**Astrophysics Research and Analysis Program**
**Abstracts of Selected Proposals**
**(NNH17ZDA001N-APRA)**

Below are the abstracts of proposals selected for funding for the Astrophysics Research and Analysis program. Principal Investigator (PI) name, institution, and proposal title are also included. 170 proposals were received in response to this opportunity. On October 12, 2018, 36 proposals were selected for funding. Five proposals were partially selected.

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**Steven Allen/Stanford University**
**Development of Integrated Readout Electronics for Next Generation X-ray CCDs**

The Physics of the Cosmos Program Annual Technology Report of 2017 lists "Fast, low-noise, megapixel X-ray imaging arrays with moderate spectral resolution" as one of the fields with the highest priority for technology maturation. The Lynx large mission concept now under study by NASA for presentation to the 2020 Decadal Survey in Astronomy and Astrophysics includes a notional high-definition X-ray imaging instrument (HDXI). This instrument requires a combination of readout rate, noise, spatial resolution and size that cannot be met by currently-mature technologies. One of the most significant challenges is the targeted 300 fold increase in frame rate compared to Chandra, with constrained power and mass budgets.

This technological challenge is being addressed from two sides: improvement of the CCD technology and its output stages; and segmentation of the CCD readout architecture with an associated increase in output nodes. Both approaches require concurrent development of the readout electronics to utilize the novel CCD output stages, to provide the (substantial) increase in channel density to match the CCD segmentation, and to mature the required interconnect and integration technology.

Building on our experience with Athena and LSST, and utilizing circuit concepts that have been successfully used for both pn-CCDs (JFET outputs) and DEPFETs (buried gate PMOS pixels), we propose to design, manufacture and test a prototype readout ASIC suitable for future X-ray missions. This will be integrated and tested with a high-speed Lynx prototype CCD detector currently in development at MIT-Lincoln Labs. We anticipate that our 16-channel prototype ASIC will be capable of reading the MIT-LL CCDs at an output rate of 5Mpix/sec and with a noise performance as low as 3.2 electrons, in line with the requirements for the notional Lynx HDXI. Our test setup will leverage existing X-ray detector facilities at MIT, including a commercial data acquisition system, allowing us to study different CCD outputs and their behaviors, various signal filtering options and specific implementations in an efficient and goal-oriented manner.

A key aspect of our study is to investigate the feasibility of using massively parallel Analog-to-Digital Converters and digital shaping techniques for signal filtering. In principle, this offers the potential for substantial gains, providing exquisite control in studies of noise, settling times, clock coupling, amplifier response and crosstalk, allowing us to tune for optimum performance with short turnaround times. In parallel, we will also investigate a more traditional state-of-the-art analog filter approach incorporating dual slope integrators, with the potential addition of zero-suppressed readout to reduce the required analog multiplexing bandwidth.

Our study would represent NASA's first comprehensive investigation of architectures and requirements for optimized readout electronics for future large-format X-ray imaging detectors. We will deliver a deeper understanding of the merits and challenges of alternative approaches, and recommend a path toward a scalable readout electronics solution for future missions with high-performance, megapixel X-ray imaging sensors.

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**James Babb/Smithsonian Institution/Smithsonian Astrophysical Observatory**
**Collisional Processes for Astrophysics and Mid/Far-Infrared Astronomical Spectroscopy**

Astronomical observations in the mid/far-infrared wavelengths continue to advance our understanding of the evolution of stars and galaxies. The fine structure emission lines in the mid/far-infrared wavelengths arising from, for example, highly-charged atomic ions (mid-IR) and oxygen atoms (far-IR) are important targets of observations with the NASA Astrophysics missions JWST and/or SOFIA, as well as the archival past missions Herschel, Spitzer, and the Infrared Space Observatory (ISO). In the case of ions, because they are created by high energy phenomena originating in cores and shocks of astronomical objects, their fine structure lines bridge data from these missions to data from, for example, Chandra, as well as to optical data from HST.

The fine structure emission lines are highly valued diagnostics of energies and densities in galaxies, planetary nebulae, and stars and as probes of warm gases in circumstellar disks and outflows. Diagnostic values of the fine structure emission lines depend on the ionization potentials of the ions as well as their fine structure transitions (leading to emission lines) in response to collisions with electrons, hydrogen atoms, and other species.

We will provide reliable calculations of fine structure changing collisions of [O I] and H, [Ne II] and H, and [Ne III] and H using a fully quantum-mechanical scattering approach. The associated excitation and cooling rate coefficients will be applicable to modeling of astrophysical phenomena observed using mid/far-infrared astronomical spectroscopy and traced through gas around active galactic nuclei and irradiated protoplanetary disks, with particular relevance to JWST/MIRI, including several Early Release Science projects. The data will lead to better models of ionic fine structure lines as diagnostics of

astrophysical environments using spectroscopic observations from air- and space-borne missions in the mid- and far-infrared wavelengths.

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**Eduardo Bendek/NASA Ames Research Center**
**Enabling Imaging Astrometry Detection and Mass Measurement of Earth-like Planets**

Accurate measurement of exoplanetary masses is a critical step in addressing key aspects of NASA,Äôs science vision. New technologies to implement an astrometric instrument capable of measuring masses of earth-analog planets aboard as a part of NASA,Äôs future mission portfolio will be required: this is simply the only viable avenue to attaining these data. Here we propose to advance Diffractive Pupil (DP) technology, capable of performing mass measurements down to 1 Earth mass, to TRL-5. This will immediately empower the possibility for dedicated astrometric missions, and perhaps most enticing, it will enable astrometric observing modes to be added (with relatively low cost and impact) to any mission boasting a sufficiently stable direct imaging platform. Astrometry is the only technique that can unequivocally measure exoplanet masses regardless of the system alignment, and serves to independently confirm direct imaging detections, yielding more precise planet orbits than direct imaging alone. Most critically, detection noise floors make it uniquely suited to habitable zone orbits for Earth-mass objects around sun-like stars: true Earth-analogs. Therefore, this technology can confer unique scientific benefits to future flagship missions. In particular, because these missions are expected to yield one or two dozen exoearths, measurements of mass add very significant value to the science of habitability in the solar neighborhood.

The proposed work has three areas that complement each other to develop an efficient and reliable technology: 1) Data reduction and calibration algorithms will be fully developed (including those for a diffractive pupil optimized for single and binary stars). To fully benchmark the methodology, confronting the signal recovery with real data from an optical laboratory testbench is essential. 2) A prototype instrument that performs an end-to-end astrometry demonstration in air and in vacuum will be built and tested. This astrometric instrument will include a star simulator with capability to inject simulated planetary orbital signals, together with a telescope equipped with a diffractive pupil, and laser metrology for detector calibration. 3) A study of implementation aboard the HabEx mission in which the diffractive pupil is implemented at an intermediate location in the optical path (not on the telescope primary mirror) will be performed. Such a scenario calls for calibration of the upstream path by way of the telescope metrology system. During year 1 we will improve existing distortion calibration algorithms (Ames and Sydney) and integrate and test the instrument in air at Ames. In parallel, JPL will build the laser metrology system and calibrate the camera. During year 2 the data reduction pipeline will be tested using real data, and the instrument moved to JPL where the laser metrology will be integrated and the system ready for full vacuum testing. In parallel, the HABEX implementation analysis will be initiated. In year 3, vacuum tests will be undertaken at JPL, while simultaneously the HABEX analysis will be finalized. This

proposal leverages successful execution of APRA-09 and TDEM-13 that brought the DP technology to TRL-4. Ames Research Center and JPL will partner for the execution of this proposal utilizing previous investments and expertise in laser metrology from JPL and distortion calibration at Ames.

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**Julian Borrill/University of California, Berkeley**
**Overcoming Systematic Effects In Cosmic Microwave Background Missions**

Fluctuations in the temperature and polarization of the Cosmic Microwave Background (CMB) encode a wealth of information about the parameters of cosmology and fundamental physics. The challenge for CMB scientists has always been to detect these tiny signals in the face of potentially overwhelming statistical and systematic uncertainties. While statistical uncertainties can be reduced by gathering larger and larger data-sets, reducing systematic effects requires both minimizing them in the design of any mission and mitigating them in the analysis of its data.

Next-generation missions will attempt to measure the energy scale of inflation from the imprint of primordial gravitational waves in the B-mode polarization of the CMB. As the faintest CMB signal, at the nano-Kelvin level or below, its detection will require both the largest data-sets ever gathered and the tightest control of systematic effects ever achieved. A critical question in the design of such missions is identifying which systematic effects can already be sufficiently mitigated in software, and which require advancements in hardware to meet its goals.

Addressing this question proceeds in three steps, and builds on the CMB mission data synthesis and reduction capabilities developed and deployed at scale in our previous APRA project. Firstly we will develop the the algorithms and implementations needed to mitigate the known systematic effects to sufficient precision, with a particular focus on pre-processing the mission time stream data in order to produce the cleanest possible sky maps. Secondly, since their efficacy will depend on the details of the mission survey strategy, we will optimize the survey parameters with respect to the ability to mitigate systematics. Finally, using this mitigation-optimized survey strategy we will identify the sources of systematics residuals that exceed our science threshold and use them to place requirements on instrument performance.

Possible reviewers would include Dr Charles Lawrence (Charles.R.Lawrence@jpl.nasa.gov), Dr Brendan Crill (Brendan.P.Crill@jpl.nasa.gov) and Professor Shaul Hanany (hanany@umn.edu ).

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**Charles Bradford/Jet Propulsion Laboratory**
**The Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE): a Pathfinder for Next-Generation Extragalactic FIR Spectroscopy -- JPL co-I**

This is the JPL Co-I proposal for STARFIRE, the main proposal is led by Joaquin Vieira at University of Illinois.

Understanding the formation and evolution of galaxies over cosmic time is one of the foremost goals of astrophysics and cosmology today. The cosmic star formation rate has undergone a dramatic evolution over the course of the last 14 billion years, and dust-obscured star forming galaxies (DSFGs) are a crucial component of this evolution. A variety of important, bright, and unextincted diagnostic lines are present in the far-infrared (FIR) which can provide crucial insight into the physical conditions of galaxy evolution, including the instantaneous star formation rate, the effect of AGN feedback on star formation, the mass function of the stars, metallicities, and the spectrum of their ionizing radiation. FIR spectroscopy is technically difficult but scientifically crucial. The FIR waveband is impossible to observe from the ground, and spans a crucial gap in the spectroscopic coverage between the Atacama Large Millimeter/submillimeter Array (ALMA) in the sub/mm, and the James Webb Space Telescope (JWST) in the mid-IR. Stratospheric balloons offer a platform which can outperform current instrument sensitivities and are the only way to provide large-area, wide-bandwidth spatial/spectral mapping at FIR wavelengths.

We propose an aggressive program of instrumentation development and experimental study called the Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE), with the goal of demonstrating the key technical milestones necessary for FIR spectroscopy. STARFIRE will provide a technological stepping stone to the future space-borne instrumentation such as the Origins Space Telescope (OST, formerly the Far-IR Surveyor) or a Probe mission. STARFIRE will address the two key technical issues necessary to achieve this:

1) Low-emissivity, high-throughput telescope and spectrometer optics for the FIR;
2) Background-limited detectors in large format arrays, scalable to >10,000 pixels.
We will do this by constructing an integral-field spectrometer from 240 - 420 microns coupled to a 2-meter low-emissivity carbon-fiber telescope. The development of the optics will utilize the capabilities of the Arizona Steward Observatory mirror lab and the unique expertise of our spectroscopic experts to create high-throughput optics. For the detectors, we will leverage the highly advanced development work of the Caltech / JPL group to develop and field kinetic-inductance detectors (KIDs). KIDs represent the most promising route to economical, large format submillimeter detector arrays.

