Below are the abstracts of proposals selected for funding for the Outer Heliosphere Guest Investigators 2019 program. The abstracts are listed alphabetically by Principal Investigator (PI) name and include institution and proposal title. Fifteen compliant proposals were received in response to this opportunity. On March 5, 2020, five proposals were selected for funding.

James Cordes/Cornell University
Interstellar Turbulence Near the Heliospheric Boundary

Our primary goal is to understand the local interstellar medium (ISM) as probed by the Voyager Interstellar Mission (VIM) in terms of a global picture for the ISM that includes multiple gas phases and, in particular, residence of the solar system in a low-density cloud in a local hot bubble extending past nearby stars. Local plasma densities (from VIM) and inferred densities and magnetic fields from long lines of sight to pulsars will be analyzed in terms of the density power spectrum and magnetic-field/density correlations. We will also use extant multi-epoch observations of bow shocks around pulsars produced by their relativistic winds and supersonic motions.

Previous work has indicated consistency of VIM and radio astronomy data with a Kolmogorov spectrum extending over 16 orders of magnitude in length scale. However, spacecraft and astronomy data have not been fully reconciled. Pulsar data indicate a high dynamic range in spectral amplitude, requiring consideration of distinct interstellar density and temperature regimes. The density spectrum also needs linkage to the detailed interstellar environment of the solar system. We will assess whether the wide apparent spectral extent of the density spectrum is due to a turbulent cascade from the largest (10-100 parsec) to the smallest (10 m) scales that have been estimated or, alternatively, that turbulence exists differs between interstellar phases.

The specific activities of the project are to (1) analyze VIM data with particular emphasis on the local interstellar electron density and magnetic field events; (2) better characterize the wavenumber spectrum; (3) compare in situ results with pulsar data on a variety of lines of sight; and (4) model local ISM structure using all data.

Data from both Voyagers will be analyzed, including new subaveraging methods of power spectra from the Plasma Wave Subsystem to seek weak plasma lines during quiescent periods. These will be aggregated with published analyses of strong plasma lines from active periods to maximize the range of length scales for electron density estimates. As appropriate, magnetometer data from Voyager 2 will also be analyzed. The work will expand greatly on Lee & Lee (2019, DOI:10.1038/s41550-018-0650-6), which analyzed only Voyager 1 data and did not make use of the spectral range implied by complementary, extensive pulsar data sets.
Pulsar data comprise dispersion measures (electron column densities), scattering measurements (intensity scintillation and pulse broadening from multipath), and Faraday rotation, all underlying existing models for the Galactic distribution of free electrons and their turbulence spectrum. The PI has developed two global Galactic models over the past 25 years that are widely used. However, smaller scale features, such as the local ISM are not yet well modeled. We propose developing such a model through the combined analysis and interpretation mentioned above. Recent parallax distances of pulsars from interferometry and pulse timing allow three-dimensional modeling of the local mean and RMS density from integrated quantities.

The proposal team includes members who obtained scattering, parallax, and bow-shock data (Chatterjee, Cordes) and have used it for large scale Galactic modeling (Cordes). Co-I Chatterjee will aggregate data and, with PI Cordes, will mentor the graduate student, who will analyze Voyager data in collaboration with Co-I Spangler, who has worked on data and theory for both the ISM and the interplanetary medium, including characterization of interstellar turbulence, and will serve as a liaison with the instrument team at U. Iowa for the Plasma Diagnostic Experiment on the Voyager spacecraft.

Understanding the local ISM and solar-ISM interactions with reference to large-scale properties is closely aligned to Goal 3 of the Heliophysics Decadal Survey and any future interstellar missions by NASA.

Vladimir Florinski/University of Alabama in Huntsville

The Heliopause: the Magnetic Boundary of the Solar System

Humankind has achieved a crucial milestone in space exploration with the two Voyager space probes crossing the magnetic boundary of the solar system, known as the heliopause, and, for the first time, entering the galactic space. We propose a focused investigation to elucidate the global dynamical properties of the heliopause based on Voyager plasma, magnetic field, and energetic particle observations, with the global context provided by IBEX all sky maps and spectra of energetic neutral atoms, conducted by a team of scientists with experience in both disciplines. The project will aim to answer the following two science questions: (1) What is the role of magnetic interchange instability in aligning the magnetic fields on the two sides of the boundary?, and (2) What is the nature of the plasma depletion layer (PDL) on the interstellar side of the boundary?

