

Astro2020 Science White Paper

Opportunities for Astrophysical Science from the Inner and Outer Solar System

Thematic Areas:

- Planetary Systems
- Star and Planet Formation
- Formation and Evolution of Compact Objects
- Cosmology and Fundamental Physics
- Stars and Stellar Evolution
- Resolved Stellar Populations and their Environments
- Galaxy Evolution
- Multi-Messenger Astronomy and Astrophysics

Principal Author:

Name: Michael Zemcov

Institution: The Rochester Institute of Technology & the Jet Propulsion Laboratory

Email: zemcov@afd.rit.edu

Phone: 585 475 2338

Co-authors: Iair Arcavi (Tel Aviv University), Richard G. Arendt (CRESST

II/UMaryland/GSFC), Etienne Bachelet (Las Cumbres Observatory), Chas Beichman (JPL),

James Bock (Caltech/JPL), Pontus Brandt (JHU-APL), Ranga Ram Chary (IPAC/Caltech),

Asantha Cooray (UCI), Diana Dragomir (MIT), Varoujan Gorjian (JPL), Chester E. Harman

(NASA GISS), Richard Conn Henry (JHU), Carey Lisse (JHU-APL), Philip Lubin (UCSB), Shuji

Matsuura (Kwansei Gakuin University), Ralph McNutt (JHU-APL), Jayant Murthy (Indian

Institute of Astrophysics), Andrew R. Poppe (UC Berkeley-SSL), Michael V. Paul (JHU-APL),

William T. Reach (USRA/SOFIA), Yossi Shvartzvald (IPAC/Caltech), R. A. Street (Las Cumbres

Observatory), Teresa Symons (RIT), Michael Werner (JPL)

Abstract: Astrophysical measurements away from the 1 AU orbit of Earth can enable several astrophysical science cases that are challenging or impossible to perform from Earthbound platforms, including: building a detailed understanding of the extragalactic background light throughout the electromagnetic spectrum; measurements of the properties of dust and ice in the inner and outer solar system; determinations of the mass of planets and stellar remnants far from luminous stars using gravitational microlensing; and stable time-domain astronomy. Though potentially transformative for astrophysics, opportunities to fly instrumentation capable of these measurements are rare, and a mission to the distant solar system that includes instrumentation expressly designed to perform astrophysical science, or even one primarily for a different purpose but capable of precise astronomical investigation, has not yet been flown. In this White Paper, we describe the science motivations for this kind of measurement, and advocate for future flight opportunities that permit intersectional collaboration and cooperation to make these science investigations a reality.

1 Context

The outer solar system is a unique, quiet vantage point from which to observe the universe around us. At most wavelengths, the sensitivity of an instrument near the Earth is limited by light from the circumsolar dust cloud. Reductions in this bright foreground would permit tremendous gains in sensitivity and temporal stability. However, we have been slow to take advantage of this resource. Since Pioneer 10, there have been a relative handful of astrophysical studies using data from beyond the Earth’s orbit [1–16], corresponding to a meager 3.5 results per decade. **In this White Paper we make the case that astrophysical observation well beyond the Earth’s orbit can enable a wide range of virtually untapped astrophysical science.**

2 Opening Novel Astrophysics From a Unique Vantage Point

2.1 Understanding the Solar Dust Cloud

Both the composition and structure of our circumsolar dust cloud is relatively well understood locally to the Earth [*e.g.* 17–20]. Instruments on solar orbiting spacecraft such as *Spitzer* have helped by providing Zodiacal Light (ZL) measurements along alternate lines of sight that are not constrained to originate at the Earth, and have highlighted the presence of local density enhancements in the ZL dust cloud at 1 AU [21]. However, beyond 1 AU we have little understanding of the structure of the interplanetary dust (IPD) cloud. This is a major hindrance as we begin to probe the equivalent structures in exoplanetary systems [*e.g.* review by 22]. Models indicate that there should be structures associated with the Edgeworth-Kuiper Belt (EKB; [23]), to which we see many analogs in the circumstellar disks around other stars. We have virtually no understanding of how these disks map to our own, where we can hope to study composition and small-scale structure directly. **Observations probing the light from IPD at a variety of wavelengths along different sight lines are necessary to develop a three-dimensional understanding of the morphology of our own dust disk and to contrast it with those of exoplanetary systems.**