In addition to the development and demonstration of crucial technologies for the FIR, STARFIRE will perform groundbreaking science. We will survey two 0.1 square degree fields centered on GOODS-S and the South Pole Telescope Deep Field, both of which have rich ancillary data. Scientifically, we will:

1) Obtain spectroscopic line detections of ~100 galaxies in the atomic fine structure lines [CII](158 microns) (at 0.5<z<1.5), [NII](205 microns) (at 0.2<z<1 ), [OI](63 microns) (at 2.8<z<5.7 ) and [OIII](88 microns) (at 1.7<z<3.8);
2) Establish the mean star formation rate (proportional to [CII] luminosity), metallicities (proportional to the [CII]/[NII] ratio), and AGN content (proportional to the [OIII] luminosity) of galaxies using a stacking analysis of known sources in the field;
3) Produce deep maps of the 3D structure of the Universe by redshift tomography ("intensity mapping") with [CI], and [CII] X [NII] cross-spectra, to constrain the cosmic star formation history at cosmic noon, and lay the important groundwork for extending this technique to even higher redshifts to eventually explore the epoch of reionization.

STARFIRE will probe an under-explored wavelength range with unprecedented sensitivity using a new astrophysical technique, and is a step toward NASA's goal of a future FIR space mission.

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**James Buckley/Washington University**
**Development of a novel imaging calorimeter for gamma-ray and cosmic ray studies.**

We propose to develop an accelerator beam-test instrument to demonstrate the performance of a new type of imaging calorimeter aimed at a future gamma-ray/cosmic-ray mission. The proposal would fund the development, construction and evaluation of a prototype instrument with 150mm√ó150mm active area and consisting of 4 layers of scintillating fiber x-y trackers, and 4 layers of CsI:Na crystal read out by wavelength shifting (WLS) optical fibers. The prototype would be instrumented with silicon photomultiplier (SiPM) photodetectors and custom electronics, utilizing low power analog pipeline digitizers designed by the U. Hawaii group. Calibrations would be performed using accelerator runs at both tagged photon beam facilities and a heavy ion accelerator. This project is aimed at advancing the technical readiness level of the key detector technologies for a future MIDEX (or probe-class) mission concept known as the Advanced Particle-astrophysics Telescope (APT). The instrument design was driven by the requirements of gamma-ray searches for dark matter (requiring a pair telescope with an order of magnitude improvement in geometry factor compared to Fermi LAT) and prompt localization of gamma-ray transients such as the counterparts of gravitational-wave sources/neutron-star mergers (best accomplished by a very large-area Compton telescope). A Sun,ÄìEarth Lagrange orbit would remove Earth obscuration providing the largest instantaneous field of view, but would require the use of a relatively thin imaging calorimeter with a depth limited to <6 radiation lengths. The same instrument design would provide multiple differential ionization energy loss (dE/dx) cosmic-ray measurements over a very large area, with a very deep detector. Such an instrument would be a powerful cosmic-ray detector capable of measuring the elemental abundances of very rare, ultra-heavy r-process cosmic ray nuclei for material originating outside our solar system, connecting to the n-star merger science. With the addition of foam radiators, the CsI detectors could detect the transition radiation X-rays from very-high-energy light cosmic rays, specifically Boron and Carbon, needed to differentiate models

of cosmic-ray propagation of importance to indirect dark matter detection. The APT detector design would incorporate 20 layers of 5 mm thick CsI:Na with crossed wavelength shifting fiber (WLS fiber) readout, interspersed with 20 x,àíy scintillating optical fiber tracker (SOFT) layers using interleaved 1.5mm round scintillating fibers. The 3m√ó3m√ó2.5m detector volume consisting of passive plastic scintillating fibers and CsI crystals would be read out on the sides with SiPM photodetectors and analog-pipeline waveform digitizers. These electronics would provide adequate look-back time to include signals from the relatively slow CsI detectors in the trigger; achieving this capability within the power budget constitutes another major activity of the proposed research. Ultimately, this work would validate simulation studies that indicate that the APT instrument could achieve 10 times the sensitivity of the Fermi LAT for GeV,ÄìTeV gamma-rays, and provide more than an order of magnitude improvement in sensitivity over any other proposed gamma-ray experiment in the MeV energy range with gravitational wave source localization to better than 1 degree uncertainty. Likewise, the cosmic-ray detector would improve statistics on rare heavy elements and high-energy lighter nuclei by orders of magnitude compared to any extant experiment.

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**Marc Christophersen/Naval Research Lab**
**Nano-technology for Advanced X-Ray Microcapillary Plates**

The spectacular successes of the Rossi X-ray Timing Explorer (RXTE) and its impending shut down highlight the need for a capable successor mission. A large-area X-ray timing mission with 5-10 times the collecting area of the RXTE Proportional Counter Array (PCA) will be capable of probing the physics of extreme density, temperature, gravitation, and magnetic fields in ways that will have impacts on numerous fields of physics. These including measuring the nuclear matter equation of state and the effects of spin on the gravitational field around black holes. The Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays (STROBE-X) is the proposed next generation X-ray timing mission. STROXE-X will probe strong gravity for stellar mass to supermassive black holes and ultra-dense matter with unprecedented effective area, high time-resolution, and good spectral resolution, while providing a powerful time-domain X-ray observatory.

Currently, STROBE-X is baselined for glass-based micropore collimators (MPC). MPCs have dramatically less mass and volume than collimator traditional designs, enabling large missions at modest cost. The disadvantage from MCPs is that they are made entirely of glass. Glass has a low X-ray ÔøΩstopping powerÔøΩ. We propose to dramatically improve MPC collimator technology by adding metal layers to the inside of the micropore walls. All fabrication techniques can be applied to large area MCP arrays. Prototype will be tested for performance at the MSFC Stray Light Facility and the thermal and mechanical properties that affect its use in a full instrument concept will be studied.

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**Manel Errando/Washington University**
**Development of thin-film polymer actuators for high-resolution X-ray optics**

We propose to build and test a novel class of low-voltage thin-film actuators based on electroactive polymers to address the need for adjustable mirror control in future high-resolution X-ray missions.

Electroactive polymers can produce high strains at low voltages, being able to correct the deformations that submillimeter-thick mirror shells will experience in future X-ray missions. Fabrication of polymer-based thin films is a low-cost, scalable technology that can be easily translated to production by industrial partners. With processing temperatures below 140 degrees Celsius, electroactive polymer films can be deposited on glass mirror substrates without risk of introducing additional slumping errors. The proposed research has four specific aims: i) produce actuator arrays on 3 x 3 square inch mirror substrates to validate the technology and characterize its figure correction capabilities; ii) explore different fabrication techniques and polymer materials for parameter performance optimization; iii) conduct aging, thermal-vacuum and radiation hardness tests to verify the robustness of the proposed technology in space environment; and iv) optimize the geometry of electrode patterns to produce uniaxial, biaxial, and out-of-plane strains that can reduce the complexity of the figure correction scheme.
This research presents a viable avenue to meet the requirement of 0.5 arcsecond image resolution for the optical assembly of the Lynx mission, one of four concept studies selected in preparation for the 2020 Decadal Survey. With the high imaging resolution enabled by our proposed mirror correction technology, Lynx will be capable of detecting the first accreting black holes, study the evolution of galaxies and growth of cosmic structure, and verify the existence of a Warm-Hot Intergalactic Medium (WHIM) that could account for the large fraction of missing baryonic matter in the Universe.

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**Brian Fleming/University Of Colorado, Boulder**
**The Evolution of Galactic Structure: Quantifying the Influence of the Most Massive Stars with the SPRITE CubeSat**

We propose a four year suborbital-class research program to develop, launch, and operate the Supernova remnant, Proxies for Reionization, and Integrated Testbed Experiment (SPIRTE): a 6U CubeSat that will address two key questions in astronomy:

How do galaxies provide ionizing radiation to the IGM? The transition from a neutral to an ionized intergalactic medium (IGM) was one of the key milestones in cosmic structure formation. Finding the ionizing sources - galaxies and AGN - is a central goal of the James Webb Space Telescope (JWST), but even this flagship cannot solve one critical aspect of the problem: How much of this radiation actually escapes galaxies to reionize the IGM? Webb cannot detect the ionizing radiation itself through the opaque high-z IGM, so users will instead use redshifted UV/optical emission lines as proxies. These

proxies must be calibrated with direct measurements of ionizing radiation escape in a sample of galaxies at lower redshift. SPRITE will directly measure the ionizing spectrum in 100 $0.15 < z < 0.3$ galaxies and AGN, a sample that will surpass in number and precision all ionizing escape measurements to date and provide critical interpretive tools for core JWST science.

What controls the mass, energy and chemical flows within galaxies? OB stars dominate the ionization and kinematic drivers of galactic disks through their intense radiation, fast stellar winds, and metal dispersal in supernovae; but how do these processes interact to drive the evolution of galaxies? SPRITE will trace feedback in its earliest stages using unique far-UV diagnostics (FUV: 1000 - 1600 angstroms) and a novel spectral imaging observing mode to create multi-dimensional data cube maps of more than 50 local star forming regions and supernova remnants in the Milky Way and Magellanic Clouds. This survey will quantify the physics of radiative and kinetic energy injection into their host galaxies and provide ground-truth to sub-grid physical models in hydrodynamical simulations.

SPRITE is designed to carry out these astrophysically compelling spectral surveys while serving as a demonstration testbed for the LUVOIR Surveyor - maturing and flight-qualifying technology identified as Priority One needs in the 2017 NASA Cosmic Origins Program Annual Technology Report. The advanced optical coatings and next-generation photon-counting microchannel plate (MCP) detector in the SPRITE design represent a paradigm shift for astronomy in the FUV, enabling more optical elements and exceptionally low on-orbit backgrounds without the crippling throughput losses that would occur with conventional technologies. Our extensive on-orbit calibration program will provide critical in situ measurements of their stability and performance ahead of formal adoption by LUVOIR, HabEx, or other NASA Large-, Probe-, or Explorer-class missions. SPRITE will leverage these recent products of the APRA, SAT and Roman Technology Fellowship programs to achieve sensitivities comparable to or exceeding previous FUV Explorer-class missions in a CubeSat envelope.

The SPRITE instrument is comprised of a rectangular Cassegrain telescope feeding a compact, low resolution ($R \sim 1500$) imaging spectrograph. The science instrument is incorporated into a Blue Canyon Technologies spacecraft bus that provides power, command and data handling, attitude control, and communications. Calibration and testing will occur in existing University of Colorado (CU) UV space-instrument facilities alongside other NASA SMD missions. SPRITE will be developed in the framework of CU's student-led space sciences program, where undergraduate, graduate, and postdoctoral training is paramount.

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**James Green/University Of Colorado, Boulder**
**Holographic Designs for the Next Generation of Ultraviolet Spectrographs**

Ultraviolet Spectroscopy is an essential element in the space astronomy portfolio, and the next ultraviolet spectrograph will need to have enhanced performance in sensitivity, resolution, and multi-object capability. Whether part of a flagship, probe, or explorer class mission, the next generation of ultraviolet spectrographs should be able to take advantage of technological improvements in all aspects of their designs. Work is currently ongoing in the areas of optical coatings and detectors, but the diffraction gratings remain at the same state-of-the-art as those currently employed on HST on STIS and COS. To address the limitations of the current state of-the-art, I propose to develop holographically corrected designs utilizing low-order echelle gratings, to demonstrate how future spectrographs could provide the most performance for a future flagship or probe mission. These designs will employ aberration correction in their design (similar to FUSE and COS) to minimize the reflections and enhance their capabilities will providing high efficiency and low scatter. Straw-man holographic designs for HABEX and LUVOIR will be raytraced and published as a proof of concert of what could be achieved. A custom spectrograph design conforming to either a selected decadal UV flagship mission architecture, or a probe architecture, will be developed after the decadal releases the survey results. All work will be published in the proceedings of the SPIE.

