Astronomical opportunities from the outer solar system

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Observations from the outer solar system with a small telescope promise highly accurate measurements of the interplanetary dust cloud and the extragalactic background light.

How bright is the sky? For cosmologists, the answer depends on how galaxies formed and how luminous the first generations of stars might have been. While of fundamental importance in astronomy, measurements of extragalactic sky brightness have been frustrated by contamination from local sources, especially at optical and IR wavelengths. Even in space, away from terrestrial lights and Earth’s atmosphere, the sky brightness is dominated by zodiacal light, sunlight scattered by the interplanetary dust (IPD) in our solar system.

Our team has been studying the possibility of carrying out observations during the underused ‘cruise phase’ of a planetary science mission to the outer planets, beyond the bulk of the IPD cloud where the sky is much darker than at Earth’s orbit, one astronomical unit (AU) from the Sun. As shown in Figure 1, we estimate that the sky brightness is 30 times fainter from the orbit of Jupiter, and 100 times fainter from the orbit of Saturn, than the brightness available from Earth’s orbit. This unique vantage point would enable us to measure the extragalactic background light (EBL), as well as the structure and properties of dust in the outer solar system, with unprecedented accuracy.

We developed a concept for an optical to near-IR instrument, the Zodiacal dust, Extragalactic Background, and Reionization Apparatus (ZEBRA). As shown in Figure 2, ZEBRA is a small instrument, specialized for absolute surface brightness photometry. We designed ZEBRA for minimal mass (16.4kg), power (12.4W), and data resources, with simple interfaces to the parent satellite, and incorporating technologies that are well developed and readily available. ZEBRA uses two small wide-field telescopes operating from 0.4–5μm, to measure the EBL and to map the IPD cloud in scattered sunlight. The optics are based on three mirror off-axis designs, with multiple field and aperture stops to reduce stray light, and include a filter-wheel dark position for monitoring the detector dark current. We have developed a simple lightweight passive cooling scheme to cool the optics and detectors to <50K. ZEBRA uses two commercial 2×2k Hawaii-2RG IR detector arrays.

Figure 1. Left: Estimated brightness of zodiacal light from 1AU (astronomical unit) to 10AU (cyan curves) based on Pioneer 10 and 11 measurements out to 3AU, with shaded areas indicating the uncertainty in the extrapolation. Diffuse galactic light (DGL, green curve) arises from starlight scattered by interstellar dust and emission from the interstellar medium. The large reduction in zodiacal brightness enables a precise measurement of the extragalactic background light (EBL, a model is indicated by the red curve) and a deep search for photons from reionization, shown by the violet shaded region. Note that the reionization EBL is constrained to have the minimum level required to produce sufficient photons for reionization. Right top: For the darkest field observed by the Diffuse Infrared Background Experiment (DIRBE) from 1AU, we show contributions to the total observed intensity from zodiacal light, undetected stars, DGL, and the estimated EBL. Clearly, zodiacal light is the dominant factor in current EBL measurements from 1AU. Right bottom: The same field observed by the Zodiacal dust, Extragalactic Background, and Reionization Apparatus (ZEBRA) at 10AU with higher spatial resolution is dominated by the EBL, before any attempts are made to subtract these foregrounds. λIλ: Measure of surface brightness.

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Figure 2. The ZEBRA instrument consists of the High-resolution Absolute Module (HAM) with a 15cm telescope, and the Wide-field Absolute Module (WAM) with a 3cm telescope. Both optical assemblies use wide-field off-axis optics for stray light control. Multiposition filter wheels cover wavelengths from 0.4 to 5 µm, including broadband filters, special line filters for monitoring zodiacal brightness in solar Fraunhofer lines, and composition filters tuned to ice and silicate features in interplanetary dust. The passive cooling system, which consists of two V-groove radiators made from aluminized kapton membranes, a third radiation stage provided by the instrument, and thermal isolation with gamma alumina struts, achieves 50K with 190% power margin at 10AU. The entire instrument mass is 16.4kg and the peak electrical dissipation is 12.4W, both including 30% contingency.

Figure 3. Our solar system serves as a template for understanding circumstellar dust in exo-planetary systems. Only in our solar system do we have a census of the small bodies from which dust originates, and a complete knowledge of the planets responsible for gravitational perturbations. Dust is thought to be continuously supplied by comets, originally formed in the distant Oort Cloud and brought to the inner solar system by gravitational interactions, as well as collisions of asteroids, mostly located in the asteroid belt and in resonant orbits with Jupiter. Dust in the outer solar system may also be supplied by collisions of Kuiper Belt objects.

Observations from the outer solar system provide an excellent opportunity to measure the structure, extent, and composition of the IPD cloud (see Figure 3). Our solar system serves as a case study for understanding exo-zodiacal light levels, for future exo-planet searches. Cruise-phase observations can measure the radial distribution of the IPD cloud, and map resonant enhancements and band structures from the influence of planetary bodies. The 3D maps provide the opportunity to study the compositional distribution of dust and determine whether it arises from comets, asteroids, or both, from the inner to the outer solar system. Finally, and most excitingly, we can for the first time observe the distribution of dust in the outer solar system, to detect and map dust originating from the Kuiper Belt, a stretch of small bodies beyond the orbit of Neptune, including Pluto, Eris, and Haumea.

Outer dust clouds like the Kuiper Belt are common around other stars, but ours has been difficult to discern due to the bright zodiacal light from dust in the inner solar system. Understanding the link between the inner and outer dust clouds is crucial to estimating the amount of dust in the inner reaches of other planetary systems where we plan, someday, to make direct imaging searches for Earth-like planets. Too much IPD in a distant planetary system can obscure individual planets. Information from
ZEBRA could help us to interpret measurements of the cold Kuiper Belts made with the Spitzer and Herschel telescopes to estimate the amount of dust in the inner habitable zones of these systems, where dust levels are much harder to measure directly.

Observations from outside the IPD cloud enable definitive measurements of the intensity, spectrum, and spatial properties of the EBL. The background measures the integrated light produced by galaxies, and contains a component from the first generation of stars thought to have formed within 500 million years of the Big Bang\(^9\) (see Figure 4). These stars, formed out of primordial gas gravitationally collected in dark matter halos, produced the first UV photons that reionized the intergalactic medium. Information encoded in the EBL is one of the few experimental measures of the epoch of reionization, and can probe the energetics and formation history of first sources beyond what is possible with planned deep galaxy surveys, 21cm mapping, or cosmic microwave background polarization studies. Measurements from the outer solar system can measure not only the brightness of the EBL with high accuracy but also spectrum and spatial properties, to characterize the process of first star formation during reionization.

In addition to pursuing ZEBRA as a low-cost add-on to an outer planets mission, we are currently studying a partnership with a space demonstration of new propulsion technology.

**Figure 4.** The EBL contains all radiation emitted by sources since the Big Bang, providing a measure of the history of star and black hole formation, including the light produced by the first stars and galaxies, which reionized the intergalactic medium. Little is currently known about the luminosity and formation history of these first objects. Studies of background light will constrain the global history of star formation during the epoch of reionization by measuring the total light production of first galaxies, complementing the census of the brightest early galaxies expected to be detected by the most powerful future generation telescopes such as the James Webb Space Telescope.

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James Bock, senior research scientist at JPL and senior faculty associate at Caltech, is the US principal investigator of the Herschel/SPIRE and Planck/HFI imaging instruments. He is currently developing suborbital experiments to study cosmic microwave background polarization and to probe the near-IR extragalactic background from reionization.

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References