Tomography of the Dust Cloud Even with observations taken in many directions and over the course of a full year, converting measurements from 1 AU into a precise model of the IPD cloud structure and optical properties is challenging. By comparing data from instruments in different solar orbits, we can observe from different perspectives, compiling different combinations of data that probe different aspects of the spatial distribution of IPD. Orbits at $\lesssim 1$ AU could provide a rapidly varying sampling of the interior portion of the IDP cloud, while measurements at > 1 AU could sample many more lines of sight through the cloud. Such tomographic measurements would permit a three-dimensional map of the IPD cloud to be developed, which would address a variety of scientific questions, including the nature, composition, and evolution of dust outgassing from EKB objects and Öort-cloud comets, whether our models for dust transport in planetary systems are correct, and how our solar system’s structure relates to that we see around other stars.

Distant Look-Back Observations In the next decade we will begin to find and characterize Earth-like planets orbiting other stars, and one of the most important validations available is the suite of observations that simulate the Earth as an extrasolar planet, including direct observations [*e.g.* 24], Earthshine [*e.g.* 25], instrument calibration [*e.g.* 26, 27], spacecraft flybys [28, 29], and publicity shots from 40 AU [30]. Viewing the Earth from a large distance is the best analog to exoplanet observations [*e.g.* 31], and allows for the validation of both forward models and model

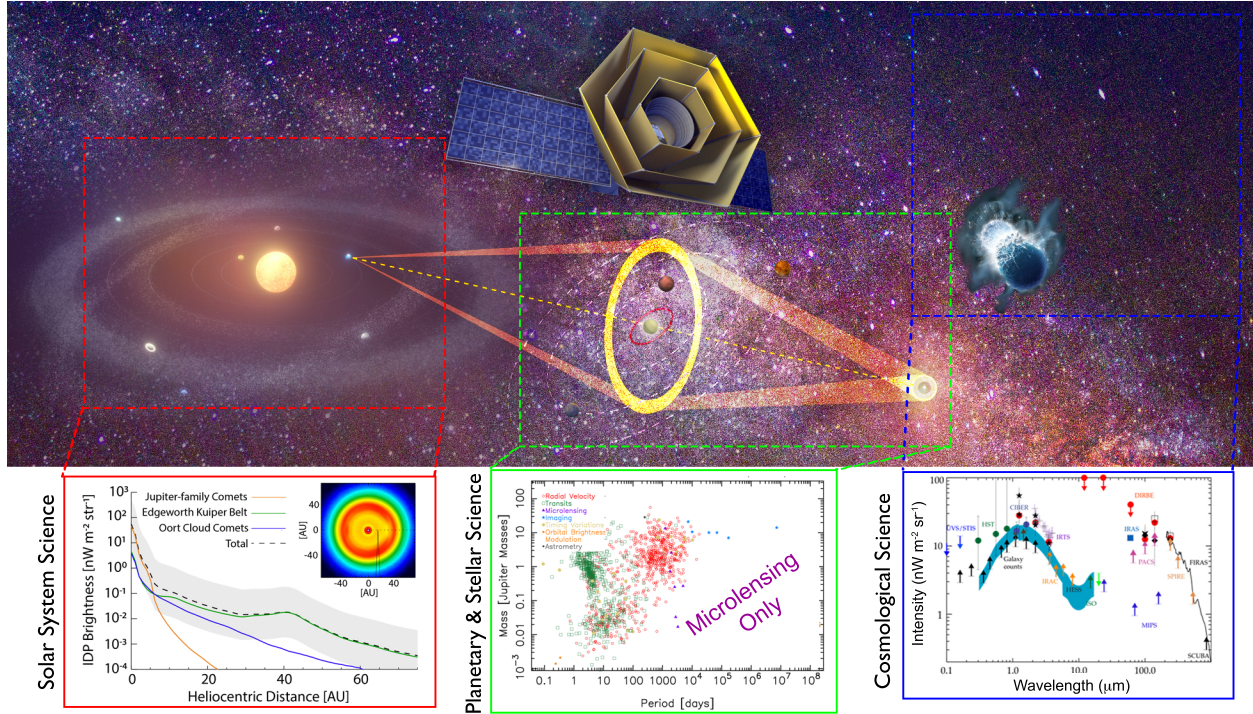


Figure 1: Observations from other vantage points in the solar system touch on a wide range of astrophysics.

retrievals. Adding large-separation spectrographic data would represent the only ground-truthed, close-to interstellar observations of a habitable – and inhabited – Earth-like planet.