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**James Green/University Of Colorado, Boulder**
**The DEUCE and INFUSE Sounding Rocket Payloads: EUV and Integral Field Spectrographs for Next-generation Space-flight Hardware Development**

We propose a four-year suborbital sounding rocket research program to expand the development of next-generation UV instrumentation at the University of Colorado (CU). The aim of this program will be to:

1) complete the ionizing radiation (Extreme-UV (EUV): 650 - 900 angstrom) measurements of nearby B-stars begun as part of our predecessor award to constrain the contribution of hot stars to reionization in the high-z universe,
2) take advantage of the unique southern launch opportunity in 2020 to make the first-ever flux calibrated measurements of low-mass stars in the 500 - 900 angstrom bandpass,
3) develop the first Far-UV (FUV: 1000 - 1600 angstrom) integral field spectrograph (IFS) as a pathfinder for a next-generation NASA mission instrument,
4) fly the IFS to study the impact of massive stars on their galactic environments by quantifying the shock-velocity distribution in a nearby supernova remnant, and
5) provide training for graduate and undergraduate students, and mentorship for NASA's future space mission PIs.

We will carry out these aims with two additional launches of the payload developed under the predecessor award, and the development and flight testing of the new IFS

instrument. All work will be performed in a university environment with a long history of postdoctoral and student training in UV astrophysics, heliophysics, and planetary science.

In the first two years of the proposed work, we will fly the Dual-channel Extreme Ultraviolet Continuum Experiment (DEUCE) payload twice: first to complete the ionizing radiation census of local B stars, and then to obtain the first EUV spectra of the nearest main-sequence stars. Our group recently completed the first flight of DEUCE to observe the ionizing spectrum of one of the only two B-stars with sufficiently low intervening neutral hydrogen column: beta Canis Majoris. A NASA vehicle subsystem failure prevented successful target acquisition on this flight, so in Year 1 of the proposed work we will launch DEUCE to recover the original science mission. In Year 2, we will fly DEUCE from Australia to obtain the first 500 - 900 angstrom spectrum of the potential exoplanet host stars alpha Centauri A and B. The long-term stability of rocky planet atmospheres is driven by EUV radiation from their parent stars, although this quantity is almost completely unconstrained by direct observation. DEUCE will constrain the exoplanet climate models used to interpret the first atmospheric spectra of Earth-like planets that will be obtained in the coming decades with JWST, LUVOIR/HabEx, and other forthcoming NASA missions.

In parallel with the DEUCE flight schedule, we will leverage recent advances in technology to demonstrate the first FUV IFS: the Integral Field Ultraviolet Spectroscopic Experiment (INFUSE). INFUSE is a 0.5 meter aperture IFS that utilizes an image slicer at the focal plane to spectrally map a 5 x 4.3 arcminute region with ~ 2 arcsecond angular resolution and moderate resolving power (R ~ 6000) in a single pointing. The INFUSE concept is enabled by the recent development of enhanced reflectivity lithium fluoride (eLiF) mirror coatings and large format, high global count-rate cross-strip anode (XS) boro-silicate glass microchannel plate (MCP) detectors - both technologies identified for maturation and flight-testing by the LUVOIR Science and Technology Definition Team (STDT). In Year 4, we will launch INFUSE to provide the first wide-field spectral maps of the shock velocity structure in a region of the Cygnus Loop supernova remnant.

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**J Eric Grove/Naval Research Lab**
**Glowbug, a Gamma-Ray Telescope for Bursts and Other Transients**

We propose to build and rapidly deploy the Glowbug telescope, a scintillator array to detect and localize gamma-ray transients with performance similar to the Fermi Gamma-ray Burst Monitor (GBM). Glowbug will immediately increase the current sky coverage for short Gamma-Ray Bursts (SGRBs) from neutron star (NS) binary (NS-NS or NS-black hole) mergers. With the recent discovery of the SGRB coincident with the gravitational wave transient GW170817, we now know such events occur with reasonable frequency. Expanded sky coverage in gamma rays is essential, as more detections of gravitational waves from such mergers by ground-based interferometers will come in the next few years, and detecting an electromagnetic counterpart is a powerful probe of merger dynamics. To minimize cost and time to first light, Glowbug is

based directly on existing detectors and electronics, and we will exploit the Naval Research Laboratory's access to the DoD Space Test Program (STP) for launch and provision of one year of mission operations at no cost to NASA.

This proposal seeks funding to build one instrument and argues the need for an expanded network of such sensors that provides all-sky coverage for SGRB detection. Glowbug will complement existing systems such as Fermi GBM and the Swift Burst Area Telescope (BAT), and it will join future systems such as BurstCube in providing low-cost coverage for gamma-ray transients. We will actively work with the BurstCube team to streamline software development and standardize user tools and data products.

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**Olivier Guyon/University of Hawaii, Honolulu**
**Integrating Advanced Wavefront Control and Image Processing for High Contrast Imaging**

To image potentially habitable exoplanets and acquire spectra of their atmospheres or surfaces, imaging systems must be capable of operating at high contrast, where ÔøΩcontrastÔøΩ is defined as the ratio of stellar brightness to planetary brightness. The amount of starlight diffracted into the science pixels, called stray light, must be minimized by combining coronagraphy and wavefront control techniques. It can be removed by actively controlling the diffraction pattern with a deformable mirror, requiring estimation of its amplitude and phase via a wavefront sensing procedure. The fraction of the stay light that can be removed in this way depends on the efficiency of this wavefront sensing step. Even this procedure for actively removing stray light may not be adequate, so, background subtraction techniques are employed in a post-processing step that identifies and removes some of the remaining stray light. The resulting detection limit contrast (the augmented contrast) must be well below the planetÔøΩs flux level. At the ~1e10 (star-to-planet) flux-ratio characteristic of potentially habitable exoplanets around Sun-like stars, achieving the required raw and augmented contrast levels is extremely challenging.

We will enhance wavefront estimation and integrate it with image post-processing, improving both raw and augmented contrasts. The new framework will deliver well-calibrated science images, utilizing the property that most of the stray light that currently limits detections can be reconstructed from wavefront sensing measurements.

Our approach relies on three related techniques:
[1] Coherent Differential Imaging (CDI) will identify in the coronagraphic image the coherent (=starlight) and incoherent (=planet light) components. The measurement, relying on coherent mixing with reference starlight, was previously developed for wavefront control. We will optimize it for contrast augmentation and develop the associated processing algorithms.
[2] Predictive Control (PC) will optimally combine past wavefront measurements to improve both wavefront correction and stray light estimation.

[3] Sensor Fusion (SF) will combine measurements from multiple sensors (such as focal plane images, coronagraphic low-order wavefront sensor, and pupil plane sensors) to estimate the wavefront state and the corresponding residual starlight image component.

Together, PC and SF will increase the efficiency, sensitivity and reliability of wavefront sensing for high contrast imaging space missions (technology gaps CG-5, CG-7), and mitigate wavefront control challenges associated with large segmented apertures (CG-6). The CDI approach, together with noise estimation from PC and SF, will provide the real-time image calibration making use of stray light information contained in the wavefront sensing telemetry (CG-4).

In parallel to numerical development and focused testbed explorations at NASA Ames, University of Arizona, and JPL, we will integrate the approaches in a common framework on the SCExAO high contrast testbed/instrument for both laboratory (daytime) and ÔøΩon-sky validation at moderate contrast levels. The testbed already provides the system-level environment required for maturing and validating multi-sensor algorithms and demonstrating their practical implementation. Wavefront-sensor based post-processing of science images will be exercised on on-sky exoplanet observation datasets for end-to-end validation at moderate contrast. Extrapolation to higher contrast environments will rely on numerical validation of achieved results, supported by testbed calibrations.

Our effort will benefit from, and validate, recent advances in detector technologies in visible and near-IR (technology gap GC-9) and machine learning techniques. Our team includes experts in these areas, as well as high contrast imaging and wavefront sensing experts.

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**Steven Hailey-Dunsheath/California Institute of Technology**
**Sensitive Mid and Far-IR Kinetic Inductance Detector Arrays for Space Astronomy**

Over the past several years, NASA has been intensively studying future astrophysics missions at mid- and far-infrared wavelengths, including the flagship-class Origins Space Telescope (OST) and the probe-class Galaxy Evolution Probe (GEP). These mission studies follow the broad endorsement of a "Far-Infrared Surveyor" mission in the 2013 30-year roadmap study chartered by NASA, and the 2010 Decadal Survey recommendation for NASA participation in the JAXA/ESA SPICA far-IR mission. Not surprisingly, the OST and GEP studies have identified detector arrays as the highest-priority technology needing development. In this proposal, we offer to address essentially all of the fundamental detector needs for OST and GEP and for sub-orbital precursors, including the full 10-400 micron wavelength range, the varied sensitivity requirements, scalability to the desired array formats, and even to open a path toward highly stable photon-counting detectors needed for mid-IR biosignature characterization of terrestrial exoplanets with OST. We address all of these needs in a timely, integrated, highly efficient program by focusing on a single underlying technology, namely direct-

absorption (microwave) kinetic inductance detectors (MKIDs or KIDs) using aluminum as the superconducting material.

Our proposal aims squarely at the needs for OST and GEP: 1) sensitivity at or below 1e-19 W/root(Hz); 2) array architecture that enables efficient absorption at wavelengths from 10 to 350 micron, and 3) scalability to focal planes of >10^5 pixels. We will begin by increasing the sensitivity of our existing 350 micron feedhorn-coupled devices (which comfortably meet sub-orbital sensitivity requirements) by 1.5 orders of magnitude with a combination of lower operating temperature, higher quality films, and a reduced volume absorber. We will also push to shorter wavelengths, targeting first 30 micron and then 10 micron detectors, through use of new, efficient, and practical absorber geometries illuminated by scalable microlens arrays. This mid-IR capability will substantially reduce the cost and complexity of GEP and provide photon counting capability for high-stability mid-IR spectroscopic characterization of terrestrial exoplanets with OST, extending the initial work with JWST/MIRI.

A successful conclusion to our proposed program would represent a substantial reduction of technological risk for future NASA mid- and far-IR missions such as OST and GEP, with demonstration of the sensitivity, wavelength range, and array formats needed for the baseline designs developed by these study teams. It would also open a path to high-stability mid-IR exoplanet characterization with OST via photon counting.

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**Johannes Hubmayr/National Institute Of Standards & Technology**
**Next-Generation Feedhorn-Coupled Kinetic Inductance Detector Arrays**

NASA missions in the millimeter, sub-millimeter, and far-infrared part of the electro-magnetic spectrum universally call for larger arrays of low-noise detectors. The microwave kinetic inductance detector is an important low-temperature-detector technology in these applications, and particularly for deployment in space. Dense, highly-multiplexed arrays with few interconnects and low-power consuming electronics lead to lower-cost, more robust satellite missions.

We propose to significantly advance the technical maturity of feedhorn-coupled microwave kinetic inductance detectors (FC-KIDs), by tackling the key challenges that have historically limited MKID performance. These challenges include achieving photon-noise-limited sensitivity at detection frequencies below 1 Hz, maintaining high-quality MKIDs when integrated in more complex superconducting integrated circuits, and attaining high yield by avoiding resonator frequency collisions. We propose innovative solutions to overcome each challenge. We will develop 1) ultra-stable (to 1 mHz), low-noise arrays with aluminum sensors; 2) silicon parallel-plate capacitors with reduced size, loss, and TLS noise; 3) multichroic, dual-polarization-sensitive MKIDs scalable from 100-1000~GHz; and 4) highly uniform, >90% yield direct-absorber coupled MKID arrays fabricated on 150 mm substrates. Each of these research directives is backed-up by solid proof-of-principle demonstrations and concrete development plans.

Relevant satellite missions for this technology include Origins Space Telescope, Inflation Probe, and Galaxy Evolution Probe.

