Balloons and Aerobots

*Lead Center: GSFC*

*Participating Center(s): JPL*

Innovations in materials, structures, and systems concepts have enabled buoyant vehicles to play an expanding role in NASA's Science Mission Directorate and Exploration Systems Mission Directorate. 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. NASA is seeking innovative and cost-effective solutions in support of terrestrial balloons in the following areas:

- Innovative concepts for reducing the UV degradation of flight components including balloon membranes, load carrying members, and parachute components;
- Innovative concepts for the measurement of strain in a thin film during flight;
- Innovative sensor concepts for balloon gas or skin temperature measurements;
- Innovative concepts for trajectory control and/or station keeping for effectively maneuvering large terrestrial balloons 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 durations of 30 days or more;
- Innovative floatation systems for water recovery of payloads;
- Innovative guided or gliding parachutes systems for use in thin atmospheres;
Innovative balloon design concepts for long duration missions that can provide any or all of the following: reduced material strength requirements, increased reliability, enhanced performance, reduced manufacturing time, reduced manufacturing cost, or improved mission flexibility; and

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. Proposals are sought in the following areas:

**Aerobot Surface Sample Acquisition Device**

NASA is soliciting concepts and prototypes for surface sample acquisition devices that can be used on aerobots to collect icy material from Titan and Mars. Typical sample volumes range from 1 to 2 cubic centimeters, with preference for a solid ice core as well as possible granular material. Collection depths of 0 to 2 cm are desired. Preferred techniques do not require close proximity of the aerobot balloon skin to the ground to reduce the probability of damaging the vehicle during sample acquisition. Examples include tethered collection devices deployed from modest altitudes (10s to 100s of meters) or short duration "touch and go" sampling from directional and/or altitude controlled aerobots. Proposed devices can be disposable (single use), but if reusable must avoid cross-contamination between samples. All devices must include solid sample transfer functionality to an analysis chamber on the aerobot itself. Concepts will be preferred that feature low mass (few kilograms or less), small volume (~1 liter) and low electrical power consumption drawn from the aerobot.

**Apex Valve for Montgolfiere Balloons**

Solar-heated Montgolfiere balloons are an attractive platform for the exploration of Mars, particularly the polar regions which experience long periods of solar illumination during summer solstice. These balloons can be altitude controlled through selective venting of the heated gas through a valve located at the apex of the balloon. Proposals are sought for concepts and prototypes for this valve to be used on a solar-heated balloon on Mars. Typical specifications include large flow area (10 m²), low mass (few kilograms), packaged into a small volume for transport to Mars (3) and consume minimal electrical energy.

**Aerial Deployment Modeling Tool**

Planetary aerobots at Mars, Titan, and Venus will likely be aerially deployed and inflated during parachute descent after arrival at the destination. Proposals are sought that would provide computer modeling tools that can simulate this complex process. Of particular importance is the ability to model the balloon shape and material stresses as a function of time, taking into account the aerodynamic forces generated by the parachute and by the uninflated or partially inflated balloon, as well as transient loads during balloon deployment from its storage container. The balloons can be either polymer films or polymer film plus reinforcing fabric laminates.

**Metal Bellows for High Temperature Venus Balloons**

Cylindrically-shaped metal bellows are a potential solution to the problem of making balloons that can tolerate the 460°C temperatures near the surface of Venus. Commercial off-the-shelf metal bellows are limited in diameter to approximately 0.4 m. NASA seeks proposals for metal bellows technology that can produce prototypes in the range of 1-2 m in diameter and 5-10 m long; tolerant of sulfuric acid; good fatigue properties at 460°C; and areal densities of up to 1 kg/m².
S4.03 Cryogenic Systems for Sensors and Detectors

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

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

- Highly efficient coolers in the range of 4-10 Kelvin as well as at 50 milli-Kelvin and below, and cryogen-free systems which integrate these coolers together;
- Highly reliable, efficient, low-cost Stirling and pulse tube cooler technologies in the 15 Kelvin and 35 Kelvin regions;
- Essentially vibration-free cooling systems such as reverse Brayton cycle cooler technologies;
- 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.

S4.04 Optics and Optical Telescopes (including X-ray, UV, Visual, IR)

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

With the reorganization of NASA activities into the Exploration Mission Directorate (EMD) and the Space Mission Directorate (SMD), there is a renewed call for novel optical technologies that extend the state-of-the-art across wavelength bands from far-IR to Gamma-ray. Missions to study the Earth and Sun, the other solar system planets and objects, and the origins and fate of the universe are proposed to operate from low Earth orbit to L2 or drift-away trajectories depending on their system of study and environmental requirements.

Among other areas of study, future planet finder missions will require lightweight optical apertures of tens of square meters with sub-nanometer surface figure errors. Infrared versions will require cooling optics to cryogenic temperatures (to 4 K). Telescopes studying the Sun and its environment in the UV and EUV (20-300 nm wavelength) require novel optical coatings and filters, high precision aspheric optics, and high-density uniform and variable line density diffraction gratings. And high-energy X-ray telescopes will study the origins and fate of the universe with
For all missions, low-mass optics and deployment structures are extremely important. Also, wavefront sensing and control systems are sought that may alleviate the stringent mass and stiffness requirements of such large optics. Finally, advanced, low-cost manufacturing, metrology, and modeling techniques will be required to make these missions possible.

