Astrophysics Research and Analysis Program
Abstracts of selected proposals
(NNH14ZDA001N-APRA)

Below are the abstracts of proposals selected for funding for the APRA program. Principal Investigator (PI) name, institution, and proposal title are also included. 151 proposals were received in response to this opportunity. On October 20, 2015, 45 proposals were selected for funding. Further selections have been deferred due to budgetary constraints.

Simon Bandler/NASA / Goddard Space Flight Center
Magnetically-coupled microcalorimeter arrays for x-ray astrophysics

The "X-ray Surveyor" has been listed by NASA as one of the four major large mission concepts to be studied in the next Astrophysics Decadal Review in its preliminary list of large concepts. One of the key instruments on such a mission would be a very large format X-ray microcalorimeter array, with an array size of greater than 100 thousand pixels. Magnetically-coupled microcalorimeters (MCC) are one of the technologies with the greatest potential to meet the requirements of this mission, and this proposal is one to carry out research specifically to reach the goals of this vision.

The "X-ray Surveyor" is a concept for a future mission that will make X-ray observations that are instrumental to understanding the quickly emerging population of galaxies and supermassive black holes at z ~10. The observations will trace the formation of galaxies and their assembly into large-scale structures starting from the earliest possible epochs. This mission would be observing baryons and large-scale physical processes outside of the very densest regions in the local Universe. This can be achieved with an X-ray observatory with similar angular resolution as Chandra but with significantly improved optic area and detector sensitivity. Chandra-scale angular resolution (1” or better) is essential in building more powerful, higher throughput observatories to avoid source confusion and remain photon-limited rather than background-limited.

A prime consideration for the microcalorimeter camera on this type of mission is maintaining ~ 1 arcsec spatial resolution over the largest possible field of view, even if this means a slight trade-off against the spectral resolution. A uniform array of 1” pixels covering at least 5’x5’ field of view is desired. To reduce the number of sensors read out, in geometries where extremely fine pitch (~50 microns) is desired, the most promising technologies are those in which a thermal sensor such an MCC can read out a sub-array of 20-25 individual 1”□ pixels. Projections based on the current state of this technology indicate that less than 5 eV energy resolution can be achieved with this sort of geometry. Theoretically, magnetically-coupled microcalorimeters are well-equipped to achieve the very highest energy resolutions, especially when several absorbers are attached to each sensor, increasing the heat capacity. This program will build upon the work carried out by

our group on metallic magnetic calorimeters (MMC) and Magnetic penetration thermometers (MPT) in the antecedent program.

In this program we will carry out development in three main areas. First, we will develop sensor geometries that are optimized for reading out sub-arrays of pixels with a single sensor of the type that is likely desired by the "X-ray Surveyor". Second, we will further develop large-format arraying prototypes with the engineering of wiring-pixel approaches that are scalable to the large-format arrays that are needed. Third, we will develop the read-out technology that will be necessary, which utilizes the next generation of X-ray microcalorimeter read-out approach, a microwave multiplexing readout.

Peter Beiersdorfer/Lawrence Livermore National Laboratory
Signature of X-ray Line Formation of Fe XVII by Charge Exchange

Fe XVII dominates the spectral emission of a large number of astrophysical X-ray sources and, thus, is of prime diagnostic importance, as illustrated in numerous measurements by Chandra and XMM-Newton. Although immense progress has been made in laboratory measurements and spectral calculations of collisional plasmas since the launch of these X-ray observatories, model calculations of the Fe XVII X-ray spectrum still do not yield agreement with laboratory measurements or astrophysical observations that is completely satisfactory. Charge exchange is another line formation mechanism that can produce Fe XVII X-ray emission. However, line formation by charge exchange is ill understood, even in the case of 'simple' K-shell spectra of hydrogenlike or heliumlike ions. Nevertheless, simple spectral markers have been developed that represent proof for the presence of charge exchange even if the details of line formation are not yet fully clear. By contrast, there are essentially no charge exchange measurements and calculations for the much more complex Fe XVII L-shell X-ray spectrum. Whether charge exchange contributes an observable amount to X-ray line formation in astrophysical situations is controversial, as (arguably) no incontrovertible spectral evidence for charge exchange has been presented from sources outside our own solar system. In part, this is due to the fact that charge exchange is a mechanism that requires an extended source to be effective, such as circum-stellar halos or super nova remnants expanding into surrounding space, and so far there have been no measurements of extended sources with high spectral resolution. In addition, laboratory measurements have not yet provided data that could serve as spectral markers for charge exchange in the Fe XVII spectrum or, for that matter, in the other L-shell X-ray emission spectra of iron, i.e., Fe XVIII through Fe XXIV. As a result, it is not yet possible to argue that an observed iron L-shell X-ray spectrum is produced fully or in part by charge exchange. The impending launch of Astro-H with its X-ray microcalorimeter instrument will change the way we will study the X-ray emission from extended sources. For the first time, we will have the spectral resolution to see individual X-ray lines from diffuse objects, and it will become possible to discern contributions from charge exchange, or, at least, put limits on the contributions of this process to the overall line formation. In order to exploit the new capability afforded by the microcalorimeter on Astro-H and to firm up the

diagnostic significance of the emission from Fe XVII and of the other L-shell iron ions, we propose to conduct a set of laboratory astrophysics experiments to identify the signature of L-shell X-ray line formation by charge exchange.

Lloyd Bell/Jet Propulsion Laboratory
A Stable, Non-Cesiated III-Nitride Photocathode for Ultraviolet Astronomy Applications

In this effort, we propose to develop a new type of cesium-free photocathode using III-nitride (III-N) materials (GaN, AlN, and their alloys) and to achieve highly efficient, solar blind, and stable UV response. Currently, detectors used in UV instruments utilize a photocathode to convert UV photons into electrons that are subsequently detected by microchannel plate or CCD. The performance of these detectors critically depends on the efficiency and stability of their photocathodes. In particular, photocathode instability is responsible for many of the fabrication difficulties commonly experienced with this class of detectors.

In recent years, III-N (in particular GaN) photocathodes have been demonstrated with very high QE (>50%) in parts of UV spectral range. Moreover, due to the wide bandgaps of III-nitride materials, photocathode response can be tailored to be intrinsically solar-blind. However, these photocathodes still rely on cesiation for activation, necessitating all-vacuum fabrication and sealed-tube operation. The proposed photocathode structure will achieve activation through methods for band structure engineering such as delta-doping and polarization field engineering. Compared to the current state-of-the-art in flight-ready microchannel plate sealed tubes, photocathodes based on III-N materials will yield high QE and significantly enhance both fabrication yield and reliability, since they do not require cesium or other highly reactive materials for activation. This performance will enable a ~4 meter medium class UV spectroscopic and imaging mission that is of high scientific priority for NASA.

This work will build on the success of our previous APRA-funded effort. In that work, we demonstrated III-nitride photocathode operation without the use of cesium and stable response with respect to time. These accomplishments represent major improvements to the state-of-the-art for photocathode technologies. In the proposed effort, we will implement III-nitride polarity control, polarization charge engineering, and alloy fraction control to demonstrate a high-QE, solar-blind photocathode with air-stable UV response. Through our design, growth, and processing techniques, we will extend the application of these photocathodes into far UV for both semitransparent and opaque mode.

Geoffrey Blake/California Institute of Technology
TeraHertz Time Domain Spectroscopy of Astrophysical Analog Materials

The section of the electromagnetic spectrum extending roughly from wavelengths of 3 millimeters to 30 microns is commonly known as the far-infrared or TeraHertz (THz) region. It contains the great majority of the photons emitted by the universe, and THz observations of molecules and dust are able penetrate deeply into molecular clouds, thus revealing the full history of star and planet formation. Accordingly, the successful deployments of the Herschel and SOFIA observatories, and the emerging capabilities of ALMA, are both revolutionizing our understanding of THz astrophysics and placing stringent demands on the generation of accurate laboratory data on the relevant gas phase and solid state materials detected. With APRA support, we have constructed a combined high bandwidth and high spectral resolution femtosecond THz Time Domain Spectroscopy (THz TDS) system and an FT-IR spectrometer, and coupled these instruments to a high vacuum chamber and cryostat and to gas phase cells including a molecular beam system. We have investigated solid materials from room temperature to 10 K, and can examine both refractory matter such as silicates and molecular ices. For the latter, we have demonstrated that the THz bands observed are uniquely sensitive to both the molecular structure of the ice and its thermal history, and thus that THz observations can provide novel insight into the dominant condensable materials in dense, cold regions. In the gas phase we can record doppler-limited data over at least a decade in bandwidth. While quite capable, the high vacuum cryostat can only study thick samples, especially ices, due to the fairly rapid adsorption of gases onto surfaces at low temperature under such conditions. It is therefore not possible to examine highly layered/structured samples or reactive species. We therefore propose here to upgrade the chamber/cryostat to ultrahigh vacuum, and implement additional sample preparation and characterization tools. With such modifications, it will be possible to characterize highly complex materials from wavelengths of 1 to 1000 microns without gaps and to both determine their optical constants and elucidate the spectral signatures that can be used to search for specific materials or compounds. We will continue to compile and make available a database of optical constants, and will also implement and release radiative transfer models for dust grain size distributions that are commonly employed in molecular astrophysics and planetary science.