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**Boris Karasik/Jet Propulsion Laboratory**
**MgB2 HEB Based Heterodyne Array for Applications Above 2 THz**

We will develop terahertz (THz) superconducting scalable heterodyne detector technology, with a focus on building large-array receivers above 2 THz and providing a wide instantaneous spectral bandwidth. High-resolution THz spectroscopy is a vital tool for studying molecular cloud structure and evolution and star formation. Large arrays are needed to study extended fields, and the wide bandwidth is required for the study of objects with high velocity dispersion, such as seen in nearby galaxies as well as the center of our Galaxy. The large bandwidth is also required for future projects that will exploit THz interferometry.

Under a previous APRA funded task, we have developed a new type of hot-electron bolometer (HEB) mixer using thin superconducting MgB2 films (Tc =36-38 K) with a sensitivity close to the state-of-the-art (noise temperature ~ 2,000 K in the range 0.6-4.7 THz). In contrast to the SOA NbN HEB mixer, the new mixer has an intermediate frequency bandwidth of 7 GHz as is required for spectroscopy of 2.7 THz [HD], 3.4 THz [OIII], 4.7 THz [OI], 5.2 THz [NIII], and numerous other high-frequency lines. The mixer also operates at 15-20 K which is beneficial for balloon and space instruments. Our current proposal will continue development of MgB2 HEB mixer with a focus on improved sensitivity, reduced local oscillator power, and achieving an array receiver. Here we are going to develop waveguide mixer elements using MgB2 devices on Si membranes. Superconducting MgB2 films on Si have been achieved for the first time in our recent work and we will build our new approach on these results.

This will be a 3-year collaborative work with participation of JPL, Temple University (Philadelphia, PA) and University of California Los Angeles (UCLA).

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**John Krizmanic/University of Maryland Baltimore County**
**Modeling of the Air Shower Signals from Cosmic Neutrinos for Space-based Experiments**

We propose to develop the first comprehensive, end-to-end simulation package for the measurement of cosmic neutrinos that is applicable to sub-orbital and space-based observations. This development is needed to adequately quantify the neutrino potential of NASA's current and future experimental efforts in cosmic neutrino detection, including, ANITA, EVA, EUSO-SPB2, and the POEMMA Astrophysics Probe. The goal is to provide an efficient and practical cosmic neutrino EAS signal generation model that will provide a standard to gauge the neutrino measurement performance of sub-orbital and

space-based experiments. Sub-orbital and space-based measurements of both the optical Cherenkov and radio emission signals from upward-moving air showers sourced from tau neutrino interactions within and below the limb of the Earth have the potential to measure the astrophysical and the cosmogenic neutrino flux above one PeV. While the existence of the cosmogenic neutrinos is implied by the baryonic component in cosmic rays, the detection of these neutrinos has remained elusive and is one of the most important measurements in Astroparticle Physics. The details of the cosmogenic neutrino spectrum provide invaluable information to the cosmic ray acceleration process, source distribution, and source evolution. Thus neutrinos are a critical and unique component of multi-messenger astronomy and astrophysics. We propose to develop a simulation package that details all aspects of the processes that lead to the air shower signals, based on different neutrino spectra, that could be used by the community as a tool to determine an instrument's neutrino sensitivity. This includes the modeling the neutrino interactions inside the Earth, propagating the tau leptons into the atmosphere, modeling the decays, forming air showers from the decay products, generating the air fluorescence, Cherenkov, and radio signals, and the propagation through the atmosphere. The atmospheric transmission and scattering effects will be modeled in detail including consideration of the uncertainties, such as those due to propagation through aerosols in the atmosphere for the optical signal and due to propagation through the ionosphere for the radio signal. Relevant atmospheric backgrounds, such as air glow, will also be modeled. The modeling will also be easily adaptable for simulating the detectable signals from UHECR and UHE neutrino air showers. This will allow for the investigation of the potential backgrounds associated with the UHECR air shower signals just over the Earth's limb and the reflection off of clouds and the ground of the downward UHECR air shower signals. The modeling will be performed in such a way to easily be used to generate the fluorescence, Cherenkov, and radio signals delivered to a specific altitude for a given instrumental field-of-view. The results of this modeling effort will allow for the calculation of the sky coverage and the pointing requirements for target of opportunity follow-up observations to extremely energetic transient events. Additionally, the framework will allow for the inclusion of different neutrino interaction cross-sections to allow for the modeling of non-standard physical processes.

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**Davide Lazzati/Oregon State University**
**Dust From Supernovae: Formation, Resilience To Sputtering And Explosion, And Diffusion In The Interstellar Medium**

The evidence of significant reddening in high redshift galaxies calls for the production of dust in massive stars and its effective dissemination into the interstellar medium. However, observations and theoretical predictions disagree on the timing of dust formation and its resilience in the harsh environment of an exploding star. We propose to perform a comprehensive study of the nucleation, growth, agglomeration, and possible crystallization of dust formed in supernova ejecta. The study will be based on both analytical calculations and numerical simulations, and a dedicated code for studying the resilience of grains to grain-grain and grain-particle collisions will be developed, based

on the physics of granular materials. Differently to previous efforts, we will perform ab initio calculations of the threshold energies for grain polymerization and crystallization, inhomogeneous conglomerates of different grain species, and study the morphology of grains grown by conglomeration of smaller particles as well as the onset of collisions and UV irradiation. This project will deliver robust prediction of the dust yields from stellar explosion into the interstellar medium, including grain species, fluffiness, crystalline structure, and size distribution.

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**Timothy Lee/NASA Ames Research Center**
**Determination Of Highly Accurate Rovibrational Line Lists For Ammonia And Its Isotopologues For Use In Analyzing Astronomical Spectra And Modeling Of Exoplanet Atmospheres**

As explicitly highlighted in the whitepaper ÔøΩThe Need for Laboratory Work to Aid in The Understanding of Exoplanetary AtmospheresÔøΩ from the observational and modeling exoplanet community, ÔøΩhigh spectral resolution opacity data for a variety of relevant molecular speciesÔøΩ is one of the important areas to ÔøΩfill critical gaps in our ability to model exoplanet atmospheric opacities, clouds, and chemistryÔøΩ. In other words, astronomers need highly accurate rovibrational line lists (including infrared intensities) of small molecules that are common in various solar system planet and moon environments, exoplanet atmospheres, brown dwarfs, and the interstellar medium (ISM). This is also being driven by the availability of ever increasingly high-resolution telescopes and instruments, including space-based such as JWST and WFIRST, plane-based such as SOFIA, and ground based such as ALMA and several planned extremely large telescopes. In order to maximize the scientific return for these missions, the line lists need to provide both accurate line positions and line strengths as well as being complete enough to be able to describe the large temperature extremes of the different environments. One such molecule is Ammonia, which widely exists in the ISM, brown dwarfs, and H2 & He dominated exoplanetary atmospheres, and thus will be an important diagnostic molecule in the characterization of interstellar environments and exoplanet atmospheres. The existing spectral databases for NH3 and its isotopologues, HITRAN and ExoMol (BYTe), are not sufficiently complete or accurate to characterize the environments where NH3 is present. Building on our previous work on NH3 and subsequent work on other molecules as well as additional experimental data, we will generate accurate and complete line lists for NH3 and D and 15N isotopologues. Further, we will expand the experimentally verified prediction accuracy up to 10,000 cm-1 above the zero-point level, extend this to the two isotopologues NH2D and NHD2, and produce reliable IR intensities. We plan to measure new experimental spectra in 7000 ÔøΩ 9500 cm-1 range for an NH3, NH2D, NHD2, and ND3 isotopologue mixture, which will be analyzed and assigned using our IR line lists, and then used to further improve the IR line lists. These line lists will be invaluable in modeling the ISM and atmospheres of various celestial objects, including exoplanet atmospheres. The spectral library and data products will be made available to the astrophysical and science communities.

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**Christopher Leitz/Massachusetts Institute of Technology/Lincoln Lab**
**Germanium Charge-Coupled Devices for Large-Format, Low-Noise Hard X-Ray Sensors**

We are proposing to develop large-format charge-coupled devices (CCDs) on bulk germanium, with sensitivity spanning both soft and hard X-ray bands (0.5 - 50 keV). These devices will demonstrate the characteristics that make silicon CCDs desirable for astronomy -- notably large format, excellent uniformity, low read noise, excellent spectral resolution, and noiseless on-chip charge summation -- in a material that covers a wider energy band than silicon. Compared to the cadmium zinc telluride detectors currently used for hard X-ray sensing, these germanium devices will be larger format, exhibit superior spectral resolution, and not require hybrid integration (bump bonding). The proposed work builds on significant internal research and development in this area at MIT Lincoln Laboratory. To date, we have demonstrated functional 1 kpixel germanium CCDs, fabricated in the same state-of-the-art tool set used to build our silicon CCDs and displaying lower read noise than comparable silicon CCDs. The goals of the proposed effort are to demonstrate a 512 x 512 x 24 micron-pitch germanium CCD with dark noise < 1 e-/pixel/second at an operating temperature of 100 K and < 5 electrons of read noise. These developments could dramatically improve the energy resolution and field of view of future imaging missions in the hard X-ray band.

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**Joan Marler/Clemson University**
**Momentum Resolved Charge Exchange Cross Section Measurements and X-ray Spectroscopy**

In this proposal to the sub-element Laboratory Astrophysics, we aim to deepen our understanding of X-ray spectra from extrasolar sources of highly charged ions interacting with neutral gases. The most common source of these X-rays is from charge exchange (CX) and is observed in the interstellar medium (ISM), Galactic center, near Supernova, and extrasolar stellar winds. The proposal will introduce a new joint experimental facility for x-ray spectroscopy. The measurements will be augmented with charge exchange cross section and spectral computations.

The CX measurements will be conducted at the Clemson Electron Beam Ion Source (EBIS) facility (co-I's Sosolik and Marler) which has the ability to produce a beam of charge state selected ions (up to H- and He-like charge states) from injected neutral targets (e.g. Period 2 and 3 elements) with tunable kinetic energies. The PI Fogle will provide a cold target recoil ion momentum spectrometer (COLTRIMS) system from Auburn University to be mated with a high resolution x-ray calorimeter spectrometer from GSFC, to be operated by co-I's Porter and Leutenegger (GSFC) and Brown (LLNL). In conjunction, these components will allow for complete velocity-dependent measurements of x-ray emission and state-selectivity for CX with HCIs that show

predominant lines in the 1/4- and 3/4-keV bands. The COLTRIMS system will produce a neutral beam interaction target that will be crossed by an ion beam. The neutral targets will include but not be limited to He, H2, CO and CO2 to be chosen due to their relevance to astronomical observations. Upon CX, electrostatic analyzers collect the ionized target recoils and the charged-changed projectiles on time- and position-sensitive detectors in coincidence. This allows for a precise measurement of momentum transfer that correlates directly to the capture state of the CX electron(s). It also allows for the relative determination of multi-electron processes such as double capture autoionization with respect to single electron capture. An incorporated triggerable x-ray spectrometer will provide the x-ray signature in coincidence with information about the beam and target products from the COLTRIMSs will result in a true triple coincidence measurement.

Coupled with the experimental measurements will be complementary computational results. The most relevant and reliable theoretical methods for modeling CX are molecular-orbital close-coupling (MOCC) approaches, which require extensive molecular structure and collision dynamics calculations. For multi-electron targets, such as He or molecules, multi-electron processes can become important but have not been incorporated routinely in models. co-I Stancil and his team will merge current MOCC code with the atomic package AUTOSTRUCTURE to compute single and double electron capture processes which will be incorporated in cascade/X-ray emission models for benchmarking against the measurements.