There is substantial evidence that Voyager 1 observed interchanged magnetic flux tubes in the so-called heliopause transition regions (HTR). We previously argued that the upwind portion of heliopause is unstable with respect to magnetic interchange and that the HTR is permeated by filamentous flux tubes containing interstellar plasma. The situations is different at Voyager 2, which did not observe flux tubes in the heliosheath, but encountered two possibly related structures beyond the heliopause. The second key Voyager 1 observation is the density ramp on the interstellar side of the heliopause, several AU in width, which is thought to be a signature of a PDL. More information about the PDL would be obtained from Voyager 2 plasma and magnetic field
observations once they are fully processed and analyzed. Global MHD models can reproduce some of the heliopause instabilities (i.e., those driven by charge exchange), but not the filamentous nature of magnetic interchange. A density ramp is also present in MHD models, but it does not have all the features of the PDL which depends on the anisotropy of the plasma temperature absent from ideal MHD.

This investigation will consist of a data analysis effort and a modeling component. We will perform a thorough analysis of Voyager 1 and 2 magnetometer and Voyager 2 plasma instrument data to characterize the flow patterns inside the HTR. Voyager 2 CRS data will then be used to investigate the properties of the flux tube-like structures based on time delay analysis between multiple LET telescopes. We will also analyze all available interstellar data for about 1 year since each respective heliopause crossing. To answer the science question, we will perform MHD and CGL-MHD simulations of the surface of the heliopause at very high numerical resolution. The team is in a unique position to carry out this work, having jointly developed an innovative triangular geodesic mesh model ideally suited for high-resolution studies of stability of thin convex shells such as the heliopause. This investigation will elucidate the nonlinear response to the instability and the formation and structure of the HTR, as well as the nature of the PDL and the plasma temperature anisotropy in the region.

The project directly addresses both the central objective of the Voyager interstellar Mission, to "Extend the NASA exploration of the solar system beyond the neighborhood of the outer planets to the outer limits of the Sun's sphere of influence, and possibly beyond", and Science Goals 3 and 4 of the Heliophysics Decadal Survey, to "Determine the interaction of the Sun with the Solar System and the interstellar medium" and to "Discover and characterize fundamental processes that occur both within the heliosphere and throughout the Universe". The border between the solar wind-filled heliosphere and the surrounding interstellar cloud is, symbolically, also the boundary between space science and astrophysics. This project will tackle its challenges by bringing together experts in both heliophysics and astrophysics to the benefit of both science communities.

**Seth Redfield/Wesleyan University**

**Exploring the next space frontier: Optimizing trajectories of future spacecraft based on the outer heliosphere and its interstellar environment**

The Sun's immediate environment controls the size, shape, and properties of the outer heliosphere and the flow of gas and dust into the solar system. For this reason, it is essential to place the measurements obtained by Voyager, IBEX, New Horizons, and future spacecraft traversing the heliopause in the broader context. Planning for future missions such as Interstellar Probe, including their instrumentations and optimal spacecraft trajectories, requires prior knowledge of the physical properties of the local interstellar medium (LISM) and its spatial distribution. Our studies of the LISM provides a unique external perspective for answering the following questions:

(1) Is the inflowing neutral and ionized helium gas measured by Ulysses, Stereo, and IBEX inconsistent with the flow vector of gas in the Local Interstellar cloud (LIC)? (2) Is
the heliosphere completely surrounded by interstellar gas containing neutral hydrogen, or are there directions where the surrounding gas is fully ionized?

(3) Our preliminary model shows that the Sun is surrounded by four partially ionized interstellar gas clouds with different flow vectors and temperatures. Is this model valid? If so, the heterogeneous properties of the surrounding gas require changes to present theoretical models that now assume that the outer heliosphere is surrounded by a homogeneous medium.

(4) To what extent does the strong EUV radiation from Epsilon CMa and other hot stars control the ionization and gas flow in clouds that are in contact with the outer heliosphere?

(5) What are the properties of the hydrogen wall located about 300 AU from the Sun that future spacecraft will measure in situ?

We have pursued a comprehensive program for analyzing high-resolution Hubble spectra of nearby stars to determine the flow vectors, temperatures, and densities of interstellar gas. Such observations are the only means of measuring the global properties of the local ISM just beyond the heliosphere. In Redfield & Linsky (2008), we identified 15 partially ionized clouds within 15 pc of the Sun that predicts interstellar radial velocities and neutral hydrogen column densities in all directions. Subsequent observations have validated our kinematic model without exception.