James Bock/California Institute of Technology
Multi-Color Anisotropy Measurements of the Cosmic Near-Infrared Extragalactic Background Light with CIBER2

We propose to carry out a program of observations with the Cosmic Infrared Background Experiment (CIBER-2), a sounding rocket instrument designed to measure anisotropy in the extragalactic background light in multiple optical to near-infrared spectral bands. Scientifically, CIBER-2 follows on the results of CIBER-1, which has detected near-infrared background anisotropy. CIBER-1 has also produced leading results on the absolute brightness of the background, the spectrum of diffuse galactic light, the

spectrum of Zodiacal light, and constraints on the Zodiacal light foreground from Fraunhofer line observations. CIBER-2 builds on the measurement techniques developed and successfully demonstrated by CIBER-1. With high-sensitivity, multi-color anisotropy measurements, CIBER-2 will elucidate the history of interhalo light production and carry out a deep search for extragalactic background fluctuations associated with the epoch of reionization.

A plausible interpretation of the infrared background anisotropy detected by CIBER-1, Spitzer and AKARI is interhalo light from stars tidally stripped from their parent galaxies during galaxy mergers. Based on the rms amplitude of the anisotropy, interhalo light produces approximately half of the background, representing a major branch of light production. Probing the history of interhalo light through improved anisotropy measurements using multiple bands and correlating with tracers of large-scale structure is essential to understand its role in the cosmic history of star formation.

The first generation of stars and their remnants are likely responsible for the reionization of the intergalactic medium, observed to be ionized out to distant quasars at a redshift of 6. The total luminosity produced by first stars is uncertain, but a lower limit can be placed assuming a minimal number of photons to produce and sustain reionization. This 'minimal' extragalactic background component associated with reionization is detectable in fluctuations at the design sensitivity of CIBER-2.

The CIBER-2 instrument is optimized for sensitivity to surface brightness in a short sounding rocket flight. The instrument consists of a 28 cm wide-field telescope operating in 6 spectral bands between 0.5 and 2.0 um, cooled to a temperature of 77 K with a liquid-nitrogen-cooled cryostat. Images are composed using 3 focal plane assemblies operating H2RG detector arrays. The instrument is currently being fabricated with international partners and nearing completion.

CIBER-2 will extend the CIBER-1 anisotropy meausurements from the near-infrared into the optical, where the EOR and IHL components of the extragalactic background can be cleanly distinguished and separated. We will study the history of IHL production by implementing a multi-band cross-correlation analysis, and use this information to carry out a deep search for an EOR component. We plan joint observations with weak lensing maps, with an optimized set of filter bands to measure spectral cross-correlations, to fully elucidate the history of IHL light production. In addition, our international partners will measure the absolute brightness of the background at optical to near-infrared wavelengths using 3 specialized linear-variable filter spectrometers.

Neil Cornish/Montana State University
Addressing key challenges in space gravitational wave astronomy

A space based gravitational wave detector will open up the source-rich low frequency portion of the spectrum that can not be accessed from the ground, making possible some

very exciting scientific studies. The rich data set collected by such an instrument will be unlike anything encountered by ground based (Laser interferometers or Pulsar timing) gravitational wave observatories, and it will take unique data analysis techniques to realize the full potential of the mission. At present, no techniques exist to exploit the discovery space opened by such a mission. Discovery potential is one of the main selling points for a mission in a new waveband. Our goal is to address this, and other key outstanding issues, by (i) Developing techniques for detecting un-modeled and un-expected signals (ii) Producing improved waveform models for spinning black hole binaries and use them to assess trade-offs in the mission design (iii) Develop robust techniques to identify possible departures from the predictions of Einstein's theory of gravity and (iv) explore the constraints that can be placed on astrophysical and modified gravity models by observing multiple systems.

Abe Falcone/Pennsylvania State University
Novel Hybrid CMOS X-ray Detector Developments for Future Large Area and High Resolution X-ray Astronomy Missions

In the coming years, X-ray astronomy will require new soft X-ray detectors that can be read very quickly with low noise and can achieve small pixel sizes over a moderately large focal plane area. These requirements will be present for a variety of X-ray missions that will attempt to address science that was highly ranked by the Decadal Review, including missions with science that over-laps with that of IXO and ATHENA, as well as other missions addressing science topics beyond those of IXO and ATHENA. An X-ray Surveyor mission was recently endorsed by the NASA long term planning document entitled "Enduring Quests, Daring Visions," and a detailed description of one possible realization of such a mission has been referred to as SMART-X, which was described in a recent NASA RFI response. This provides an example of a future mission concept with these requirements since it has high X-ray throughput and excellent spatial resolution. We propose to continue to modify current active pixel sensor designs, in particular the hybrid CMOS detectors that we have been working with for several years, and implement new in-pixel technologies that will allow us to achieve these ambitious and realistic requirements on a timeline that will make them available to upcoming X-ray missions. This proposal is a continuation of our program that has been working on these developments for the past several years.

Donald Figer/Rochester Institute of Technology
A Photon Counting Imaging Detector for NASA Exoplanet Missions

The key objective of the proposed project is to advance the maturity of a 256x256 pixel single-photon optical imaging detector. The detector has zero read noise and is resilient against the harsh effects of radiation in space. We expect that the device will have state-of-the-art performance in other parameters, e.g., high quantum efficiency from UV to 1 #m, low dark current, etc.

Kevin France/University of Colorado

Development and Flight-testing of Astronomical Instrumentation for Future NASA Astrophysics Missions

We propose a four year suborbital research program to continue the University of Colorado's efforts in the development and flight testing of instrument designs and critical path technologies for ultraviolet spectroscopy in support of future NASA Explorer, Probe-, and Flagship-class missions. This proposal builds on our existing program of high-resolution spectroscopy for the 100 - 160 nm bandpass with the development of a new high-efficiency imaging spectrograph operating in the same band. The ultimate goal of the University of Colorado ultraviolet rocket program is to develop the technical capabilities to enable a future, highly multiplexed ultraviolet spectrograph (with both high-resolution and imaging spectroscopy modes), e.g., an analog to the successful HST-STIS instrument, with an order-of-magnitude higher efficiency. We do this in the framework of a university led program where undergraduate, graduate, and postdoctoral training is paramount and cutting edge science investigations support our baseline technology development program.

In the proposed effort, we will optimize our high-resolution (R > 100,000) echelle spectrograph payload (CHESS) with the first science flight of a new, large-format CCD array provided by our collaborators at JPL and Arizona State University. We will launch CHESS to study our local interstellar environment with spectral resolving power and bandpass that cannot be achieved with any suite of current or planned space missions. In parallel with the proposed science flights of CHESS, we will design, calibrate, and launch a new high-throughput imaging spectrograph (SISTINE); the first sub-arcsecond imaging, medium spectral resolution (R = 10,000), spectrograph ever flown with spectral coverage over the entire 100 - 160 nm bandpass.

SISTINE incorporates several novel optical technologies that were highlighted as major hardware drivers for NASA's next large ultraviolet/optical/near-IR observatory by the 2014 Cosmic Origins Technology Report, including advanced mirror coatings with high broadband reflectivity (including > 20% efficiency gains below 115 nm), the first demonstration and flight test of these coatings on a shaped 0.5-meter telescope, and large-format, high-QE photon counting detectors. SISTINE will be launched to study the energetic radiation environment in the habitable zones around nearby low-mass exoplanet host stars, systems that are the top priority in NASA's search for the signatures of biological activity in the coming decade. SISTINE addresses the highest science priority in the 2010 Astronomy and Astrophysics Decadal Survey and is a crucial step towards meeting NASA's technology needs for future space observatories.

Perry Gerakines/NASA / Goddard Space Flight Center
Absolute Infrared Intensities and Interstellar Ice Abundances - From Neutrals to Ions

Infrared (IR) telescopes, such as Spitzer and SOFIA, have revealed a rich variety of chemical species trapped in interstellar ices. However, quantifying the abundances of these species has been difficult because some molecules, such as formaldehyde (H2CO), and some ions, such as ammonium (NH4+), have poorly-known IR optical parameters, such as band strengths and optical constants. In the case of NH4+, the most widely used band-intensity values are from a mere two measurements published over a decade ago. Those two experiments cannot be repeated or checked as the original publication provided no information on reaction temperature, heating rate, spectral resolution, and so forth, and the two authors are no longer active in the field. Moreover, neither kinetic data nor statistics on the two measurements were provided, clearly an unsatisfactory situation. Exacerbating the problem is that NH4+ is sometimes used as a check on the IR spectral intensities of other ions, such as OCN- (cyanate), which has its own checkered past.