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**Benjamin Mazin/University Of California, Santa Barbara**
**Improving the Spectral Resolution of Microwave Kinetic Inductance Detectors for UVOIR Astrophysics**

Microwave Kinetic Inductance Detectors, or MKIDs, are a UVOIR photon counting, energy resolving detector technology developed almost wholly under the auspices of the NASA ROSES program. Recent advances include very uniform arrays with 20,000 pixels - the largest superconducting arrays in the world. Despite recent gains in quantum efficiency and yield, the spectral resolution of R=E/dE~10 at 1000 nm remains stubbornly far from the theoretical limit of R>60 at 1000 nm. In this proposal we will focus in on energy resolution, deploying the latest techniques and materials developed for superconducting quantum qubits to lower two level system (TLS) noise, and use new traveling wave parametric amplifiers to lower amplifier noise. The combination of these two techniques will allow us to increase spectral resolution towards the theoretical limit, vastly improving the potential scientific return of future space-based MKID missions.

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**Dan McCammon/University Of Wisconsin, Madison**
**Cosmic X-ray Physics: Including a Sounding Rocket Investigation of Galactic X-ray Emission and Detector Development**

Over half the normal matter in the Universe is thought to be diffusely distributed gas at temperatures around a million degrees, but current instrumentation for studying such material is relatively poor. We propose a suborbital investigation to improve our understanding of the Galactic diffuse X-ray background that includes the development of improved instrumentation for diffuse hot gas. 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.

This work will involve a flight of our existing X-ray Quantum Calorimeter sounding rocket payload from Australia to observe the Galactic center soft X-ray bulge with 5 eV spectral resolution in the 60-1500 eV range to attempt to determine its nature and emission mechanisms. This flight should also either confirm or put upper limits on the sterile neutrino model for the 3.5 keV signal observed near the Galactic center by XMM Newton.

Our investigation also includes the development of detectors for a future sounding rocket experiment to obtain a scientifically useful spectrum of the emission in the 100-500 eV range coming from one million degree gas in the hot local bubble in the interstellar medium surrounding the Sun, with additional contributions from clumps of hot gas in the Galactic halo and interplanetary charge exchange on Solar wind ions. This will require an energy resolution of 1-2 eV FWHM and a total detector area of >2 square centimeters, a niche that larger microcalorimeter groups are not working on. Additional needs are infrared blocking filters with good transmission at these low X-ray energies and a calibration source capable of verifying the resolution and tracking the gain with sufficient accuracy. We are also assisting in a laboratory investigation of X-ray line emission from charge exchange to aid in interpreting the mixed astrophysical source of these X rays.

All of this instrumentation development is relevant to a future probe-class mission to investigate intergalactic and circumgalactic hot gas. These are the supposed repository of the "missing baryons", and key to solving the "missing metals" problem. Characterization of circumgalactic and circumcluster regions at overdensities ~200 is an essential part of understanding how matter and metals are transported into and out of galaxies, and will require a dedicated mission with a very large field of view, substantial effective area, high spectral resolution, and moderate spatial resolution.

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

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**Adam McCaughan/National Institute Of Standards & Technology**
**Megapixel arrays of superconducting UV single-photon detectors**

The LUVOIR mission will benefit from detector pixels which are highly efficient in the UV and NIR, are solar-blind, and have high count rates with low dark count rates. By these metrics, superconducting nanowire single-photon detectors (SNSPDs) are a promising detector technology, but at present no architecture exists which can read out thousands or millions of detectors -- to date, the largest demonstrated arrays have consisted of 64 pixels. We propose to advance the LUVOIR mission and the technological state of SNSPDs by implementing a multiplexing architecture capable of reading out megapixel-scale arrays of SNSPDs. In this architecture, each SNSPD pixel communicates photon detection events to a shared readout line by means of a highly localized thermal coupling. This thermally-coupled readout method not only efficiently multiplexes the pixels, but also minimizes electrical crosstalk, allowing each SNSPD pixel to operate independently. In order to bring a valuable UV detector technology closer to implementation in future missions, we propose to develop, fabricate, and demonstrate an array architecture which will enable SNSPDs to be multiplexed at the megapixel scale. Such a detector array based on superconducting nanowires would meet and exceed the requirements for future space telescopes such as LUVOIR.

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**Mark McConnell/University of New Hampshire, Durham**
**The Development of a Low Energy Compton imager for GRB Polarization Studies**

The Gamma Ray Polarimeter Experiment (GRAPE) is designed to investigate one of the most exotic phenomena in the universe ÔøΩ 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. GRAPE is a large FoV instrument with a sensitive energy range covering the peak energy distribution of GRBs. The design is based on an array of independent modules, each of which consists of an array of (high-Z and low-Z) scintillator elements read out by a multi-anode PMT (MAPMT). Our eventual goal is to fly GRAPE on a long duration balloon (LDB) platform or an orbiting platform to collect data on a significant sample of GRBs, allowing us to place constraints on fundmental GRB models. Our experience with two balloon flights (in 2011 and 2014), coupled with further design efforts focused on orbital payloads, has led to an improved polarimeter design. The new design employs a large number of optically-isolated scintillator cubes, with independent silicon photomultiplier readout, arranged in a three-dimensional array. The resulting three-dimensional location data provides a moderate level of Compton imaging capability (1 sigma angular resolution of 10-15 degrees). The imaging can not only be used to determine the GRB location (albeit with limited

accuracy), it can also be used to significantly reduce the instrumental background by limiting the impact of the cosmic diffuse flux, improving the polarization sensitivity. It is the background reduction that is most important in this case. We have already evaluated some components of this design and are now prepared to embark on an effort to fabricate a prototype to be validated on a high altitude balloon flight. The proposed four year program covers the fabrication of a prototype instrument and an engineering balloon flight Palestine in the summer of 2021.

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**Randall McEntaffer/Pennsylvania State University**
**X-ray Reflection Gratings: Limitations and Improvements**

Recent developments in off-plane diffraction gratings have placed them in the context of future NASA X-ray missions including Explorers, Probes, and the large strategic mission Lynx. Our previous NASA-supported efforts have shown improvements in diffraction efficiency, spectral resolving power, and grating alignment techniques. We recently demonstrated impressive diffraction efficiencies using blazed, large format prototype gratings. We have also demonstrated extremely high spectral resolving power using an unblazed, large format, radial profile prototype grating. However, we have not demonstrated high-performance in both efficiency and resolving power in a single grating. Our fabrication studies have identified methods for achieving the desired custom profile in a single grating. We intend to implement these methods during this project to fabricate novel reflection gratings. These gratings will be tested for diffraction efficiency and spectral resolving power to verify performance. In addition, we have also demonstrated promise for an optical alignment methodology. Using results from recent tests, key improvements have been identified that will enable achievement of grating alignment tolerance requirements. During this project we intend to align the newly fabricated gratings using an advanced optical alignment setup. The alignment will be verified using X-ray performance testing before and after environmental testing.

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**Stefanie Milam/NASA Goddard Space Flight Center**
**Submillimeter Spectroscopy of Sublimated Interstellar Ice Analogues**

Currently, high-resolution millimeter/sub-millimeter (mm/submm) spectroscopy is the only method used in the remote sensing of trace, gas phase complex species in the interstellar medium (ISM). Many of the observed species are created in ices and then released into the gas phase, but nearly all experimental studies of ice chemistry to date employ spectroscopic detection in the solid phase coupled with mass spectrometry to trace simple species OR samples are analyzed with chromatography after warm-up. Such studies therefore do not fully follow the physical and chemical routes to the formation of trace gas species in the conditions in which they form or with comparable techniques to those used in remote detection. Our team proposes to conduct a 2-year pilot study that

includes experiments on processed ices to definitively measure sublimated molecules and photoproducts and demonstrate the utility of this new technique.

Proposed Objectives for Work Plan:
- Demonstrate the ability to detect molecules during Temperature-Programmed Desorption (TPD) experiments on H2O, CH3OH, and CO samples, and optimize and calibrate the experimental set-up.
- Demonstrate the ability to detect photodesorbed species at submm wavelengths during UV photolysis of H2O and CH3OH.
- Demonstrate the ability to detect products sublimated during the exposure and warm-up of photolyzed CH3OH samples.
- Compare the results of these spectral studies with other techniques.

In order to fully understand the chemistry that leads from molecules within an ice to those in the gas phase of the ISM, we have built an experimental system to study the chemistry above the surfaces of laboratory ice samples during heating and/or photoprocessing and is complementary to ice studies conducted in the infrared (IR). This equipment is already in place and functioning at Emory University in the laboratory of co-I Widicus Weaver. The new experimental setup is designed to detect trace species that are sublimated from interstellar ice analogues by employing submm spectroscopy -- the same technique used for remote observations of complex organics in the gas phase of the ISM. Detection is accomplished by in situ spectroscopy measurements of the released gases during photoprocessing or heating of an ice. This technique offers an unprecedented sensitivity that enables the detection of desorbed photoproducts which cannot be easily distinguished using other common laboratory-based methods (e.g., mass spectrometry, or IR and Raman spectroscopies). We have previously established a proof-of-concept demonstration by detecting the sublimation of H2O from a prepared ice sample. Here, we will apply this technique to ice samples relevant to ISM.

In this new effort, we will study the photo- and thermal desorption products in a series of experiments on simple ices, including CH3OH, H2O, and CO, at temperatures ranging from ~10 to 100K to simulate environments in the ISM: including dark quiescent clouds, prestellar cores, and hot cores and hot corinos within star-forming regions.
This work represents the first effort to probe the desorbed gases from a processed laboratory ice sample at these wavelengths and provides measurements that can be used in future studies to compare directly to remote observations and indirectly to the results of interstellar chemical models. We will focus in this proposal period on detection of photodesorption and photodissociation products from pure ices as the first application of the new experimental technique. We will also establish protocols that will be applied in future proposal periods to examine the gas phase chemistry from more complex ice mixtures.

The anticipated number of new molecular detections with future missions and next generation ground-based observatories can only be imagined. Laboratory studies will be necessary for the analysis of future ground- and space-telescopes, such as ALMA, Origins Space Telescope, JWST, and SOFIA.

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**Nepomuk Otte/Georgia Tech Research Corporation**
**Development of a Photon Detection Module for the Detection of Cosmogenic Neutrinos**

The measurement of ultra-high-energy neutrinos is a long-standing quest in astroparticle physics. Neutrinos of these extreme energies are produced inside the sources of cosmic rays (CRs) and when CRs of the highest energies collide with cosmic microwave background photons. They help us identify the origin of CRs and tell us about the CR composition. The elusive nature of neutrinos and their low fluxes require large detector volumes, for example, by observing the atmosphere from balloons and space.

We prototype and test the photosensor and signal chain of a camera for a wide-angle Schmidt optics that can be deployed on a balloon or a satellite to detect neutrinos. Such an instrument detects flashes of Cherenkov light in the Atmosphere, which are the remnants of tau neutrinos interacting in the Earth. The signal chain uses siliconphotomultipliers as photosensors and AGET ASICs as readout chips. The siliconphotomultiplier is a relatively new detector concept but, nevertheless, widely used in a vast number of applications. It has features, which are of interest not only for the detection of neutrinos but other space missions as well. It is low mass, compact, and robust.

Objectives of this project include a thorough investigation of the signal chain in the lab and in the field. The results of this work help to advance the space readiness of siliconphotomultipliers, which is of interest for several proposed missions beyond the detection of neutrinos.

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**Ruth Peterson/SETI Institute**
**Stellar Infrared Spectra as a Laboratory Source for Identifying Levels of Neutral Iron and Other Elements**

Reliable, comprehensive atomic data are needed to quantify the temperature and heavy-element content of the stars and galaxies that give rise to observed fluxes and spectra. Currently, Fe I laboratory measurements of the energies of its high-lying levels are woefully incomplete. The result is a large number of unidentified absorption lines in the UV and the infrared. In the red and infrared, lines of other neutral elements such as calcium and silicon have a significant presence as well.