The previous year's Optical Technologies (S2.04) and UV and EUV Optics (S1.06) have been merged to form this year's Optics and Optical Telescopes subtopic. All previously relevant areas of research are invited in this new subtopic including:

**Optics**

- Ultra-smooth (2-3 Angstroms rms) replicated optics that are rigid and lightweight;
- Lightweight, high modulus (e.g., silicon carbide) optics and structures;
- Ultra-stable optics over time periods from minutes to hours;
- Cryogenic optics, structures, and mechanisms for space telescopes and interferometers;
- High-performance, diamond turned optics (including freeform optical surfaces);
- Large, thin, ultra-lightweight grazing incidence optics for X-ray mirrors with angular resolutions less than 5 arcsec. (>100 cm², 2 areal density);
- Wide field-of-view optics using square pore slumped microchannel plates or equivalent;
- Large, ultra-lightweight optical mirrors (2 at near-IR through visible), including membrane optics for very large aperture space telescopes and interferometers;
- UV and EUV Imaging mirrors with simultaneously large aperture (1-4 m diameter), low mass (5-20 kg/m²), accurate figure (~0.01 wave rms or better at 632 nm), and low micro-roughness (Smooth sub-mm scale image slicer and microlens array component technologies to allow fabrication of integral field spectrographs in the UV and visible, for simultaneous spectroscopy of two spatial dimensions and one spectral dimension.

**Filters**

- Large area, thin blocking filters with high efficiency at low energy X-ray energies (Ultraviolet filters with deep blocking (5) of longer and shorter wavelengths, including "solar blind" performance; novel near- to far-IR filters with increased bandwidth, stability, and out-of-band blocking performance);
- FUV and EUV coatings (filters) with improved reflectivity (transmission) and selectivity (narrow bands, broad bands, or edges). Technologies include multilayers, transmission gratings, and Fabry-Perot etalons, among others; and
- Improved X-ray and Gamma-ray modulation optics and coded aperture masks (sub-arcsecond resolution at 10 keV to 10 arcsecond resolution at 1 MeV).
Gratings

- Fabrication techniques for ultra-thin-flat silicon (or like material) for grating substrates for X-ray energies
- High resolving power diffraction gratings (>4000 lines/mm) at acceptable focal lengths and pixel sizes; and
- Improvements in grating manufacturing technologies, such as high efficiency/low scatter gratings, variable line spacing, improved echelle gratings, active grating surfaces (gratings replicated onto deformable substrates), and gratings ruled onto concave, aspheric surfaces.

Metrology

- Low-cost, high quality, large optics fabrication processes and test methods including active metrology feedback systems during fabrication, and artificial intelligence controlled systems;
- Portable and miniaturized state-of-the-art optical characterization instrumentation and rapid, large-area surface-roughness characterization techniques are needed. 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; and
- 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 for testing the figure of large, convex, aspheric surfaces to fractional wave tolerances in the visible.

Wavefront Sensing and Control

- Optical systems with high-precision controls, active and/or adaptive mirrors, shape control of deformable telescope mirrors, and image stabilization systems; and
- Advanced, wavefront sensing and control systems including image based wavefront sensors;
- Nanometer to sub-picometer metrology for space telescopes and interferometers.

Optical Design

- 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.
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, and 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 >10^{19} 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 mm^2. 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 observation 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; and

- 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

S4.06 Technologies for Gravity Wave Detection

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

Laser Technologies for Gravitational Wave Detection

NASA is now developing the Laser Interferometer Space Antenna (LISA) mission to search for gravitational waves from astrophysical phenomena such as the Big Bang, mergers of supermassive black holes, and galactic binary inspirals. Detection of gravitational waves would open a new astrophysical window on the universe with great potential for unexpected discoveries. A number of gravitational wave follow-on missions to LISA are also under study.

The disturbance caused by the passage of a gravitational wave is expected to be very small (of order picometers) and will be measured with laser interferometry. The technology areas below deal with technical problems in these measurements. Because the systems will be deployed in space, the technologies to be considered must have credible paths toward space flight qualification. Background information on LISA, along with preliminary technology
Issues of Space Qualification of LISA Laser: the LISA laser must produce >1W CW of 1.06 micron light with fiber coupled output (for example, a combination of a lower-power master oscillator (eg, NPRO) with suitable amplifier). The laser will have the following characteristics:

- 10 year lifetime;
- Power stability
- Linewidth

This task will involve investigating the issues of space qualification of the system, experimentally studying the relevant problems, and proposing a realistic plan of development of this system. Given the magnitude of the effort to develop a space qualified LISA laser, it is not expected that the outcome of this task will result in a space qualified laser; rather, the outcome should be a sufficient understanding of the important technical issues in space qualification (e.g., diode lifetime, thermal and vibrational robustness, etc.) so that a clear path towards the development of a fully space qualified system can be identified.

LISA Electro-optical Modulator: produce a phase modulator for a 1 W continuous laser beam, providing 10% power modulation depth at frequencies from 1.9 to 2.1 GHz. The modulator should be fiber coupled (input and output), at 1.06 micron wavelength. The modulator must be space qualified.

LISA Telescope Articulator: produce a mechanical actuator that can articulate the LISA telescope over a 5 mm dynamic range with a 0.1 nm resolution. The actuator must be space qualified and have noise.