2.2 Extragalactic Backgrounds

The Extragalactic Background Light (EBL) is the cumulative sum of all radiation released over cosmic time, including light from galaxies throughout cosmic history, as well as any truly diffuse extragalactic sources [32, 33]. Measurements of the EBL can constrain galaxy formation and the evolution of cosmic structure, provide unique constraints on the Epoch of Reionization, and allow searches for beyond-standard model physics [34]. The absolute brightness of the EBL has been established from Earth at many radio and X-ray wavelengths, but at most infrared, optical, and UV wavelengths a precise assessment of the sky brightness has been hampered by reflected and emitted light from IPD, which results in an irreducible $> 50\%$ uncertainty (and at some wavelengths significantly larger) on the absolute emission from the EBL [e.g. 35]. **By observing beyond the interplanetary dust, observations from the outer solar system can eliminate these uncertainties and definitively determine the absolute brightness of the EBL.**

The Optical/Near-IR EBL The optical/near-IR EBL encodes direct emission from stars integrated over time, so constrains the aggregate stellar population of the universe and nucleosynthesis in stars through cosmic history. By measuring the intensity and spectrum of the diffuse optical/near-IR EBL between 0.3 and 10 microns, we can: perform a census of the total mass density in stars and the fraction of them in diffuse structures; search for sources of diffuse emission which might arise from dark matter annihilation; determine the fraction of baryons that have been processed through stars and active galactic nuclei during the epoch of reionization; and understand the rate at which stars and supermassive black holes build up over cosmic time.

The Mid-IR/Far-IR Here the EBL is dominated by thermal emission from small dust grains in galaxies, with high redshift sources from cosmic noon making the largest contribution [36]. By measuring the far-IR EBL, we can reveal the contribution from low-mass star-forming galaxies and thereby obtain a complete census of obscured star formation, measure obscured AGN activity, and trace the growth of dust and its evolution as a function of metallicity and cosmic time. Ultimately, this measurement offers a way to trace the evolution of the stellar initial mass function over time, which is one of the key uncertain parameters required in the conversion of luminosity to baryonic matter density.

The Ultraviolet In the UV, the diffuse astrophysical background is thought to be largely due to light from local O and B stars scattered from dust in the ISM. Advanced spectral decomposition techniques are required to separate the extragalactic component from dust and atomic scattering, as well as other emission processes [e.g. 37]. Spectroscopic measurements far from the scattered solar light will help elucidate the origin of the galactic and extragalactic UV background, including any exotic physics that may be present [38].

2.3 Breaking Mass-Distance Degeneracies in Gravitational Microlensing

Photometry of stars in our galaxy can detect microlensing of the galactic source population, and observations of the microlensing light curves obtained at two locations in the solar system allows us to break degeneracies in models for the masses and parallax of the lensing system [39, 40]. Microlensing is the most effective method for finding exoplanets beyond the snow line of their stars, where the sensitivity of other planet discovery techniques drops off rapidly, with 53 systems detected so far [41]. **Because this method does not require the detection of light from the lens itself, it allows the detection and weighing of not only free-floating planets and brown dwarfs [42], but also compact stellar remnants like black holes [43].**

As has been demonstrated using observations from the Earth and *Spitzer*, *Kepler*, and *EPOXI* [44–47], stellar and planetary mass lensing can be observed with suitable facilities far from Earth. A given lensing event will project into some radius in the solar system, which is characteristic of the mass of the lens and its geometry. As an example, a $1 M_{\odot}$ object at 4 kpc lensing a source at 8 kpc can be viewed within a $r = 4.0$ AU region wherein observers at different positions in the solar system will see the object lens the source star with different maxima and times of peak magnification. An observatory further out in the solar system is sensitive to much larger masses, with a $10 M_{\odot}$ black hole at 4 kpc lensing a source at 8 kpc having a characteristic radius of 25 AU. Surveying towards the Bulge, Plane and Magellanic Clouds would enable us to explore the populations of low-mass stellar and planetary systems along multiple lines of sight and hence give insight into the distribution of these objects in different evolutionary environments in the Galaxy, and offers the unique possibility of measuring the mass function of quiescent black holes of $M \sim 20 M_{\odot}$ to allow us to distinguish whether they originate from stellar evolution [48] or possibly in the early Universe [49].