Most recently we have concentrated on the immediate environment of the Sun by computing a three-dimensional model for the LIC, identifying the 4 partially ionized clouds that are in direct contact with the outer heliosphere, and showing that EUV radiation from the star Epsilon CMa photoionizes the outer edges of these clouds and creates a hydrogen hole covering a wide solid angle as seen from the center of the LIC. We also tentatively concluded that the inflow vector of gas from the LIC is inconsistent with the neutral helium flow vectors measured by recent spacecraft. These tentative results and the science questions above need to be tested in this future study to be funded by this proposal and prepare for in situ measurements of particles and fields by a future spacecraft traversing the LISM.

The tasks of this program will be to:

(a) compute three-dimensional models of the clouds that are in contact with the outer heliosphere to answer questions (2) and (3),

(b) compute thermal structures within the 4 clouds from the line widths of different ions to search for effects of external EUV radiation on the skin properties of these clouds to answer question (4),

(c) develop a model for the temperature, density, and flow properties of gas on all sides of the heliopause and compare with the inflow properties (direction, speed and
temperature) measured by the Ulysses, Stereo and IBEX spacecraft to answer question (1), and

(d) predict the properties of the interstellar gas that the Voyager and future interstellar spacecraft will enter to answer question (5).

This information is critically needed for planning the trajectories and instrumentation of future space missions such as Interstellar Probe.

Pawel Swaczyna/Princeton University
Angular Scattering of Neutral Atoms: Observations and Interpretation from IBEX and Consequences for IMAP

Science goals and objectives:

Interstellar neutral (ISN) atoms penetrating the heliosphere provide a remote diagnostic of the very local interstellar medium (VLISM). Fluxes of ISN atoms are modified in the outer heliosheath by charge exchange (CX) collisions, which result in the production of secondary ISN atoms. A large part of our understanding of the VLISM and the outer heliosphere comes from the attenuation of the ISN signal as observed at 1 au to the source that lies outside the heliosphere. For this reason, details of the CX process are crucial for interpreting the plasma properties in the heliosphere and its vicinity. So far, analyses of the ISN atom observations from IBEX-Lo and Ulysses/GAS have neglected elastic scattering and assumed that particles in CX collisions conserve momenta of parent particles, i.e., that there is no angular scattering in these collisions. Recent theoretical calculations of the differential CX cross section between protons and hydrogen atoms show that this assumption is not valid for collision speeds of the order of tens of kilometers per second, as expected in the outer heliosheath, and hence this process impacts the distribution function of secondary atoms. We will quantitatively verify the importance of angular scattering for the populations of ISN atoms observed by IBEX-Lo and in the future by IMAP-Lo. We will answer the following scientific questions:

Q1. How does angular scattering in CX and elastic collisions change distribution functions of ISN atoms at 1 au? How is this change reflected in IBEX-Lo observations?

Q2. Are physical parameters of the VLISM obtained from analyses of the ISN helium observations from IBEX-Lo affected by angular scattering in the outer heliosheath?

Q3. Do IBEX-Lo observations support an out-of-equilibrium distribution of the pristine ISN atoms ahead of the heliosphere?

We will address whether discrepancies between models and IBEX-Lo observations manifested by statistically too high chi-square estimators are explained by angular scattering (Q1). We will further check if the lack of these physical mechanisms in the prior analyses resulted in biased parameters of interstellar flow deduced from ISN atom observations (Q2). Finally, we will determine (Q3) whether claims of non-Maxwellian
distributions of the ISN helium population are supported in the light of angular scattering in the outer heliosheath. One reason for departure from equilibrium can be a close distance from the edge of the local interstellar cloud, as indicated by the UV observations of absorption lines of nearby stars.

Data:

We will use the ISN data (IBEX-Lo observations in the energy steps 1–3) published in the IBEX data releases 3, 6, 9, and 11. We also plan to make predictions for IMAP-Lo observations based on anticipated specifications.