We propose to correct these problems associated with abundance determinations of selected interstellar ices. We will combine two recent successful efforts from our laboratory and measure band intensities for NH4+ and OCN-, as well as HCOO- (formate). To unravel the interstellar formate band requires that we also properly determine its spectral baseline to distinguish from co-absorbing species, primarily formaldehyde (H2CO). Since the latter also has, at best, poorly-determined IR absolute intensities, we will measure them at multiple temperatures and ice phases for this project. This work will build on our recent success in deriving optical constants from IR spectra for interstellar hydrocarbon and nitrile ices (Hudson et al., 2014a, 2014b), and in generating NH4+ in situ for a study of Jupiter's atmosphere (Loeffler and Hudson, 2015). As a bonus, the proposed measurements also will enable the determination of band-strengths for such ions as CN-, NO3-, HS-, and ClO4-. High-quality IR intensities of neutral covalently-bonded ice molecules have been measured and published by our team. We now propose to make the transition to ions.

Joe Hill-Kittle/NASA / Goddard Space Flight Center
Next Generation X-ray Polarimeter

The emission regions of many types of X-ray sources are small and cannot be spatially resolved without interferometry techniques that haven't yet been developed. In order to understand the emission mechanisms and emission geometry, alternate measurement techniques are required. Most microphysical processes that affect X-rays, including scattering and magnetic emission processes are imprinted as polarization signatures. X-ray polarization also reveals exotic physical processes occurring in regions of very strong gravitational and magnetic fields. Observations of X-ray polarization will provide a measurement of the geometrical distribution of gas and magnetic fields without

foreground depolarization that affects longer wavelengths (e.g. Faraday rotation in the radio).

Emission from accretion disks has an inclination-dependent polarization. The polarization signature is modified by extreme gravitational forces, which bend light, essentially changing the contribution of each part of the disk to the integrated total intensity seen by distant observers. Because gravity has the largest effect on the innermost parts of the disk (which are the hottest, and thus contributes to more high energy photons), the energy dependent polarization is diagnostic of disk inclination, black hole mass and spin. Increasing the sensitive energy band will make these measurements possible. X-ray polarimetry will also enable the study of the origin of cosmic rays in the universe, the nature of black holes, the role of black holes in the evolution of galaxies, and the interaction of matter with the highest physically possible magnetic fields. These objectives address NASA's strategic interest in the origin, structure, and evolution of the universe.

We propose a two-year effort to develop the Next Generation X-ray Polarimeter (NGXP) that will have more than ten times the sensitivity of the current state of the art. NGXP will make possible game changing measurements of classes of astrophysical sources that were previously unobtainable within realistic observation times e.g. Active Galactic Nuclei (AGN).

Standard photoelectric X-ray polarimeter designs are both quantum efficiency (QE) limited and challenging to calibrate due to diffusion of electron signal as it drifts through the gas. Drifting negative ions decreases diffusion to the thermal limit thereby decoupling sensitivity from drift distance and enabling larger detector areas that can be at the focus of larger diameter mirrors and single reflection concentrator optics. NITPCs also allow the selection of constituent gasses and pressures to be based on the optimization of modulation and QE rather than diffusion properties. This versatility enables a large improvement in sensitivity without driving cost and with only moderate increase to mass and power of the detector and/or instrument. Furthermore, the energy band of NGXP will be tunable to maximize the science return. Following the efforts of this proposal NGXP will be proposed as sounding rocket experiment and as a candidate instrument for future opportunities.

The GSFC polarimeter group has demonstrated NITPCs for several detector concepts. This proposal leverages the previous effort and team expertise with goals to establish the NITPC as the baseline for narrow field observations of faint persistent sources and to improve the technology readiness of associated technologies such as stainless steel gas electron multipliers and finer readout pitch.

William Jones/Princeton University
SuperBIT: Wide-field, Sub-arcsecond Imaging from the Super-Pressure Balloon Platform

The scientific potential of diffraction-limited imaging from mid-latitude ultra-long duration balloon payloads is immense. The combination of diffraction-limited angular resolution, extreme stability, space-like backgrounds, and long integrations enables transformative opportunities in studies ranging from the weak lensing of galaxy clusters and cosmic shear, to the search for exoplanets. Pioneering research, spear-headed by the co-investigators of this proposal, has led to the development of the precision tip/tilt and de-rotation systems that are required to realize the potential of the super-pressure balloon (SPB) platform for deep, wide-field imaging.

Under a separately funded Canadian Space Agency program, a half-meter class telescope has been integrated with a prototype sub-arcsecond pointing system. We propose a highly focused five-year program to develop and fly a comparable instrument on the mid-latitude SPB platform, demonstrating the imaging capability during an ultra-long duration balloon flight while providing space-quality weak lensing measurements for a large catalog of galaxy clusters. This instrument will provide imaging with a half-degree field of view and 0.3-arcsecond resolution in five bands between 300 and 1000 nm, with sensitivities in the shape-band exceeding 24th magnitude (> 5 sigma) in 300 seconds of integration.

We propose an observing schedule that is split between a performance verification sample, a photometric and spectroscopic calibration set, a deep field, and a science catalog. The performance verification set prioritizes a sample of thirty clusters that have been previously well studied with the HST Advanced Camera for Surveys, the Chandra X-ray observatory, and for which there are Compton-Y parameter data from millimeter wavelengths. The photometric calibration set will be selected from the COSMOS field. The science catalog will draw from a set of more than 150 Sunyaev-Zel'dovich, X-ray, and optically-selected clusters spanning a wide range of cluster masses and morphologies. Aside from demonstrating the technical approach, these data will enable a systematic program to constrain the mass-observable relations over an unprecedented scale.

This proposal leverages the experience and capabilities of the JPL, Toronto, Princeton, and Durham groups. A successful demonstration of the technical approach and the scientific potential will motivate future development of facility-class instruments on the SPB platform.

Philip Kaaret/University of Iowa
HaloSat - A CubeSat to Study the Hot Galactic Halo

We propose to develop, build, and fly HaloSat, a CubeSat capable of measuring the oxygen line emission from the hot Galactic halo. A dedicated CubeSat enables an instrument design and observing strategy to maximize the halo signal while minimizing foregrounds from solar wind charge exchange interactions within the solar system. We will use HaloSat to map the distribution of hot gas in the Milky Way and determine whether it fills an extended, and thus massive halo, or whether the halo is compact, and thus does not contribute significantly to the total mass of the Milky Way.

HaloSat can be accomplished at modest cost using a CubeSat, a novel platform for space astrophysics missions. We will use a commercially available CubeSat bus and commercially available X-ray detectors to reduce development risk and minimize overall mission cost. HaloSat builds on the initiatives of GSFC/Wallops Flight Facility (WFF) in the development of CubeSats for low cost access to space and relies on the technical expertise of WFF personnel for spacecraft and mission design and operations. The team, from University of Iowa (UI), GSFC, Johns Hopkins, and CNRS (France), contains experts in X-ray detector development and data analysis and the astrophysics of hot plasmas and Galactic structure. The UI team will include a number of junior researchers (undergraduates, graduate students, and a postdoc) and help train them for future leadership roles on NASA space flight missions.

Henric Krawczynski/Washington University in St. Louis
Continued Development of Small-Pixel CZT and CdTe Detectors for Future High-Angular-Resolution Hard X-ray Missions

The Nuclear Spectroscopic Telescope Array (NuSTAR) Small Explorer Mission was launched in June 2012 and has demonstrated the technical feasibility and high scientific impact of hard X-ray astronomy. We propose to continue our current R&D program to develop finely pixelated semiconductor detectors and the associated readout electronics for the focal plane of a NuSTAR follow-up mission. The detector-ASIC (Application Specific Integrated Circuit) package will be ideally matched to the new generation of low-cost, low-mass X-ray mirrors which achieve an order of magnitude better angular resolution than the NuSTAR mirrors. As part of this program, the Washington University group will optimize the contacts of 2x2 cm^2 footprint Cadmium Zinc Telluride (CZT) and Cadmium Telluride (CdTe) detectors contacted with 100x116 hexagonal pixels at a next-neighbor pitch of 200 microns. The Brookhaven National Laboratory group will design, fabricate, and test the next generation of the HEXID ASIC matched to the new X-ray mirrors and the detectors, providing a low-power 100x116 channel ASIC with extremely low readout noise (i.e. with a root mean square noise of 13 electrons). The detectors will be tested with radioactive sources and in the focal plane of high-angular-resolution X-ray mirrors at the X-ray beam facilities at the Goddard and Marshall Space Flight Centers.

James Lawler/University of Wisconsin
Lab Astro for Studies of Fe-Group Nucleosynthesis

Laboratory measurements of spectroscopic data on Fe-group atoms and ions for elemental abundance studies of metal-poor (old) galactic halo stars are proposed. Improved and expanded spectroscopic data, especially atomic transition probabilities, are critical to understanding the synthesis of Fe-group elements in early core collapse SuperNovae (SNe) or hypernovae. There is substantial evidence that the relative abundances of Fe-group elements were different in the early Galaxy than in the present epoch, and that the increasing importance of Type Ia SNe cannot explain these differences. Limitations of traditional stellar photospheric models based on Local Thermodynamic Equilibrium (LTE) and 1-Dimensional (1-D) approximations are a challenge in mapping the Fe-group abundance patterns as a function of metallicity. These challenges are being addressed in a systematic fashion using a very sensitive high-resolution UV spectrometer at the U. of WI and data from the Hubble Space Telescope (HST) on metal-poor stars. Certain very weak UV lines that connect to the dominant population reservoir levels Fe-group IONS are immune to non-LTE/3D effects. Accurate lab measurements on such lines and many other lines in combination with UV data from the HST will yield maps of non-LTE effects/3D effects in various stellar photospheres and reliable Fe-group abundance patterns as a function of metallicity. Large sets of accurate lab measurements on Mn I, Mn II, Ti I, Ti II, Ni I, V I and V II have been completed, applied in abundance determination on metal-poor stars, and published. New measurements on Cr II, Co II, and Fe II, are proposed along with applications on metal-poor stars.