We have made significant progress on Fe I line identification by using high-resolution, high-quality archival ultraviolet and optical spectra of a dozen warm and cool stars as the Fe I laboratory source, relying on the warmer temperatures of these stars to populate higher excitation levels than is possible with the NIST laboratory furnace. We established

the identification and energy of 124 previously unknown Fe I levels by demanding an exact match of the positions of at least four Kurucz predicted lines of each unknown level to observed but unidentified stellar absorption features (Peterson & Kurucz 2015; Peterson, Kurucz, & Ayres 2017). For each newly-identified line that was sufficiently strong and unblended, we determined a semi-empirical gf-value by forcing its observed strength to agree with that predicted by the spectral calculations for each relevant star. Level identifications, their energy levels, and these gf-values are all part of each publication, and the complete Fe I line list with theoretical gf-values is made available on the Kurucz web site at the same time.

Here we propose to add stellar infrared spectral comparisons to our arsenal, to expand the energy range of the search for lines of an individual level. This should add enough lines to identify a sizable number of otherwise intractable levels, refine the energies of our previous determinations, and contribute reliable gf-values for all sufficiently unblended infrared lines. Our goal is to double the number of our Fe I level identifications, which should add identifications for nearly 2000 features that are potentially detectable in spectra from the UV to the mid-IR in the Sun and red giants. We plan to add identifications for other neutral species where feasible.

Our program is highly relevant to the Laboratory Astrophysics solicitation of APRA. It is a semi-empirical study designed to improve the quantitative understanding of the Fe I atom by interpreting observed solar and stellar spectra as the "laboratory" source of Fe I features in absorption with theoretical modeling of the Fe I atom and of the spectra themselves, over a panchromatic wavelength range from the ultraviolet to the proposed infrared.

Our infrared spectral observations and analysis techniques are already well suited to this task. Fig. 1 of Peterson et al. (2017) showed that our analysis reproduces very well the high-quality, high-resolution spectra in the H band obtained by others for three stars spanning a temperature range of 1500K. It also illustrates how the infrared spectra pinpoint the positions of newly-identified Fe I lines, which more tightly constrains the energies for the corresponding levels.

Infrared line identifications are particularly timely for clarifications of flux distributions of infrared sources at virtually all redshifts, such as those to be characterized with spectroscopy from JWST NIRCam, NIRspec, and MIRI and Keck NIRES. In high-resolution echelle spectra such as those from HST STIS and Keck HIRES, our findings will improve substantially the modeling of individual stellar UV spectral features and the definition of the UV continuum, essentials for deriving reliable elemental abundances.

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**Paul Reid/Smithsonian Institution/Smithsonian Astrophysical Observatory**
**On-orbit X-ray telescope figure monitoring and control for adjustable X-ray optics for the Lynx Mission Concept**

Adjustable X-ray optics are a potential technology to achieve the difficult requirements (imaging resolution, collecting area, telescope size and mass) of the Lynx mission concept - a potential successor to the Chandra X-ray Observatory. While adjustable optics by themselves have numerous technical advantages over more conventional mirror technologies, on-orbit figure monitoring offers the opportunity to utilize the full potential of adjustable optics by enabling mirror figure correction on-orbit in response to disturbances to mirror figure due to the changing thermal environment resulting from varying spacecraft exposure to the Sun. The ability to correct on-orbit for thermally induced changes represents a capability that is non-existent with any other mirror technology, and could prove critical for the first high angular resolution thin mirror x-ray telescope. Development of this capability may: (1) ease telescope thermal control system requirements, (2) ease constraints on telescope pointing with respect to the Sun, and (3) relax constraints on mirror mounting athermalization, simplifying design and building Lynx.

Our approach to achieve on-orbit figure monitoring and control is to incorporate semiconductor strain gauges directly in the fabrication of the adjustable X-ray optics, and use the measured change in local strain to determine changes in mirror temperature and shape for subsequent [remote] figure correction. Semiconductor strain gauges are used to measure strains as small as 10 parts per billion, consistent with 0.5 arcsec imaging for some bending spatial wavelengths. In this research program, we will develop the capability to direct deposit semiconductor strain gauges on piezoelectric mirror cells, investigate the limiting accuracy of strain measurements, and understand the separate sensitivity of the strain gauges to temperature changes. We will develop the technology to deposit strain gauges insensitive to mirror in-plane strain, and thereby sensitive only to mirror temperature. We will develop analysis algorithms and incorporate measured mirror temperature data to correct the measured bending strain for thermal effects, and develop suitable control algorithms to use that information to correct mirror figure. We will also investigate the short and long term stability of the strain gauges to assess feasibility for a 5 year planned mission plus telescope assembly and potential continued operation post nominal, and methods of determining and accounting for any strain gauge calibration drift.

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**Kevin Ryu/Massachusetts Institute of Technology/Lincoln Lab**
**Development of High-Density Wiring Capability for Advanced X-Ray Microcalorimeters**

Microcalorimeters offer exciting opportunities for X-ray astronomy, with energy resolution that is about a factor of 100 better than the silicon CCDs, which is the current work-horse detector technology being used in current imaging spectrometer satellite

missions such as Chandra and XMM. Instruments based on the microcalorimeters can help answer a broad range of important scientific questions as noted in the X-ray mission concepts study reported commissioned by NASA's Program Office for the Physics of the Cosmos. "Lynx" has been listed by NASA as one of the four major mission concepts to be studied in the next Astrophysics Decadal Review. One of the key instruments on such a mission would be a very large format X-ray microcalorimeter array, with an array size of over 100,000 pixels.

Currently, one of the main limitations on the achievable microcalorimeter array size is due to the challenge of fabricating high-density, high-yield microstrip superconducting wiring between all the pixels in the array, especially when the pixel pitch becomes very small. In order to realize the large focal plane array envisaged for the Lynx X-ray Microcalorimeter (LXM), with over 100,000 pixels (which is a factor of 100 larger than current state-of-the-art), with pixel pitches as small as 25 microns (corresponding to 0.5 arc-seconds) in some regions, fine-pitch multi-level superconducting wiring with high yield is essential. To achieve this, we propose to demonstrate the viability of this approach by building prototype large-format microcalorimeter arrays as a collaboration between MIT Lincoln Laboratory (MIT/LL) and NASA/GSFC. In this approach, MIT/LL would fabricate the base-layer multi-level superconducting wiring layer, taking advantage of over a decade of investment in infrastructure and process development that makes MIT/LL a leader in this field of development. GSFC would then fabricate and test the microcalorimeter arrays, integrating with the MIT/LL wiring. MIT Lincoln Laboratory recently demonstrated a functional chip with a world record integration of over 800,000 Josephson Junctions, in a process utilizing eight levels of superconducting wiring layers each with submicron resolution.

The goal of the proposed effort is to demonstrate the integration of the high-density wiring capability with GSFC's new advanced X-ray microcalorimeters using wiring designs consistent with being able to read out full arrays of the scale needed for the LXM. Since there are currently two leading microcalorimeter technologies under development focused on meeting LXM requirements, transition edge sensors (TES) and metallic magnetic calorimeters (MMC), we will develop separate designs for each, and fabricate these designs together for efficiency. If the proposal is accepted, GSFC will support this development as part of an existing work package titled, "Advanced X-ray Microcalorimeters".

We will optimize the process and design parameters for both detector technologies, and increase sensitivity for the MMCs by using as thin an insulation layer as possible between the sensor and pick-up coil. We will also generate more advanced wiring designs for hybrid arrays utilizing more layers of wiring, incorporating superconducting ground-plane layers in-between micro-strip wiring to avoid cross-talk, and allowing heat-sinking fabrication as would be needed for a full scale array (MMCs and TESs). Further benefits of high-density wiring, such as miniaturization of components, will be investigated.

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**Daniel Savin/Columbia University**
**Laboratory Studies of Dissociation Recombination with Cold Molecular Ions for Diffuse Cloud Studies by NASA Astrophysics Missions**

We propose to advance our understanding of how diffuse atomic clouds transition to diffuse molecular clouds, an important first step in the star formation process. Observing this transition is challenging as H2 lacks a permanent dipole moment, making direct detections extremely difficult. Also, the commonly used H2-surrogate CO is readily photodissociated in diffuse clouds. We will improve the community's ability to use OH+, HCl+, and ArH+ to trace out the astrophysical properties of this transition. These molecules enable us to measure in diffuse clouds the cosmic ray ionization rate of atomic H, to infer the molecular hydrogen fraction, to constrain the far-ultraviolet interstellar radiation field, and to use proxies to trace out the difficult-to-detect H2 molecule and infer H2 column densities and masses.

Using OH+, HCl+, and ArH+ to trace out the properties of diffuse clouds requires an accurate understanding of the underlying gas-phase astrochemistry controlling the abundances of these molecules. Key to this are reliable rate coefficients for dissociative recombination (DR) of electrons with OH+, HCl+, and ArH+. Accurate quantum mechanical calculations are lacking due to the theoretical and computational challenges of handling the many-body systems and the infinite number of intermediate states involved. Laboratory measurements are the only reliable means to generate the needed DR data. But previous experimental work is of limited use due to the moderate to high levels of internal excitation of the molecular cations (typically ~300-1000 K), which is much hotter than diffuse cloud temperatures.

We will carry out the first DR measurements for OH+, HCl+, and ArH+ with internal excitations of ~10 K, generate DR data suitable for astrochemistry, incorporate these data into diffuse cloud models, and investigate the astrophysical implications of our new chemical data. The DR measurements will be carried out using the recently commissioned heavy ion Cryogenic Storage Ring (CSR) which is located at the Max Planck Institute for Nuclear Physics (MPIK) in Heidelberg, Germany. No other facility in the world is capable of carrying out the proposed DR measurements. Furthermore, we will investigate the astrophysical implications of our new DR data using astrochemical models which we have developed to interpret diffuse cloud observations.

For data management, we will publish our findings in refereed journals. The data behind the figures and tables in our papers will be made available electronically through supplementary material provided with the published papers.

Our research into diffuse clouds addresses NASA's Strategic Goal 1: "Expand the frontiers of knowledge, capability, and opportunity in space". The expected advances in knowledge from our work meets NASA's Strategic Objective 1.6: "Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars". Our findings will thereby enable us to address the Science Goal of NASA's Science Mission Directorate Astrophysics Division, namely "[e]xplore the origin and

evolution of galaxies, stars, and planets that make up our universe". Specific NASA missions that our proposal is relevant to include: Herschel Space Observatory, Hubble Space Telescope, Infrared Space Observatory, Kuiper Airborne Observatory, and Stratospheric Observatory for Infrared Astronomy.

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**Gene Serabyn/Jet Propulsion Laboratory**
**Advanced Vortex Phase Masks And Techniques**

The optical vortex coronagraph has shown great performance advances over the last several years, both in the laboratory and on the world's largest telescopes. Our primary objective here is to push the development of optical vortex phase masks in the directions needed by NASA for coronagraphic space missions currently under study - this includes masks capable of deeper contrasts and broader bandwidths for missions such as Habex and LUVOIR, and removing polarization sensitivity and increasing throughput by developing scalar vortices.

Our proposed work has several specific goals aligned with individual mission needs. 1) We will extend the high-contrast bandwidth performance of liquid crystal polymer masks; bandwidths of 20-30% would minimize the number of vortex masks that need to be flown on any given mission, and would allow their effective use with spectrometers. 2) We will develop masks capable of reaching 10e-10 contrast. 3) We will develop masks with a reflective central spot conducive to use with low-order wavefront sensors. 4) We will develop scalar vortices without intrinsic polarization sensitivity. These masks will be tested on our existing Infrared Coronagraphic Testbed at JPL and High Contrast Spectroscopic Testbed at Caltech. The ultimate high-performance, broadband visible wavelength masks would be made available for testing in JPL's general purpose coronagraphic testbed (as part of the SAT/TDEM program, if approved).

