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 sophisticated instruments (surpassing Chandra, Spitzer, and Hubble) with larger and better optics and more sensitive detector systems. Future mission may include spacecraft in formation-flying; optics that fold and deploy and can be assembled on orbit; as well as larger arrays of detectors: bolometers, microcalorimeters, and room temperature semiconductors. Some of these arrays may contain billions of pixels. Our missions cover the full range of the electromagnetic spectrum (from sub-mm to gamma-rays) 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 terrestrial 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 Sensor and Detector Technology for Visible, IR, Far IR and Submillimeter

Lead Center: JPL
Participating Center(s): GSFC

NASA astrophysics missions currently under development, such as the Herschel and Planck, (http://science.hq.nasa.gov/missions/phase.html) have been enabled by improvements in detectors. Beyond 2007, advances are expected in detectors, readout electronics, and other technologies, particularly those enabling polarimetry and large format imaging arrays for the visible, near IR, IR and 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://safir.jpl.nasa.gov/index.shtml), SPICA (http://www.ir.isas.ac.jp/SPICA/), CMBPOL, and SNAP (http://snap.lbl.gov). Space science sensor and detector technology innovations are sought in the following areas:

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 < 10 K, greatly reducing background noise from the telescope. In order to take advantage of this potentially huge gain in sensitivity,
improved far infrared/submillimeter detector arrays are required. The goal is to provide noise equivalent power as low as $10^{-20}$ W Hz$^{1/2}$ over most of the spectral range in a 10,000 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.

In addition to technologies specific to the astrophysics missions previously mentioned, the following cross-cutting technologies are also of interest:

- Large (4 meter), lightweight, deployable antennas for frequencies between 180 to 660 GHz. Reflectors for such antennas with surface densities of 10 kg/m$^2$ or less.
- Broadband (> 2 GHz, 4 GHz preferred), modest resolution (10 MHz), low power (< 5 watt) digital spectrometers for submillimeter spectroscopy. This may include enabling technologies such as:
  - Efficient FPGA firmware for spectral analysis including polyphase filterbanks;
  - High speed, low power, space qualifiable digitizers with analog bandwidths of > 5 GHz and preferably up to 18 GHz, sample rates > 5 Gs/s, 4 to 6 bit resolution, and simple interface to present FPGAs;
  - Hardware (ex. ASICs) for low power implementation of digital signal processing.
- Broad bandwidth, low power, flight qualifiable spectrometers. Band of interest is 6 to 18 GHz or higher with ~200 MHz resolution.
- Reliable, tunable, spurious free, and flight qualifiable local oscillators for SIS mixers covering 190 to 270 GHz and 600 to 660 GHz.
- Broadband cryogenic isolators covering 6 to 18 GHz.

While focused technology and instrument developments are progressing for missions in the development phases such as the Space Interferometry Mission (SIM) and the James Webb Space Telescope (JWST), ambitious mission concepts are being pursued for future opportunities to address cosmology questions, galactic/stellar astrophysics and extrasolar planet finding quests. Innovative concepts that will significantly advance the state of the art in sensitivity, spectral coverage, array format, power dissipation, and other instrument critical parameters are sought. Also solicited are proposals that address key improvements in current techniques and devices in terms of performance, reliability and technology maturity. In such efforts, the proposer must demonstrate expertise and capability with respect to the existing technique/device/process/system. Optical/electronic devices that enhance or complement the detector function in an instrument are also of interest. Examples are micro shutter arrays to select objects across a focal plane for spectroscopy, timing and analog to digital converters for large focal plane instruments. The optical and near-IR requirements include giga pixel arrays, exceptionally stable sensitivity and precision calibration.

<table>
<thead>
<tr>
<th>Spectral Coverage</th>
<th>Detector Functionality</th>
<th>Parameters to Push</th>
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<tbody>
<tr>
<td>0.1 um - 1.0 um</td>
<td>Improving silicon response in UV and NIR, smart pixel arrays, solar blind response detector arrays, energy resolving calorimeter arrays</td>
<td>Sensitivity, array format size, high purity silicon processes</td>
</tr>
<tr>
<td>1.0 um - 4.0 um</td>
<td>New sensor materials, Large format cryogenic readout multiplexers, Large format (&gt;1x1k) array hybridization techniques</td>
<td>Sensitivity, array format size</td>
</tr>
<tr>
<td>4.0 um - 40 um</td>
<td>Low power cryo operated multiplexers, new sensor materials (e.g., novel dopants for extrinsic Si detectors)</td>
<td>Sensitivity, array format size (~megapixels)</td>
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Supporting Device Categories