Stuart Loch/Auburn University
A resolution to the low temperature electron recombination problem for astrophysical plasmas.

Recent and ongoing work on electron recombination of atomic systems has revealed a range of ions where rates are underestimated or overestimated, sometimes by an order of magnitude, due to the positioning of resonance(s) near to the ground state threshold. Consequently, these ion stages may have a significant effect on diagnostics of abundances, temperatures, and densities.

We propose to (1) implement a new type of survey calculation to identify which ions exhibit sensitivity to near threshold resonances; (2) quantify the resulting uncertainties in the DR rates for these ion stages; (3) show that the recently proposed process of "below threshold DR" can provide accurate rate coefficients for ions with critical sensitivity to near threshold resonances, and (4) archive and release these rates for use in astrophysical spectral studies.

To achieve these results we will use a range of methods to calculate electron recombination, including both semi- and fully-relativistic approaches. The new theory for the inclusion of below threshold recombination was recently derived in the literature and will be used in this proposal.

The work would be of significance for a range of NASA objectives and missions. These would include the analysis of low temperature photo-ionized plasmas. It would determine the atomic systems for which the low temperature recombination rate coefficients can be used with confidence, and provides a means to remove the sensitivity of the remaining rate coefficients to their near threshold resonances. As such it would lead to an improved understanding of these plasmas and their role in the cosmos.

Christopher Martin/California Institute of Technology
FIREBALL-2: Pioneering Space UV Baryon Mapping (Lead Institution)
CoI: David Schiminovich/Columbia University

This is the lead proposal of a multi-institutional submission.
The Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall-2) is designed to discover and map faint emission from the Intergalactic Medium (IGM) for low redshift galaxies. This balloon is a modification of FIREBall-1 (FB-1), a path-finding mission built by our team with two successful flights. FB-1 provided the strongest constrains on IGM emission available from any instrument at the time.

FIREBall-2 has been significantly upgraded compared to FB-1, and is nearly ready for integration and testing before an anticipated Spring 2016 launch from Ft. Sumner, New Mexico. The spectrograph has been redesigned and an upgraded detector system including a groundbreaking high QE, low-noise, UV CCD detector is under final testing and will improve instrument performance by more than an order of magnitude. CNES is providing the spectrograph, gondola, and flight support team, with construction of all components nearly complete. The initial FIREBall-2 launch is now scheduled for Spring 2016.

FIREBall-2 combines several innovations:
-First ever multi-object UV spectrograph
-Arcsecond quality balloon pointing system, developed from scratch, improved from FB-1
-Partnership of national space agencies (NASA & CNES); highly leveraged NASA resources
-A Schmidt corrector built into the UV grating for better optical performance and throughput
-A total of four women trained in space experimental astrophysics, including 3 Columbia Ph.Ds. and 1 Caltech Ph.D.
-A total of 7 graduate students trained on FIREBall-1 (3) and FIREBall-2 (4), with opportunities for more in future flights.

FIREBall-2 will test key technologies and science strategies for a future mission to map IGM emission. Its flights will provide important training for the next generation of space astrophysicists working in UV instrumentation. Most importantly, FIREBall-2 will detect emission from the CGM of nearby galaxies, providing the first census of the density and kinematics of this material for low z galaxies and opening a new field of CGM science.

Benjamin Mazin/University of California

Fundamental Performance Improvement of Microwave Kinetic Inductance Detectors for UVOIR Astrophysics

Ultraviolet, Optical, and near-Infrared Microwave Kinetic Inductance Detectors (UVOIR MKIDs) are one of the most powerful new technologies to emerge out of the NASA APRA detectors program in the last decade. This proposal seeks to build on previous APRA grants to drastically improve the performance of UVOIR MKIDs.

Like an X-ray microcalorimeter ultraviolet, optical, and near-IR (UVOIR) MKIDs are cryogenic detectors capable of detecting single photons and measuring their energy without filters or gratings. Our team has created this technology from the ground up, and fielded a 2024-pixel UVOIR MKID array on five separate observing runs at 5-m class telescopes. With 34 observing nights successfully completed and two astronomy papers published using MKID data (the first astronomy papers published using MKID data at any wavelength), UVOIR MKIDs are at TRL 5-6 for ground-based astronomy, and TRL 3 for space-based astronomy.

The outstanding potential of these detectors was recognized in the recent NASA long term vision, “Enduring Quests, Daring Visions", which recognized on page 88 that MKIDs have tremendous potential for future NASA UVOIR space missions, especially for finding Earth twins around nearby stars: “…microwave kinetic inductance detectors (MKIDs) would be a game-changing capability…".

Current UVOIR MKIDs feature array sizes in the 10-30 kpix range, energy resolution R=16 at 254 nm, ~70% pixel yield, and quantum efficiency that goes from 70% in the UV to 25% in the near-IR. These arrays, fabricated out of Titanium Nitride (TiN) on a high resistivity silicon substrate, are fully functional for ground-based science.

However, our current MKIDs are far away from their theoretical limits, especially in yield (70% vs. 100%) and energy resolution (R=10 vs. R=100 at 400 nm). The yield is of especially urgent concern as missing pixels make accurate photometry difficult, especially for rapidly time variable sources like compact binaries that we have been studying. The yield is low because the reactively sputtered TiN that we make our MKIDs from is extremely sensitive to deposition conditions, and the resistivity and hence resonant frequency of the MKIDs varies dramatically across a wafer, as shown in. Our

energy resolution is low because of a combination of factors related to the MKID material and the two level system (TLS) noise from our capacitors.

In order to improve our current energy resolution, yield, and quantum efficiency we need to move in new directions. This proposal will focus on two main improvements: making better MKID resonator materials, and making lower noise capacitors.

Dan McCammon/University of Wisconsin
Cosmic X-ray Physics: Sounding rocket investigations of the diffuse X-ray background, including instrument development

We propose an investigation to improve our understanding of the Galactic diffuse X-ray background. The ultimate purpose of this is to determine the role of hot phases of the interstellar medium in mediating stellar feedback in star formation, in transport of metals, and in determining the structure and evolution of the Galaxy. It directly addresses SMD's astrophysics goal No. 2, to explore the origin and evolution of the galaxies, stars and planets that make up our universe.

This work will involve a flight of an existing payload with small modifications in Woomera, South Australia, to observe the Galactic soft X-ray bulge and attempt to determine its nature and emission mechanisms. This flight should also either confirm or put strict upper limits on the "sterile neutrino" model for the 3.5 keV signal observed near the Galactic Center by XMM-Newton. Our investigation includes the development of thermal detectors with superconducting transition edge thermometers capable of 1-2 eV FWHM energy resolution in the 100-400 eV range with the intent of obtaining a scientifically useful spectrum on a sounding rocket flight of the emission from one million degree gas in this energy range. This will require a total area of 1-2 square centimeters for the detector array. To enable routine testing of such detectors in the lab and for necessary in-flight gain and resolution monitoring, we are trying to develop a pulsed-UV laser calibration source. In collaboration with Goddard Space Flight Center, we are investigating the practicality of waveguide-below-cutoff filters to provide the necessary attenuation of infrared radiation for these detectors while still allowing good x-ray transmission below 150 eV.

The detectors, calibration source, filters, optimal high-rate pulse analysis and flight experience with the detector readouts are all relevant to future NASA major missions. The detectors we're working on for a low-energy sounding rocket flight would be an excellent match to what is needed for a probe-class mission to map the hot intergalactic medium. If the laser calibration source works well, it would offer huge advantages for a mission like Athena. The metal mesh filters would be particularly valuable in allowing thermal detectors (microcalorimeters) similar to those used here in the X-ray range to be applied to the EUV and vacuum ultraviolet where they offer large potential gains over existing detectors. The ability to analyze overlapping events with minimal loss of resolution could avoid much of the rate/resolution tradeoff of current microcalorimeter

data processing schemes. These investigations will provide the primary training for our graduate students, and will involve a substantial number of undergraduates.