Methodology:

We will utilize the existing forward model of ISN atom transport in the heliosphere and detection by the IBEX-Lo sensor (Schwadron et al. 2015, ApJS 220:25). Model ISN atom fluxes will be evolved due to CX and elastic collisions as they move through the outer heliosheath. We will use the plasma properties in the outer heliosheath resulting from the global simulations of the heliosphere (Zirnstein et al. 2016, ApJL 818:18). Model results and IBEX-Lo data will be analyzed using methods that account for multiple sources of IBEX-Lo uncertainties (Swaczyna et al. 2015, ApJS 220:26).

Relevance:

We will analyze ISN atom observations using methods beyond the IBEX mission to determine the physical state of the interstellar medium and find the role of angular scattering in the interaction of ISN atoms from the VLISM with the heliosphere. Therefore, this proposal directly addresses the interaction of the Sun with the interstellar medium included in Decadal Survey Goal 3: “Determine the interaction of the Sun with the solar system and the interstellar medium”, and as such is relevant for the OH-GI program.

Eric Zirnstein/Princeton University
Identifying the Origin of Energetic Neutral Atoms Measured by IBEX along the Voyager Directions

Description of Objectives:

We propose to investigate the temporal evolution of the heliospheric energetic neutral atom (ENA) spectrum to understand its origin as a function of radial distance from the Sun. The heliosphere is formed from the interaction of the solar wind (SW) plasma with the partially ionized, local interstellar medium (LISM), forming a large-scale cavity in space (100’s-1000’s au in size). The supersonic SW emitted from the Sun is compressed and heated at the SW termination shock (TS), producing a region of subsonic plasma and suprathermal particles (inner heliosheath, IHS). Outside the boundary separating the solar and interstellar plasma (heliopause), there is a region of compressed and heated LISM plasma that diverts around the heliopause (outer heliosheath, OHS). ENA fluxes
generated by charge-exchange can originate from both the IHS and OHS regions, and their superposition creates the ENA spectrum observed at 1 au by the Interstellar Boundary Explorer (IBEX). In fact, it is widely believed the IBEX “ribbon,” a bright and narrow structure of ENAs in the sky, originates from the OHS via multiple charge-exchange processes.

The main objective is to understand the origin of the evolving ENA spectrum at 1 au observed by IBEX and what contribution the IHS and OHS regions make to the ENA spectrum. We narrow the focus to ENAs observed from the Voyager 1 and 2 directions such that IBEX data are analyzed in the context of in situ plasma measurements by Voyager, with support by published models of the heliosphere. Topical science questions are answered:

(SQ1) What is the difference in ENA evolution along the Voyager 1 and 2 directions? How do these differences relate to what the Voyagers observe?

(SQ2) Is the ENA evolution from the Voyager directions consistent with a source entirely from the IHS? Or, is there a source from the OHS?

(SQ3) How does the relative contribution of ENAs from the IHS versus OHS change with angular distance from the ribbon peak? What does this imply about the ribbon’s origin?

Methodology:

We analyze the first 9 years of publicly available IBEX ENA data and past/current Voyager 1 and 2 observations of the IHS and OHS plasmas. Data analyses are supported by validated and published models of the 3D time-dependent heliosphere and ENA fluxes from the IHS and OHS, which are necessary to understand the complex physical processes responsible for the observed ENA spectrum.

The objectives are achieved by analyzing IBEX ENA intensities and spectral indices as a function of energy and time in the Voyager directions. We utilize Voyager 1 and 2 observations of the plasma source, supported by a published 3D time-dependent simulation of the heliosphere, to understand the ENA evolution (SQ1). The simulation’s boundary conditions are constrained by publicly available ACE and Wind data at low ecliptic latitudes and Ulysses and IPS data at higher latitudes near 1 au. Published models of ENA fluxes at 1 au from the IHS and OHS support the analysis of IBEX ENA data along the Voyager directions to estimate the timing of plasma and ENA propagation and provide observable differences in ENA evolution at 1 au (SQ2). Finally, we analyze ENA data as a function of angular distance in the sky between the Voyager directions and the ribbon peak, quantifying the difference in ENA evolution close to and far from the ribbon peak and thus the origin of ENAs between IHS and OHS sources with implications for the ribbon’s origin (SQ3).

Relevance:
This proposal, which investigates outer heliosphere data with independent analyses beyond the IBEX mission, is relevant to the OH-GI program and thus NASA interests and directly addresses two of the high-level science goals from the Heliophysics Decadal survey: (3) Determine the interaction of the Sun with the Solar System and the interstellar medium, and (4) Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.