2.4 Time Domain Astrophysics

Though already many instruments take advantage of the quiet environment away from the Earth at the L2 point of the Earth-Sun system (e.g. *WMAP*, *Herschel*, *Planck*, *Gaia*, with *JWST*, *Euclid*, and *WFIRST* planned), larger physical separations and even smaller temporal variability can be achieved elsewhere in the solar system. **A platform away from Earth offers the possibility of a uniquely quiet and stable environment from which to make observations.**

Table 1: Summary of science cases and requirements.

Science Topic	Type	Wavelength Range	Angular Resolution	Heliocentric Distance
Solar IPD Structure	Spectrographic Survey	Optical/Near-IR	$\sim 10''$	< 10 AU
EKB Disk	Spectrographic Survey	Far-IR	$\sim 10''$	> 10 AU
Earth Imaging	Pointed Spectro-photometry	Optical/Near-IR	$< 1''$	> 100 AU
Absolute EBL	Spectrographic Survey	UV to Sub-mm	$\sim 10''$	> 5 AU
Microlensing	Pointed Photometry	Optical/Near-IR	$< 1''$	Any
Transient Follow-Up	Pointed Spectro-photometry	Optical/Near-IR	$\sim 1''$	Any

Hyper-Stable Photometry Any observation requiring stability on long time scales (exoplanet detection, SN light curves, variable star photometry) would benefit from access to the outer solar system. The stable thermal and RF environment would permit instruments that are not affected by slow annual variations that can be present [e.g. 50, 51].

Transient Counterpart Identification Astronomical transients, such as supernovae, kilonovae/macronovae (merging neutron stars), and tidal disruption events are important laboratories of extreme physics. Critical phases of these events, or even entire events, can be missed due to an unfavorable geometry of the Earth, the Sun, and the event. One notable example is the recent counterpart to the gravitational wave event GW170817 [52, 53]; had GW170817 occurred just one week later, it would have been Sun-constrained to Earth-based ultraviolet, optical, and infrared telescopes, the electromagnetic counterpart would not have been found, and the broad insights gained from the event would have been lost. Similarly, the nearest superluminous supernova to date, SN 2017egm, became unobservable due to Sun constraints just 2–3 weeks after peak brightness [e.g. 54, 55]. A platform elsewhere in the solar system could observe events that are Sun-constrained from Earth, and thus provide both unique observations at critical phases and wavelength coverage not available from ground-based platforms.

3 Strawman Mission Concepts

Though it could have a transformative impact on a wide range of astrophysical fields [e.g. 56], a mission to the outer solar system that includes instrumentation expressly designed to perform astrophysical science has not yet been flown. Previous proposals for both stand-alone missions [57, 58] or astronomical instruments piggybacked on other missions [59] have proven more politically than technically challenging. This is unfortunate, as a piggyback concept is a cost-effective way to multiply the science return of expensive missions to the outer solar system.

Strong advocacy from the astrophysical community could make positive collaboration and cooperation between the different NASA divisions a realistic outcome.

A possibility that has been discussed over the years is an Interstellar Probe to the pristine ISM [60–66]. The current incarnation of this concept would travel to 1000 AU in a 50-year mission [67]. Astrophysical measurements during its cruise phase would offer a unique opportunity to generate both high-impact science during the long quiescent periods en route to the ISM, as well as to build and maintain technical expertise in the spacecraft and instruments over the generations of scientists and engineers required to execute such a mission. An Interstellar Probe could be a true flagship of space science, offering an unique opportunity to fulfill some of the promise of astrophysical observation far from Earth.

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