The ability to image faint exoplanets and disks very close to bright stars is key to NASA's strategic goal of creating a census of extrasolar planets and measuring their properties, and calls for the development of very high-contrast coronagraphic techniques, such as the vortex phase mask, which can reach very small angles. Our planned work will allow us to produce high-quality vortex phase masks specifically needed by NASA's high contrast coronagraphic mission concepts such as Exo-C, Habex and LUVOIR. In the near term, our masks will be used with the Picture-C coronagraphic balloon, and various ground-based telescopes.

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**Erik Shirokoff/University Of Chicago**
**Advanced On-Chip, Submm-Wavelength Spectrometers Using Superconducting Detectors.**

This program will develop and characterize ultra-sensitive on-chip spectrometers covering the sub-mm and mm-wavelength observing bands from 3 mm to 230 microns. This builds upon a successful program, SuperSpec, which has demonstrated the basic filterbank operation, a proof of principle that large-format spectrographs for the far-IR and submillimeter can be miniaturized onto silicon chips. Using superconducting mm-wave transmission line components and extremely small-volume kinetic inductance detectors (KIDs), we have constructed and are currently preparing to deploy a ground-based demonstration instrument covering the 1 mm atmospheric band.

This is a key enabling technology for the next-generation cryogenically-cooled far-IR flight missions as well as near-future sub-orbital platforms such as balloon-based spectrometers and future SOFIA instruments. However, obtaining full scientific return from these powerful future far-IR missions requires 3 crucial advances in the SuperSpec filerbank technology: (1) improving filterbank loss by a factor of >10; (2) improving the detector sensitivity in order to meet the requirements of the low-background space platforms; (3) extending operation from the mm-wave to 230 microns.

In order to meet these goals, we will build on our experience with superspec, as well as advances in dielectric material quality, fabrication techniques, and kinetic-inductance detector (KID) design approaches to accomplish each of these goals. A successful demonstration of these technologies will not only benefit future spectroscopic instruments, but will be immediatly useful for instruments operating in the submm and for KID-based instruments designed for a wide range of science targets.

We will begin by adjusting the filterbank electromagnetic design for a silicon inner layer dielectric as this promises factors of up to 50 times lower loss than the current materials. We will build and test silicon-dielectric prototypes, beginning at the current 200--300 GHz band, but then moving up to the 400--700 GHz band. We will explore both deposited amorphous silicon (a-Si) using a new low-loss recipe as well as a crystalline silicon (c-Si) "fliped-SOI" process using silicon-on-oxide (SOI) wafers.

Meanwhile we will develop more sensitive KIDs to embed in the spectrometers. In particular, we will adapt our spectrometer design to accommodate very small volume aluminum KIDs, which promises significant improvements in sensitivity required for low-loading applications.

Finally, we will explore superconducting transmission lines made from both sputtered and atomic layer deposited (ALD) NbTiN and NbN. These materials have a transition temperature much higher than niobium and should allow us to extend the operation of our basic filterbank architecture to THz frequencies.

In addition to a number of test structures sample devices, we will produce a series of four demonstration pixels: [FB-1]: a prototype covering the full 200-300 GHz band with resolving power (R) of at least 1000 and negligible dielectric loss. [FB-2]: a similarly low-loss submm prototype covering the 850-650 micron bands with similar resolving powers. [FB-HR]: a mm-wavelength device designed to achieve the highest possible resolving powers, targeting R~5000. [FB-T]: a sparse filterbank covering regions of the 0.8-1.3 THz filterbank to demonstrate high-frequency operation. The first three of these devices are intended to be field-ready at the conclusion of this program, and the fourth easily adapted for future instruments.

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**Johannes Staguhn/Johns Hopkins University**
**Development of an Ultra-Stable Mid-Infrared Detector Array for Space-Based Exoplanet Transit Spectroscopy**

The discovery of the Trappist-1 system, which consists of an ultra cool M-dwarf star orbited by 7 planets, 3 of which are located in the habitable zone, has demonstrated that these types of plane-tary systems around dwarf stars are very common. Such systems are well suited for the study of exoplanets. In particular the search for bio-signatures in the atmosphere of planets in the habita-ble zone around M-stars will be a high-priority science goal of future space missions. The mid-infrared (mid-IR) band between 6 and 15 microns is probably the best available band for this science, because the band contains spectral lines of methane, ozone, and nitrous oxide. The coexistence of those in a planet's atmosphere would be a very strong indicator for life on the planet.

Mid-IR transit spectrometers on future space missions such as Origins Space Telescope (OST) will be the instrument of choice to detect these bio-signatures in exoplanets around M-dwarfs. However, current mid-IR detectors are based on impurity band conduction (IBC) devices such as Si:As detectors, which have significant problems with stability. As a result, those detectors are not expected to provide the required stability of ~ 5 ppm needed for a reliable detection of the aforementioned spectral lines. While efforts are under way to improve IBC detectors, it is un-clear how far the performance can be improved.

Here we propose the development of an ultra-stable mid-IR Array Spectrometer demonstration for Exoplanet Transits (MIRASET), which includes a calibration system that, as we show, is needed to achieve the required sensitivity for the detection of atmospheric bio-signatures in habitable-zone planets around M-dwarfs. The spectrometer will be demonstrated with arrays of Transition Edge Sensor detectors (TES). These devices are known to be intrinsically very stable and the required detector parameters (sensitivity, dynamic range) for space based mid-IR transit spectroscopy can be easily met with existing devices. No new detector developments are re-quired. This project will include the development of a high-accuracy calibration system with a stable reference source which itself will be monitored by an out of band (0.5 Œºm) detector at a wavelength at which the precision of the measurements exceeds that of an in-band

calibration. This scheme will allow for real time monitoring of the detector gain, which we anticipate will result in a background limited performance with the required stability of better than 5 ppm for the detection of bio-signatures in a designated spectrometer flying e.g. on the OST space tele-scope, and as such will help to answer one of NASA's main questions: "are we alone?"

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**Eric Switzer/NASA Goddard Space Flight Center**
**Measuring the Cosmological Evolution of Gas and Galaxies with the EXperiment for Cryogenic Large-aperture Intensity Mapping (EXCLAIM)**

The EXperiment for Cryogenic Large-aperture Intensity Mapping (EXCLAIM) is a high-altitude balloon spectrometer designed to deepen our understanding of star formation in a cosmological context. It will map the sub-mm emission of redshifted carbon monoxide (CO) and singly-ionized carbon ([Cii]) lines in windows comprising $0 < z < 3.5$. These lines trace the precursors of star formation but have only preliminary characterization beyond the nearby universe, with most previous efforts limited to the brightest objects or galaxies selected in other surveys. Rather than detect individual galaxies, EXCLAIM will measure the statistics of brightness fluctuations of redshifted, cumulative line emission. This approach is known as intensity mapping, and the Enduring Quests Daring Visions Roadmap establishes it as a priority in the Visionary Era, to "completely map the content of selected volumes of space that represent slices through all of cosmic time." EXCLAIM is a pathfinder to future missions that will probe early star formation and reionization. A blind, complete census of redshifted CO and [Cii] addresses New Worlds, New Horizons Decadal Survey priorities to understand baryons in galaxies and the context of their dark matter halos.

EXCLAIM will address significant outstanding questions: What factors led to the dramatic decline in star formation from z~2 to the present? What is the typical abundance and excitation of the molecular gas which forms stars? How well does CO trace H_2 in our galaxy? Is intensity mapping a viable approach to push to high redshift? We will address these questions by flying six redundant spectrometers configured from 421-540 GHz (lambda/delta_lambda=R=512), permitting cross-correlation of [C ii] 158 um and CO J=6-5, 5-4, and 4-3 emission with galaxies in the Baryon Oscillation Spectroscopic Survey (BOSS).

EXCLAIM's strategy is to start with the most feasible intensity mapping demonstration: the brightest emission lines at relatively low redshift in cross-correlation with a rich spectroscopic galaxy catalog. EXCLAIM is the only CO/[C ii] intensity mapping survey specifically designed for corroborated cross-correlation, and takes advantage of overlap with BOSS that is only possible in a conventional flight from the North. Conventional flights simplify logistics and reuse, making this a versatile instrument for testing sub-mm technology in a space-like environment.

Due to dramatically reduced column depth and pressure broadening at float, the atmosphere has windows that approach space-like photon backgrounds and are significantly darker than emission from 300 K telescope optics. To exploit these low photon backgrounds, EXCLAIM employs an all-cryogenic telescope (1.5 K) with a 74 cm projected aperture coupled to the microSpec on-chip spectrometer. microSpec implements an on-chip Rowland spectrometer coupled to kinetic inductance detectors. Lithographic construction achieves mass and volume much lower than free-space gratings, making the architecture appealing for future space-borne instruments.

Our team has led the field in the development of large, balloon-borne cryogenic apertures, the on-chip Rowland spectrometer, and intensity mapping through cross-correlation. EXCLAIM reuses the design of the Primordial Inflation Polarization ExploreR (PIPER) gondola, housekeeping electronics, software, and 100mK cooling with a continuous adiabatic demagnetization refrigerator. Commissioning (2021) and science (2022) flights are planned. Using data from these flights, we will constrain models of galaxy evolution, and enable new approaches to studying our universe.

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**Varun Verma/National Institute Of Standards & Technology**
**Superconducting Nanowire Single-Photon Detectors for Exoplanet Spectroscopy in the Mid-Infrared**

Superconducting nanowire single-photon detectors (SNSPDs) have emerged as the highest-performing single-photon detectors from the UV to the mid-infrared. These detectors combine very high efficiencies (> 90% in the infrared at 1.55 um), ultralow jitter (~100 ps or less), zero readout noise, and very low dark count rates ( < 10-4 Hz) . Recently, we have developed SNSPDs operating in the mid-infrared from 2 - 7 um. Basic models of the physics of the detection process suggest that by reducing the width of the nanowires to ~ 10 - 20 nm, and tuning the composition of the superconducting material, one may be able to demonstrate single-photon detection at wavelengths extending to 60 um. In addition, recently-developed multiplexing techniques should allow the fabrication of small arrays consisting of ~ 1000 pixels or more, which could potentially be useful for spectroscopy and imaging. The primary advantages of using SNSPDs in this wavelength range are high stability of detector gain as a function of temperature and bias current, true single-photon sensitivity, zero readout noise, and extremely low dark count rate. In addition, SNSPDs would not suffer from many of the problems inherent with arrays of currently used blocked impurity band (BIB) detectors such as reset anomaly, last-frame effect, droop, drift, multiplexer glow, and latent images.

One of the many goals of the Origins Space Telescope (OST) is the study of exoplanets. This study makes up roughly one-third of the science case for OST. In particular, part of OST's mission is the detection of biosignatures such as ozone, nitrous oxide, and methane in the atmospheres of Earth-sized planets transiting the habitable-zones of nearby stars. The spectroscopy of exoplanet atmospheres requires mid-infrared detector arrays combining high stability over time (a few ppm over several hours), high sensitivity

(ideally single-photon sensitive), high system efficiency, and low noise. We propose to develop kilopixel-scale arrays consisting of single-photon-sensitive superconducting nanowire detectors that are sensitive in the range of 6 - 20 um wavelengths that would meet the requirements for any future instruments directed towards exoplanet transit spectroscopy, for example the mid-infrared spectrometer and coronagraph (MISC) planned for the Origins Space Telescope. As outlined above, the excellent stability and single-photon sensitivity of these detectors would be ideal for such an application requiring data collection over the course of hundreds of transits of an exoplanet across its parent star, each of which can last several hours or longer.