Mark McConnell/University of New Hampshire
Optimization of the GRAPE Polarimeter Design

The Gamma Ray Polarimeter Experiment (GRAPE) is designed to investigate one of the most exotic phenomena in the universe - gamma-ray bursts (GRB). There has been intense observational and theoretical research in recent years, but research in this area has been largely focused on studies of time histories, spectra, and spatial distributions. Theoretical models show that a more complete understanding of the inner structure of GRBs, including the geometry and physical processes close to the central engine, requires the exploitation of gamma-ray polarimetry. Over the past several years, we have developed the GRAPE instrument to measure the polarization of gamma-rays from GRBs over the energy range of 50 to 500 keV. The GRAPE design is a modular one in which several independent modules are required to achieve sufficient sensitivity. A single module fits on the front end of a 2-inch square flat-panel multi-anode photomultiplier tube (MAPMT). The first operational balloon flight took in place in September of 2011 from Ft. Sumner, NM. The purpose of the 2011 flight was to validate the science capability of GRAPE by measuring the Crab polarization with a collimated array of 16 modules. The limited success of that flight led to a second validation flight (also from Ft. Sumner) in the fall of 2014, with significantly improved shielding and a larger array of modules. That flight proved too short to make a full observation of the Crab. Although we did not succeed in measuring the polarization of the Crab with a high degree of confidence, we feel that we are nonetheless prepared to move forward with our program. Our next goal is to fly GRAPE on a long duration balloon (LDB) platform to collect data on a significant sample of GRBs. Our experience with the first two balloon flights, coupled with further design efforts focused on orbital payloads, has led to an improved polarimeter concept that represents a natural evolution of the current design. It is this new concept that we are now proposing to develop and test before embarking on a long-duration balloon program. This new design, with improved sensitivity, will ensure that the science objectives can be achieved within the context of a viable balloon program.

Julie McEnery/NASA / Goddard Space Flight Center
Steps towards a Medium-Energy Gamma-ray Mission

We propose to develop, fabricate, and test a small-scale medium-energy (0.2 - ~500 MeV) gamma-ray telescope, optimized for photon detection in both the Compton-scattering and pair-production regimes. The instrument will consist of a double-sided Si-strip tracking detector with energy deposition readout, a composite CdZnTe-strip (CZT) and CsI(Tl)-log calorimeter with high spatial and good energy resolution, and a highly efficient anti-coincidence detector (ACD). This instrument will be a prototype for a

potential future MIDEX-scale mission (ComPair) designed to provide a more than order of magnitude increase in sensitivity to the MeV gamma-ray Universe compared to past missions. ComPair will provide a significant improvement in both angular and energy resolution over previous instruments operating in the 0.2$-$100 MeV range, offering a truly new window on this poorly explored energy range.

In this proposal, the team proposes to develop and test the key detection elements for ComPair, integrate these elements in a prototype telescope, perform a series of beam tests to demonstrate the performance, and perform a balloon test flight to study the background rejection capability of the prototype instrument. As a result, we will establish the proof of concept for a Si-CZT Compton-Pair space telescope and elevate the TRL for the ComPair technology to 6-7.

Jeff McMahon/University of Michigan
Broad-bandwidth Metamaterial Antireflection Coatings for Sub-Millimeter Astronomy and CMB Foreground Removal

Sub-millimeter observations are crucial for answering questions about star and galaxy formation; understanding galactic dust foregrounds; and for removing these foregrounds to detect the faint signature of inflationary gravitational waves in the polarization of the Cosmic Microwave Background (CMB). Achieving these goals requires improved, broad-band antireflection coated lenses and half-wave plates (HWPs). These optical elements will significantly boost the sensitivity and capability of future sub-millimeter and CMB missions.

We propose to develop wide-bandwidth metamaterial antireflection coatings for silicon lenses and sapphire HWPs with 3:1 ratio bandwidth that are scalable across the sub-millimeter band from 300 GHz to 3 THz. This is an extension of our successful work on saw cut metamaterial AR coatings for silicon optics at millimeter wave lengths. These, and the proposed coatings consist of arrays of sub-wavelength scale features cut into optical surfaces that behave like simple dielectrics. We have demonstrated saw cut 3:1 bandwidth coatings on silicon lenses, but these coatings are limited to the millimeter wave band by the limitations of dicing saw machining. The crucial advance needed to extend these broad band coatings throughout the sub-millimeter band is the development of laser cut graded index metamaterial coatings. The proposed work includes developing the capability to fabricate these coatings, optimizing the design of these metamaterials, fabricating and testing prototype lenses and HWPs, and working with the PIPER collaboration to achieve a sub-orbital demonstration of this technology. The proposed work will develop potentially revolutionary new high performance coatings for the sub-millimeter bands, and cary this technology to TRL 7 paving the way for its use in space. We anticipate that there will be a wide range of applications for these coatings on future NASA balloons and satellites.

Samuel Moseley/NASA / Goddard Space Flight Center
Âµ-Spec: An Integrated Spectrometer for Terahertz Space Spectroscopy

Under APRA funding, we have developed a fully integrated R~64 submillimeter spectrometer. Using only single crystal Si and superconductors, our fabrication process is designed with the goal of minimizing loss in the spectrometer. High performance designs have been developed for all the required elements of the spectrometer. For example the slot antenna, power divider microstip delay lines, absorbers, and M icrowave Kinetic Inductance detectors (MKIDs) have been designed and buit, and the performance of a system operating at R~ 64 has been demonstrated. We l propose to develop and test a spectrometer with R~300. This device can be produced to sufficient accuracy with known fabrication tolerances. After the successful demonstration of the R~300 instrument, the devices will be ready for application in balloon or airborne applications.We will measure loss in the transmission lines to establish the limits of resolving power in such a materials system and will develop a phase adjuster to allow a diffraction limited delay network at the full resolution allowed by loss in the materials. We will demonstrate the performance of this system with R~1000 by the end of the proposed program. Arrays of such integrated spectrometers are ideal building blocks for a high redshift survey instrument, and its compact size may allow significant science to be done on Explorer Class Missions.

Frederick Porter/NASA / Goddard Space Flight Center
High Energy Laboratory Astrophysics using an X-Ray Microcalorimeter with an Electron Beam Ion Trap

Since the summer of 2000 we have successfully deployed a high-resolution x-ray microcalorimeter spectrometer, based on the spaceflight XRS instrument, at the Electron Beam Ion Trap (EBIT) facility at the Lawrence Livermore National Laboratory. Over the last 15 years, this highly successful partnership has made fundamental measurements in laboratory astrophysics including the measurements of the absolute cross sections of all the Fe L shell transitions from Fe XVII to Fe XXIV, line ratios in Fe and Ni L shell transitions, measurements of Fe K shell emission over a wide range of electron energies, and direct measurements of charge exchange emission from highly ionized Fe, O, N, and most recently L shell S, using a variety of donor gases. This work has resulted in the publication of over 40 peer-reviewed articles with many more either submitted or in preparation. The newest addition to the facility, the ECS microcalorimeter spectrometer, developed under this program, has performed flawlessly as a facility-class instrument since 2007.

We propose here to continue our highly successful partnership and deploy new technology to resolve lines in the important 1/4 keV band that encompasses the M-shell iron emission and the L shell emission, including charge exchange, of many of the lower-Z elements, such as Si, S, Mg, Ne, Ca, and Ar.

This work is highly relevant to NASA objectives as it allows for the unambiguous connection between spectroscopic observations with Chandra, XMM, Astro-H, and future spectrometers aboard missions like Athena, and the physics occurring in the cosmological source. Our program aids these measurements by benchmarking the spectroscopic synthesis models used to interpret all x-ray observations. Without laboratory measurements to support these models, it is not a priori certain that the models are correct, and the observational data correctly interpreted. This is especially true for charge exchange measurements, where there are substantially differences between theory and measurement in K shell emission, and no useful theory at all in L shell emission.

Stephen Rinehart/NASA / Goddard Space Flight Center
BETTII: The Balloon Experimental Twin Telescope for Infrared Interferometry (Phase 2) - High Angular Resolution Astronomy at Far-Infrared Wavelengths

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) is an eight-meter baseline far-infrared interferometer to fly on a high altitude balloon. The combination of the long baseline with a double-Fourier instrument allows BETTII to simultaneously gain both spatial and spectral information; BETTII is designed for spatially-resolved spectroscopy. The unique data obtained with BETTII will be valuable for understanding how stars form within dense clusters, by isolating individual objects that are unresolved by previous space telescopes and my measuring their spectral energy distributions. BETTII will be also used in future flights to understand the processes in the cores of Active Galactic Nuclei. In addition to these scientific goals, BETTII serves as a major step towards achieving the vision of space-based interferometry.

Suzanne Romaine/Smithsonian Astrophysical Observatory
Merging Technologies to develop light weight, high throughput X-ray optics

X-ray astronomy is highly dependent upon focusing optics as illustrated by the profound influence that results from the Chandra, XMM-Newton, Suzaku and NuSTAR observatories are having upon astrophysics. Several future X-ray missions will require much larger area, and/or better angular resolution telescopes. However, they will face strict limits upon their mass and cost. Any innovation that can reduce the mass, lower the cost or improve the resolution of a telescope would be important as it would allow future missions to occur sooner and be more effective. Success in fabricating and testing new lighter weight, stronger material substrates will allow high throughput X-ray integral mirror shell telescopes like XMM-Newton to be substantially lighter weight, with improved angular resolution.