<table>
<thead>
<tr>
<th>Spectral Coverage / Function</th>
<th>Technology</th>
<th>Parameters to Push</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm wave</td>
<td>MMIC packaging</td>
<td>Cost, cryo operation</td>
</tr>
<tr>
<td>Digital spectrometer (back-end for coherent receivers)</td>
<td>Autocorrelation spectrometers, high resolution FFT spectrometers</td>
<td>15 GHz or greater bandwidth (autocorrelation), 2 GHz or greater bandwidth (FFT &gt;32K points); low power, compact configurations</td>
</tr>
<tr>
<td>Shutter arrays for multi-object spectrographs</td>
<td>Micro-electromechanical shutter arrays or new technologies to do the same thing better</td>
<td>Reliability, low off state scatter or leakage, cryo operability</td>
</tr>
<tr>
<td>Infrared optical filters</td>
<td>Thin film or other technologies to realize ~1” aperture filters</td>
<td>High out of band rejection, well defined passbands (especially in 4-40um), cryo operation</td>
</tr>
<tr>
<td>Array hybridizing techniques</td>
<td>New, high yield bump bonding techniques</td>
<td>Yield, format size</td>
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</tbody>
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S4.02 Detector Technologies for UV, X-Ray, Gamma-Ray and Cosmic-Ray Instruments

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 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 >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:

- 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

S4.03 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 Manufacturing and Metrology for Telescopes
Lead Center: GSFC
Participating Center(s): JPL, MSFC

This subtopic focuses on optics manufacturing, metrology of optical surfaces, and mitigation of optical surface errors through direct manipulation of the optical surface and/or wavefront sensing and control techniques and technologies.
Optics manufacturing includes all areas associated with generation and maintenance of the optical surface, including both mirror and grating surfaces (and volumes). Improvements in substrate materials, hybrid structures, replication from masters, lightweighting techniques, and figuring and polishing (especially near-edge for segmented optics) are all sought.

Metrology of optical surfaces includes test methods and hardware to measure the surface to fractional wave tolerance, especially for large, aspheric optics and/or while the part is still mounted on the figuring/polishing apparatus or spindle. Metrology systems with artificial intelligence that can deterministically feed back to the polishing instrument, e.g., with a map of dwell times for subaperture polishing.

Mitigation of optical surface errors includes phase retrieval and wavefront sensing and control techniques and instrumentation, optical systems with high-precision controls, active and/or adaptive mirrors, shape control of deformable telescope mirrors, and image stabilization systems.

**S4.05 Data Analysis Technologies for Potential Gravity Wave Signals**

*Lead Center: GSFC*

NASA is developing the Laser Interferometer Space Antenna (LISA) mission to search for gravitational waves from astrophysical phenomena such as the Big Bang, mergers of super massive 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 and will be measured with laser interferometry. Technologies are sought to deal with the data analysis of the gravitational wave signals in these measurements. Background information on LISA along with preliminary data analysis discussions can be found in the Proceedings of the 5th International LISA Symposium, Estec, Noordwijk, The Netherlands, 12-15, July 2004, published in the Classical and Quantum Gravity Journal, Vol 22, Number 10, 21 May 2005.

Software development for application of the Hilbert-Huang Transform to gravitational wave data analysis: *The Hilbert-Huang Transform (HHT) is a new method of time-series analysis which is specifically target to the analysis of non-linear, transient signals (N. Huang, et al., "The empirical mode decomposition and the Hilbert spectrum for non-linear and non-stationary time series analysis", Proceedings of the Royal Society of London, A (1998) v. 454, 903-995). It will have a direct application to data analysis for LISA, Big Bang Observer (BBO), and other space-based gravitational wave missions in particular, and more generally to any mission with non-linear, transient data. For this task the vendor will be asked to build a software package that will provide a full HHT analysis of the data, using as an example a NASA-provided simulated LISA data stream, and incorporating a user-friendly interface. The vendor will need to familiarize himself with the HHT algorithm, and show relevant experience in the development of related software packages.*

**S4.06 Terrestrial Balloon Technology**

*Lead Center: GSFC*

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 trajectory control and/or station keeping for effectively maneuvering large terrestrial balloons in either the horizontal latitude or vertical altitude plane or both;
- Innovative floatation systems for water recovery of NASA's scientific payloads;
- Innovative guided or gliding parachutes systems for use in thin atmospheres.