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**Joaquin Vieira/University Of Illinois, Urbana-Champaign**
**The Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE): a Next-Generation Experiment for Galaxy Evolution Studies**

Understanding the formation and evolution of galaxies over cosmic time is one of the foremost goals of astrophysics and cosmology today. The cosmic star formation rate has undergone a dramatic evolution over the course of the last 14 billion years, and dust-obscured star forming galaxies (DSFGs) are a crucial component of this evolution. A variety of important, bright, and unextincted diagnostic lines are present in the far-infrared (FIR) which can provide crucial insight into the physical conditions of galaxy evolution, including the instantaneous star formation rate, the effect of AGN feedback on star formation, the mass function of the stars, metallicities, and the spectrum of their ionizing radiation. FIR spectroscopy is technically difficult but scientifically crucial. The FIR waveband is impossible to observe from the ground, and spans a crucial gap in the spectroscopic coverage between the Atacama Large Millimeter/submillimeter Array (ALMA) in the sub/mm, and the James Webb Space Telescope (JWST) in the mid-IR. Stratospheric balloons offer a platform which can outperform current instrument sensitivities and are the only way to provide large-area, wide-bandwidth spatial/spectral mapping at FIR wavelengths.

We propose an aggressive program of instrumentation development and experimental study called the Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE), with the goal of demonstrating the key technical milestones necessary for FIR spectroscopy. STARFIRE will provide a technological stepping stone to the future space-borne instrumentation such as the Origins Space Telescope (OST, formerly the Far-IR Surveyor) or a Probe mission. STARFIRE will address the two key technical issues necessary to achieve this:
1) Low-emissivity, high-throughput telescope and spectrometer optics for the FIR;
2) Background-limited detectors in large format arrays, scalable to >10,000 pixels.
We will do this by constructing an integral-field spectrometer from 240 - 420 microns coupled to a 2-meter low-emissivity carbon-fiber telescope. The development of the optics will utilize the capabilities of the Arizona Steward Observatory mirror lab and the unique expertise of our spectroscopic experts to create high-throughput optics. For the detectors, we will leverage the highly advanced development work of the Caltech / JPL

group to develop and field kinetic-inductance detectors (KIDs). KIDs represent the most promising route to economical, large format submillimeter detector arrays.

In addition to the development and demonstration of crucial technologies for the FIR, STARFIRE will perform groundbreaking science. We will survey two 0.1 square degree fields centered on GOODS-S and the South Pole Telescope Deep Field, both of which have rich ancillary data. Scientifically, we will:
1) Obtain spectroscopic line detections of ~100 galaxies in the atomic fine structure lines [CII](158 microns) (at $0.5<z<1.5$), [NII](205 microns) (at $0.2<z<1$ ), [OI](63 microns) (at $2.8<z<5.7$ ) and [OIII](88 microns) (at $1.7<z<3.8$);
2) Establish the mean star formation rate (proportional to [CII] luminosity), metallicities (proportional to the [CII]/[NII] ratio), and AGN content (proportional to the [OIII] luminosity) of galaxies using a stacking analysis of known sources in the field;
3) Produce deep maps of the 3D structure of the Universe by redshift tomography ("intensity mapping") with [CI], and [CII] X [NII] cross-spectra, to constrain the cosmic star formation history at cosmic noon, and lay the important groundwork for extending this technique to even higher redshifts to eventually explore the epoch of reionization.

We note there is significant discovery potential with STARFIRE, since it will be probing an under-explored wavelength range with unprecedented sensitivity using a new astrophysical technique. STARFIRE is critical to the NASA roadmap of developing technologies for a future FIR space mission.

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**Benjamin Williams/University of California, Los Angeles**
**Frequency-Agile And High-Power Terahertz Laser Local Oscillators**

Many molecular species that comprise 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, validate theories of galactic evolution, and to probe protoplanetary disks. The next frontier for heterodyne spectroscopy is the 2-6 THz region - a spectral range which is well matched to the use of terahertz quantum-cascade (QC) lasers as local oscillators (LOs). This proposal looks beyond the state-of-the-art, to the development of large format heterodyne arrays which contain on the order of 20-200 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 mixer power requirement, but to account for large 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 where observation time is limited.

In our recent work, we demonstrated a new architecture for terahertz quantum-cascade (QC) lasers capable of delivering scalable output power a near-diffraction limited output beam: the quantum-cascade vertical-external-cavity-surface-emitting-laser (QC-VECSEL). The enabling technology for this proposed laser is an amplifying metasurface reflectarray, which is made up of a sparse array of low-quality-factor antenna-coupled sub-cavities loaded with QC gain material. The sub-cavities on the metasurface radiate coherently into a high-quality-factor external cavity mode, which sets the beam shape and allows for scalable power combining. In previous work, we made two key proof-of-concept demonstrations: (a) a 3.4 THz QC-VECSEL which emitted continuous-wave power of 5 mW in a single-mode and in a high-quality beam at a temperature of 83 K with a wall plug efficiency of approximately 0.13%, and (b) the ability to continuously tune the frequency of QC-VECSEL by changing the cavity length, albeit with inconsistent beam pattern, power levels, and occasional multi-moding.

Our overarching research goal in this successor proposal is demonstrate the QC-VECSEL as a credible frequency-agile local-oscillator. In the first theme, we propose to achieve 10x improvement in continuous-wave wall-plug efficiency from ~0.1% to 1% at 77 K, to allow generation of 10-100 mW with 1-10 W power dissipation at frequencies of 2.7 and 4.7 THz. In the second theme, we propose to demonstrate robust and repeatable tunability of a single mode over 15% of its center frequency near 2.7 THz while maintaining beam quality and power. In the third theme, we will demonstrate frequency-locking of the QC-VECSEL to a microwave reference over its tuning range, which is necessary to stabilize the LO output to resolve complicated lineshapes and allow long receiver integration times. This will be a critical demonstration, as the VECSEL cavity is very different than the monolithic THz QC-lasers that have been frequency/phase locked in the past. Furthermore, demonstration of this level of performance in terms of power, efficiency, beam quality, and tunability will be firsts for any type of stabilized THz QC-laser under consideration for a local oscillator, and would enable new possibilities for frequency-agile heterodyne instruments that could access multiple lines of interest. Additionally, in the course of the program, we will demonstrate the first QC-VECSELs at 4.7 THz which is close to the important OI line 4.745 THz (a major coolant for photo-dissociation regions in molecular clouds).

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**David Windt/Reflective X-Ray Optics LLC**
**Hard X-ray Multilayer Coatings for HEX-P and Other Future Missions**

OBJECTIVES: To enable construction of next-generation hard X-ray telescopes, this project aims to (a) develop Co-, Ni-, and Pt-based X-ray multilayer coatings having high reflectance up to ~200 keV, in order to maximize telescope effective area and extend energy coverage beyond NuSTAR, and (b) develop techniques to mitigate multilayer-coating-stress-induced deformation of thin-shell mirror substrates, in order to achieve hard X-ray telescope angular resolution of 15 arc-seconds or better.

METHODS/TECHNIQUES: The proposed project comprises two parallel investigations: one focuses on the development of new hard X-ray multilayers, the other on the development of new deposition techniques that will work with these multilayer coatings to mitigate stress-induced deformations of thin-shell mirror substrates. In support of the first investigation, new multilayers will be designed, fabricated, and tested using established procedures: both depth-graded and aperiodic multilayers will be designed with our IMD software; prototype coatings will be deposited using magnetron sputtering; coating structure and properties will be analyzed using X-ray diffraction, atomic force microscopy, transmission electron microscopy, wafer curvature, and other techniques as required; and "at-wavelength" performance will be measured using our novel hard X-ray reflectometer. Film deposition conditions and techniques that yield optimum performance will be identified, and in particular a new ion source will be used for ion-assisted growth of light metal films in order to realize sputtered Ni- and Co-based multilayers having lower roughness, and thus higher reflectance, than can be otherwise achieved. In support of the second investigation, two complementary techniques will be explored to mitigate substrate deformation resulting from multilayer film stress, extending to hard X-ray multilayer coatings similar techniques that are now being developed for Ir-based coatings operating at lower energies for Lynx. The two mitigation techniques are: 1) stress-balancing using Cr adhesion layers; and 2) double-side coatings acting in opposition. Both techniques will be explored in order to identify the most effective approach. Surface figure of both glass and silicon thin-shell segments, provided by GSFC, will be measured before and after coating using optical interferometry. Two-dimensional control of coating thickness, using novel technology already under development, will be used to spatially control film stress and thereby achieve sufficient figure preservation in thin-shell substrates.

SIGNIFICANCE: Coating performance drives both effective area and angular resolution in the case of light-weight X-ray telescopes constructed from thin-shell mirror substrates. Without the development of new multilayer coatings having higher X-ray reflectance, and operating at higher X-ray energies, it will not be possible to meet the sensitivity and energy coverage requirements of future missions such as HEX-P. Additionally, without new techniques that sufficiently mitigate coating-stress-induced substrate deformations in thin-shell substrates, it will not be possible to achieve the higher angular resolution required for HEX-P or other future missions enabled by multilayer-coated X-ray telescopes designed to address key science objectives of NASA's Physics of the Cosmos (PCOS) program.

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**Andreas Zoglauer/University of California, Berkeley**
**Applying Supervised Machine Learning Approaches to the Reconstruction of High-energy Tracked Compton and Low-energy Pair Events**

Combined Compton-scattering and pair-creation telescopes are a key technology for future observations in the gamma-ray energy range. They are the design of choice of two envisioned future satellite missions, ComPair/AMEGO (Moiseev+ 2017) and e-

ASTROGAM (De Angelis+ 2017), and will allow us to perform unprecedented measurements of extreme particle accelerators (e.g. GRBs, AGN), study the life cycle of matter generated in stars and supernovae, search for dark matter signatures, and much more.

The standard analysis toolset used by both ComPair/AMEGO and eASTROGAM is MEGAlib (e.g. Zoglauer+ 2006). Its default set of algorithms goes back to the development of the MEGA Compton and pair telescope (Zoglauer 2005). However, while the event reconstruction for untracked Compton events has been advanced in the context of COSI (e.g. Kierans+ 2017), the intermediate energy band (2-3 MeV to ~20 MeV), ranging from tracked Compton events to low-energy pair events, has not seen similar advances. This energy range faces several key data science challenges which have to be overcome, such as (1) determining the direction-of-motion of short electron tracks with 2-4 interacting layers, (2) distinguishing single tracks from Compton recoil electrons which perform turn-arounds (e.g. going from upward to downward moving) from low-energy pair events with large opening angles, (3) deciding if the event is a charged particle, shower, pair, or Compton event with a single or multiple tracks, (4) determining energy lost in passive material for electrons going from tracker to calorimeter or in the structure of the tracker and in non-functioning strips/wafers (both are especially important for Compton events which require that the full energy is measured for correct reconstruction), (5) distinguishing the hits in the calorimeter caused by electrons moving from tracker to calorimeter from Compton interactions of the scattered gamma ray, (6) determining the full energy of electron and positron from sometimes very nearby interactions in the calorimeter as an uneven energy distribution between electron and positron influence the origin determination, and (7) identifying Bremsstrahlung hits in the detector, especially for Compton events as they need to be distinguished from additional Compton scatters.

For COSI, we have recently seen significant improvements in the performance of the event reconstruction approaches for (untracked) Compton events using supervised machine-learning approaches such as random forests of boosted decision trees and neural networks to find the correct path of the gamma rays in the COSI detectors. Here we propose to apply the latest machine learning approaches to the reconstruction of tracked Compton events and low-energy pair events. The approach taken will be similar to what was done for COSI: using simulations, where the event type and path are well known, train a set of different machine learning approaches (random forests, various neural networks), to perform: (1) decision of event type, (2) clustering of hits which belong together e.g. tracks, (3) determining start point of tracks, (4) determination if hits are from Compton interactions or Bremsstrahlung, (5) estimate energy losses in in passive material, (6) determining the Compton path using electron track information, and more. The best metric to determine the performance of the new approaches is the same as the one used for COSI, the angular resolution measure, ARM, as well as the scatter plane deviation for the track direction. All code developments will be available within the publicly available MEGAlib framework.

This proposal for "development of new data analysis methods for future satellite missions" will help unlock the full performance of future tracking Compton and pair telescopes in the difficult transition region, and ultimately further NASA's goal to "discover how the universe works".

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