The main objective of our program is to construct a lower mass telescope with better resolution than the replicated nickel telescopes currently being constructed. Our innovative approach merges the current electroforming technology with lower density

materials which have higher stiffness, higher hardness and one-third the density of nickel. This will lead to lower mass, lower cost moderate-resolution-missions with higher effective area. Our goal is to demonstrate superior angular resolution for mirror shells that are lighter-weight than those currently fabricated by other integral shell replication methods. This technology will reinvigorate SMEX and MIDEX class options for X-ray astronomy, aiding the success of the Explorer program.

Farid Salama/NASA / Ames Research Center
Laboratory Studies of Astrophysically Significant Carbon Molecules And Ions in Support of Space Missions

We intend to investigate the spectral properties and energetic characteristics of carbon-bearing molecules and nanosized molecules of interest to the Astrophysics Research and Analysis Program. Using Ames unique laboratory facility, the Cosmic Simulation Chamber (COSmIC), which combines a supersonic jet expansion with cavity ringdown spectroscopy and Reflectron time-of-flight mass spectrometry, we will measure for the first time laboratory spectra of large carbon molecules, radicals and positive and negative ions that can be directly compared to space data for the unambiguous detection of specific species in space. We will also monitor the formation of carbon clusters and nanomolecules from molecular precursors and measure their spectral signatures. These laboratory data are crucial to the support of planned missions (JWST) and to on-going, recently-serviced missions (SOFIA, COS/HST, Herschel). The goal is also to address some of the most fundamental unresolved issues in astrophysics: the molecular inventory of the interstellar medium and its relationship to molecular complexity and ultimately to the origin of life, the formation of interstellar dust from gas-phase atoms and molecules. These goals are the focus of current as well as future (post-HST era) missions considered by NASA.

Mark Schattenburg/Massachusetts Institute of Technology
High Precision Assembly of Thin Mirror X-ray Telescopes

Lightweight high resolution x-ray telescope optics are one of the key technologies under development for next-generation x-ray telescopes. The ultimate goal of this effort is to realize optics with spatial resolution rivaling Chandra (<1 arc-sec) but with collecting areas that are larger by orders of magnitude. In the USA several institutions, including GSFC, MSFC, Harvard-SAO, MIT and Northwest University are working on a variety of approaches to this problem. An excellent example is the NuSTAR x-ray telescope, which teamed Cal Tech, GSFC, Columbia University and LLNL to produce a superb set of hard x-ray optics. The telescope was composed of thousands of 0.2 mm-thick glass mirrors which were epoxied into place around a spindle structure. While very light weight, this process resulted in ~1 arc min resolution. We want to achieve ~100 times better with similar mass. A group at NASA GSFC has recently demonstrated an alternative thin-glass assembly procedure that has achieved ~7 arc sec resolution with x-ray tests.

Further progress towards 1 arc-sec will require mirrors with improved figure, lower stress coatings, improved alignment, better metrology, and low stress bonding. Many of the difficulties with current mirror assembly practice stem from the use of epoxy as a bonding agent. Epoxy has many disadvantages, including high shrinkage, large CTE and creep, resin aging effects, water absorption, outgassing, low tensile strength, exothermicity, and requiring large amounts of time and/or heat to cure. These effects can cause errors that become â€œfrozen inâ€ to the bond with no possibility of correction. We propose to investigate replacing epoxy with low temperature, low shrinkage solder alloys. We use these solders in conjunction with high power, millisec-long pulses from a fiber IR laser to deliver controlled amounts of heat into the bond area. We have demonstrated that laser pulses can be used to actuate carefully designed bonds by permanently compressing or expanding a very thin and brief surface melt in the solder by amounts controlled in the nanoscale range, allowing post assembly correction of the mirror mount points. We believe this technology will be one of the keys to realize a sub-1 arc-sec thin-glass x-ray telescope.

Chris Shelton/Jet Propulsion Laboratory

A High-Performance Deformable Mirror with Integrated Driver ASIC for Space Based Active Optics

Direct imaging of exoplanets is key to fully understanding these systems through spectroscopy and astrometry. The primary impediment to direct imaging of exoplanets is the extremely high brightness ratio between the planet and its parent star. Direct imaging requires a technique for contrast suppression, which include coronagraphs, and nulling interferometers. Deformable mirrors (DMs) are essential to both of these techniques.

With space missions in mind, Microscale is developing a novel DM with direct integration of DM and its electronic control functions in a single small envelope. The Application Specific Integrated Circuit (ASIC) is key to the shrinking of the electronic control functions to a size compatible with direct integration with the DM.
Through a NASA SBIR project, Microscale, with JPL oversight, has successfully demonstrated a unique deformable mirror (DM) driver ASIC prototype based on an ultra-low power switch architecture. Microscale calls this the Switch-Mode ASIC, or SM-ASIC, and has characterized it for a key set of performance parameters, and has tested its operation with a variety of actuator loads, such as piezo stack and unimorph, and over a wide temperature range. These tests show the SM-ASIC's capability of supporting active optics in correcting aberrations of a telescope in space.

Microscale has also developed DMs to go with the SM-ASIC driver. The latest DM version produced uses small piezo stack elements in an 8x8 array, bonded to a novel silicon facesheet structure fabricated monolithically into a polished mirror on one side and mechanical linkage posts that connect to the piezoelectric stack actuators on the other.

In this Supporting Technology proposal we propose to further develop the ASIC-DM and have assembled a very capable team to do so. It will be led by JPL, which has considerable expertise with DMs used in Adaptive Optics systems, with high-contrast imaging systems for exoplanet missions, and with designing DM driver electronics. On its part Microscale will continue its design and fabrication of the ASIC-DM combination. Both the SM-ASIC and the DM are currently at a Technology Readiness Level (TRL) of 3; the major goal of the proposed effort is to raise the TRL of the combined system to 4 by scaling up the array formats and by testing, characterizing, and operating multiple generations of the integrated DM-ASIC systems in a laboratory environment.

We propose a three year effort, with these tasks:

Year 1:

Optimize the influence function of an 8x8 DM for active / adaptive optics, by modeling and fabricating different geometric parameters of the facesheet, with its mechanical linkage posts.

Fabricate an SM-ASIC and an 8x8 piezo stack DM, and evaluate their performance.

Characterize and optimize the integration processes to achieve a driver/DM combination that can support high contrast imaging of exoplanets.

Test the control resolution of the ASIC in driving actuators using a commercial interferometer, to ensure the ASIC can command the piezo stack actuator to nanometer levels. The goal, by year three, is control to a small number of picometers; 10-20 pm (surface) may be a practical goal, while 5 pm is the ultimate goal.

Year 2:

Fabricate 16x16 piezo stack DMs and matching driver ASICS, and repeat Year 1 tasks with the larger format devices.

Year 3:

Fabricate 32x32 DMs and SM-ASICs, and repeat Year 1 tasks with the larger format devices.

Fabricate versions of the 32x32 devices that can be formed into a 2x2 array, to make a composite 64x64 DM/driver.

Fabricate such a composite 64x64 DM/ASIC and evaluate its performance.

Gordon Stacey/Cornell University

Development of Silicon-substrate Based Fabry-Perot Etalons for far-IR Astrophysics

We propose to design, construct and test silicon-substrate-based (SSB) mirrors necessary for high performance Fabry-Perot interferometers (FPIs) to be used in the 25-40 um mid-IR band. These mirrors will be fabricated from silicon wafers that are anti-reflection coated (ARC) by micromachining an artificial dielectric meta-material on one side, and depositing optimized gold-metalized patterns on the other. Two mirrors with the

metalized surfaces facing one-another form the Fabry-Perot cavity, also known as the FPI etalon. The exterior surfaces of the silicon mirrors are anti-reflection coated for both good transmission in the science band, and to prevent unwanted parasitic FPI cavities from forming between the four surfaces (one anti-reflection coated, one metalized for each mirror) of the FPI etalon.

The mirrors will be tested within a Miniature Cryogenic Scanning Fabry-Perot (MCSF) that we have designed through support of a previous NASA grant (NNX09AB95G). This design is based on our long experience in constructing and using scanning FPI in the mid-IR to submm range, and fits within test-beds we have on hand that are suitable for both warm and cold tests.

The key technologies are the ARC and tuned mirrors that are enabled by silicon nano-machining techniques. The creation of these SSB mirrors promises greatly improved performance over previous versions of mid-IR to submm-band FPIs that are based on mirrors made from free-standing metal mesh stretched over support rings. Performance is improved both structurally and in terms of sensitivity, and is measured as the product of the cavity finesse times transmission. Our electromagnetic modeling suggests that SSB mirrors will improve this product by a factor of 2 over the best free standing mesh etalons available. This translates into a factor of sqrt(2) improvement in sensitivity per etalon, or a full factor of 2 when used in a tandem (dual etalon) FPI spectrometer. The SSB improvements are due to both the stiff (~ 0.8 mm thick) silicon substrate and the silicon nanofabrication techniques and include the effects of (1) precisely tuned reflective surfaces, (2) very smooth mirror surfaces leading to greater cavity efficiency, (3) reduced susceptibility to vibrations due the silicon support structures, (4) reduced susceptibility to defect finesse due to reduced mounting stress, and (5) greatly improved mechanical robustness that could result in space-qualified hardware. These improvements are enabled by the combination of silicon-based technologies and our sophisticated electromagnetic modeling.

The finished products have many science applications. For example, the SSB mirrors within an MCSF would convert the FORCAST or HAWC+ cameras on SOFIA into imaging spectrometers capable of widescale mapping of the mid to far-IR fine structure lines from the Galactic Center, Galactic star formation regions and external galaxies. In fact, this new etalon technology could be used in any mid to far-IR camera, converting the camera into a moderate (100 to 4000) to high resolving power (~100,000) imaging spectrometer at modest cost. A particularly interesting application could be a large format (~10 cm diameter) FPI that could deliver resolving powers in excess of 5000 for a 10 m space telescope, which might be the incarnation of the next major far-IR space mission (see NASA Cosmic Origins Newsletter, V4, No. 1, March 2015).

Our program addresses NASA's Strategic goal 1: "Expand the frontiers of knowledge, capability, and opportunity in space."; Objective 1.6: "Discover how the Universe works, explore how it began and evolved, and search for life on planets around other stars," specifically "Technology development and demonstration." It also addresses Strategic Goal 2 via Objective 2.4: "Advance the Nation's STEM education and workforce

pipeline by working collaborative with other agencies to engage students, teachers, and faculty in NASA's missions and unique assets."

Phillip Stancil/University of Georgia
Molecular Ro-vibrational Collision Rates for Infrared Modeling of Warm Interstellar Gas from Full-dimensional Quantum Calculations

We propose to compute accurate collisional excitation rate coefficients for rovibrational transitions of CS, SiO, SO, NO, H_2O, and HCN due to H_2, He, or H impact. This extends our previous grant which focused on 3- and 4-atom systems to 4- and 5-atom collision complexes, with dynamics to be performed on 6-9 dimensional potential energy surfaces (PESs). This work, which uses fully quantum mechanical methods for inelastic scattering and incorporates full-dimensional PESs, pushes beyond the state-of-the-art for such calculations, as recently established by our group for rovibrational transitions in CO-H_2 in 6D. Many of the required PESs will be computed as part of this project using ab initio theory and basis sets of the highest level feasible and particular attention will be given to the long range form of the PESs. The completion of the project will result in 6 new global PESs and state-to-state rate coefficients for a large range of initial rovibrational levels for temperatures between 1 and 3000 K. The chosen collision systems correspond to cases where data are limited or lacking, are important coolants or diagnostics, and result in observable emission features in the infrared (IR). The final project results will be important for the analysis of a variety of interstellar and extragalactic environments in which the local conditions of gas density, radiation field, and/or shocks drive the level populations out of equilibrium. In such cases, collisional excitation data are critical to the accurate prediction and interpretation of observed molecular IR emission lines in protoplanetary disks, star-forming regions, planetary nebulae, embedded protostars, photodissociation regions, etc. The use of the proposed collisional excitation data will lead to deeper examination and understanding of the properties of many astrophysical environments, hence elevating the scientific return from the upcoming JWST, as well as from current (SOFIA, Herschel, HST) and past IR missions (Spitzer, ISO), and from ground-based telescopes.

Susan Trolier-McKinstry/Pennsylvania State University
High Resolution Adjustable Mirror Control for X-ray Astronomy

The goal of the proposed program is to enable increased angular resolution and collection areas for future major X-ray observatories by incorporating control of the mirror surfaces after fab-rication and mounting. We propose to develop and implement a method for preparing adjustable optics with integrated control elements on curved mirror segments for future X-ray space telescopes. Development of such mirror elements will provide a major advance to the field of X-ray astronomy, by enabling mirrors with half an arcsecond angular resolution using thin, lightweight glass to significantly increase the

collection area. This is an enabling technology for mission concepts such as the X-ray Surveyor.

This proposal supports NASA's goals of technical advancement of technologies suitable for future missions, and training of graduate students.

Scott Wakely/University of Chicago
HELIX: The High Energy Light Isotope Experiment
CoI: Stephane Coutu/Pennsylvania State University
CoI: Jim Musser/Indiana University
CoI: Scott Nutter/Northern Kentucky University
CoI: Gregory Tarle/University of Michigan

This is the lead proposal for a new suborbital program, HELIX (High-Energy Light Isotope eXperiment), designed to make measurements of the isotopic composition of light cosmic-ray nuclei from ~200 MeV/nuc to ~10 GeV/nuc. Past measurements of this kind have provided profound insights into the nature and origin of cosmic rays, revealing, for instance, information on acceleration and confinement time scales, and exposing some conspicuous discrepancies between solar and cosmic-ray abundances. The most detailed information currently available comes from the ACE/CRIS mission, but is restricted to energies below a few 100 MeV/nuc. HELIX aims at extending this energy range by over an order of magnitude, where, in most cases, no measurements of any kind exist, and where relativistic time dilation affects the apparent lifetime of radioactive clock nuclei. The HELIX measurements will provide essential information for understanding the propagation history of cosmic rays in the galaxy. This is crucial for properly interpreting several intriguing anomalies reported in recent cosmic-ray measurements, pertaining to the energy spectra of protons, helium, and heavier nuclei, and to the anomalous rise in the positron fraction at higher energy.

HELIX employs a high-precision magnet spectrometer to provide measurements which are not achievable by any current or planned instrument. The superconducting magnet originally used for the HEAT payload in five successful high-altitude flights will be combined with state-of-the-art detectors to measure the charge, time-of-flight, magnetic rigidity, and velocity of cosmic-ray particles with high precision. The instrumentation includes plastic scintillators, silicon-strip detectors repurposed from Fermilab's CDF detector, a high-performance gas drift chamber, and a ring-imaging Cherenkov counter employing aerogel radiators and silicon photomultipliers.

To reduce cost and technical risk, the HELIX program will be structured in two stages. The first stage, which is the subject of this proposal, will focus on the design and construction of the main HELIX instrument, and the measurement of key light isotope ratios from ~200 MeV/n to ~3GeV/n. A future stage 2 will build on this work, incorporating evolutionary enhancements to the instrumentation to extend the energy reach into the challenging ~10 GeV/n range. The stage 1 instrument achieves a

maximum detectable rigidity of ~800GV and charge range from Z=1 to Z=10. The high field of the HEAT magnet will make it possible to reach the required mass resolution dm/m = 2.5% over the energy range of concern with very small systematic limitations due to multiple Coulomb scattering in the thin tracker. This is a decisive advantage over the current AMS-02 instrument which employs a permanent magnet with an average field ~7 times smaller than that of HELIX.

The primary scientific goals of the full HELIX program are:
- a high-statistics measurement of the 10Be/9Be 'clock ratio' to ~10 GeV/nuc
- a high-statistics measurement of the 3He/4He ratio to ~12GeV/nuc
- the first measurements of 22Ne/20Ne above 1 GeV/nuc
- the first measurements of 7Li/6Li, and 10B/11B above 1 GeV//nuc

A number of secondary goals will also be pursued including the measurement of several other isotopic and elemental abundance ratios and fluxes, as well as the primary Helium flux to ~125 GeV/nuc, where there is currently disagreement between AMS-02 and PAMELA on the shape of the energy spectrum.

The proposed work will be conducted by a team of US scientists and engineers with extensive experience in cosmic-ray observations on balloons or in space, and, specifically in magnet spectroscopy, with the SMILI, P-BAR, and HEAT programs. Significant participation from a crew of more than 10 graduate and undergraduate students forms an important educational element of the program.

John Wefel/Louisiana State University
CALET: Flight Operations and Data Analysis
CoI: Walter Binns/Washington University in St. Louis
CoI: Jonathan Ormes/University of Denver

The CALET (CALorimetric Electron Telescope) Mission to the ISS has been under development for the past decade as a Japanese led international mission involving Italy and the United Sates. Over the past five years we have worked with our international partners to ready CALET for launch and to prepare the systems needed for a successful experiment at the frontiers of Particle Astrophysics. CALET will extend measurements of the cosmic ray electron, nuclei and gamma-ray components into the trans-TeV energy region, beyond the energy reach of current experiments, to investigate possible new astrophysics at the highest energies. CALET is now ready for launch on HTV-5, having completed environmental testing (Acoustic, T/V, EMI/EMC) at the JAXA space center. Working with the international team, we have developed a detailed Instrument Model, have participated in accelerator testing of CALET components, and have developed the detailed formats and processing scheme for the flight data. Moreover, we have established the US CALET Data Center at Louisiana State University, have acquired the hardware, developed the software and verified the connectivity with the Waseda Operations Center in Japan. The US Data Center will distribute data to the US

investigators, will process and analyze the CALET data stream to obtain science results, and will prepare the CALET data products for archiving at the HEASRC facility at GSFC. Under this proposal we ask for support of the first portion of the flight operations and data processing/analysis for the CALET mission. Launch is anticipated before the end of CY15, allowing the US team to transition from pre-launch to on-orbit operations and to be a major partner in this new particle astrophysics mission. The US Team consists of Louisiana State University (lead institution), Goddard Space Flight Center, Washington University in St. Louis, and The University of Denver.

Benjamin Williams/University of California, Los Angeles
High-power terahertz lasers with excellent beam quality for local oscillator sources

Many molecular species that compose the interstellar medium have strong spectral features in the 2-5 THz range, and heterodyne spectroscopy is required to obtain ~km/s velocity resolution to resolve their complicated lineshapes and disentangle them from the background. Understanding the kinetics and energetics within the gas clouds of the interstellar medium is critical to understanding star formation processes and validating theories of galactic evolution. Herschel Observatory's heterodyne HIFI instrument provided several years of high-spectral-resolution measurements of the interstellar medium, although only up to 1.9 THz. The next frontier for heterodyne spectroscopy is the 2-6 THz region. However, development of heterodyne receivers above 2 THz has been severely hindered by a lack of convenient coherent sources of sufficient power to serve as local oscillators (LOs).

The recently developed quantum-cascade (QC) lasers are emerging as candidates for LOs in the 1.5-5 THz range. The current generation of single-mode THz QC-lasers can provide a few milliwatts of power in a directive beam, and will be sufficient to pump single pixels and small-format heterodyne arrays (~10 elements). This proposal looks beyond the state-of-the-art, to the development of large format heterodyne arrays which contain on the order of 100-1000 elements. LO powers on the order of 10-100 mW delivered in a high-quality Gaussian beam will be needed to pump the mixer array - not only because of the microwatt mixer power requirement, but to account for large anticipated losses in LO coupling and distribution. Large format heterodyne array instruments are attractive for a dramatic speedup of mapping of the interstellar medium, particularly on airborne platforms such as the Stratospheric Observatory for Infrared Astronomy (SOFIA), and on long duration balloon platforms such as the Stratospheric Terahertz Observatory (STO), where observation time is limited.

The research goal of this proposal is to demonstrate a new concept for terahertz quantum-cascade (QC) lasers designed to deliver scalable continuous-wave output power in the range of 10 to 100 mW or more in a near-diffraction limited output beam: a chip-scale THz quantum-cascade vertical-external-cavity-surface-emitting-laser (QC-VECSEL). We focus here on the development of a chip-scale version of size < 1 cm3 that oscillates in a single mode and can readily fit on a cold stage. The enabling technology for this

proposed laser is an active metasurface reflector, which is comprised of a sparse array of antenna-coupled THz QC-laser sub-cavities. The metasurface reflector is part of the laser cavity such that multiple THz QC-laser sub-cavities are locked to a high-quality-factor cavity mode, which allows for scalable power combining with a favorable geometry for thermal dissipation and continuous-wave operation. We propose an integrated design, modeling, and experimental approach to design, fabricate, and characterize amplifying reflective QC metasurfaces and QC-VECSEL lasers. Demonstration laser devices will be developed at 2.7 THz and 4.7 THz, near the important frequencies for HD at 2.675 THz (for measurements of the hydrogen deuterium ratio and probing past star formation), and OI at 4.745 THz (a major coolant for photo-dissociation regions in giant molecular clouds). High resolution frequency measurements will be performed on a demonstration device at 2.7 THz will using downconversion with a Schottky diode sub-harmonic mixer to characterize the spectral purity, linewidth, and fine frequency tuning of this new type of QC-laser.

This proposed laser is supporting technology for next-generation terahertz detectors.

Eric Wulf/Naval Research Laboratory
Front End Spectroscopy ASIC for Germanium Detectors

Large-area, tracking, semiconductor detectors with excellent spatial and spectral resolution enable exciting new access to soft (0.2-5 MeV) gamma-ray astrophysics. The improvements from semiconductor tracking detectors come with the burden of high density of strips and/or pixels that require high-density, low-power, spectroscopy quality readout electronics. CMOS ASIC technologies are a natural fit to this requirement and have led to high-quality readout systems for all current semiconducting tracking detectors except for germanium detectors. The Compton Spectrometer and Imager (COSI), formerly NCT, at University of California Berkeley and the Gamma-Ray Imager/Polarimeter for Solar flares (GRIPS) at Goddard Space Flight Center utilize germanium cross-strip detectors and are on the forefront of NASA's Compton telescope research with funded missions of long duration balloon flights. The development of a readout ASIC for germanium detectors would allow COSI to replace their discrete electronics readout and would enable the proposed Gamma-Ray Explorer (GRX) mission utilizing germanium strip-detectors. We propose a 3-year program to develop and test a germanium readout ASIC to TRL 5 and to integrate the ASIC readout onto a COSI detector allowing a TRL 6 demonstration for the following COSI balloon flight.

Our group at NRL led a program, sponsored by another government agency, to produce and integrate a cross-strip silicon detector ASIC, designed and fabricated by Dr. De Geronimo at Brookhaven National Laboratory. The ASIC was designed to handle the large (>30 pF) capacitance of three 10 cm^2 detectors daisy-chained together. The front-end preamplifier, selectable inverter, shaping times, and gains make this ASIC compatible with a germanium cross-strip detector as well. We therefore have the

opportunity and expertise to leverage the previous investment in the silicon ASIC for a new mission.

A germanium strip detector ASIC will also require precise timing of the signals at the anode and cathode of the device to allow the depth of the interaction within the crystal to be determined. Dr. De Geronimo has developed similar timing circuits for CZT detector ASICs. Furthermore, the timing circuitry of the ASIC is at the very end of the analog section, simplifying and mitigating risks in the redesign. In the first year, we propose to tweak the gain settings and to add timing to the silicon ASIC to match the requirements of a germanium detector. The design specifications of the ASIC will include advice from our collaborators Dr. Boggs from COSI and Dr. Shih from GRIPS. By using a master ASIC designer to integrate his proven front-end and back-end with only minor modifications, we are maximizing the probability of success.

NRL has a commercial cross-strip germanium detector with 30 pF of capacitance per strip, including the flex circuit from the detector to the outside of the cryostat. The COSI and GRIPS detectors have a similar capacitance per strip on the outside of their mechanically cooled cryostat. The second year of the program will be devoted to testing the newly fabricated germanium cross-strip ASIC with the NRL germanium detector. At the end of the second year, NASA will have a TRL 5 ASIC for germanium detectors, allowing future missions, including COSI, GRX, and GRIPS, to operate within their thermal and electrical envelopes. At the end of the third year, a detector on COSI will be instrumented with the new ASIC allowing for a TRL 6 demonstration during the following COSI balloon flight.

Nan Yu/Jet Propulsion Laboratory
Optical frequency comb-based local oscillator phase noise cancellation in time-delay-interferometer for gravitational wave detection

Time-delay-interferometer (TDI) is well established as an effective technique to mitigate laser phase noises in laser interferometer gravitational wave detection (GWD). Just as important in the TDI scheme is the ability to suppress the rf local oscillator noise (LO) in the optical heterodyne measurements. We show that LO noises can be effectively and elegantly cancelled by employing optical frequency combs in which the rf signal phases are coherent with the optical phases. In addition, the deployment of optical combs eliminates the need for separate ultra-stable oscillators. This is a simpler and more reliable approach than the modulation scheme, and it can be applied to the most generalized TDI combinations. In this proposed effort, we will investigate the application of optical combs in TDI and demonstrate in a test bed simultaneous noise cancellations in both ranging lasers and rf LOs in a generalized TDI configuration.

Jonas Zmuidzinas/California Institute of Technology
Phonon Recycling for Ultrasensitive Kinetic Inductance Detectors

Initially proposed (Day et al. 2003; Zmuidzinas 2012) in 1999 by our Caltech/JPL group, and thanks to strong support from NASA, the superconducting (microwave) kinetic inductance detector (MKID or KID) technology continues to develop rapidly as it transitions into applications. The development effort worldwide is intensifying and NASA's continued support of KID development is essential in order to keep pace.

Here we propose to investigate and demonstrate a new, low-TRL concept, which we call phonon recycling, that promises to open broad new avenues in KID design and performance. Briefly, phonon recycling allows the detector designer to tailor the responsivity and sensitivity of a KID to match the needs of the application by using geometry to restrict the rate at which recombination phonons are allowed to escape from the detector. In particular, phonon recycling should allow very low noise-equivalent power (NEP) to be achieved without requiring very low operating tem- peratures. Phonon recycling is analogous to the use of micromachined suspension legs to control the flow of heat in a bolometer, as measured by the thermal conductivity G. However, phonon recycling exploits the non-thermal distribution of recombination phonons as well as their very slow decay in crystals at low temperatures. These properties translate to geometrical and mechanical requirements for a phonon-recycled KID that are considerably more relaxed than for a bolometer operating at the same temperature and NEP.

Our ultimate goal is to develop detector arrays suitable for a far-infrared (FIR) space mission, which will impose strict requirements on the array sensitivity, yield, uniformity, multiplexing density, etc. Through previous NASA support under the Strategic Astrophysics Technology (SAT) program, we have successfully demonstrated the MAKO submillimeter camera at the Caltech Submillimeter Observatory and have become familiar with these practical issues. If our demonstration of phonon recycling is successful, we will have a path for continuously adapting the high-background, high-NEP detectors we have demonstrated on the ground to the ultralow-NEP detectors needed for space.