Breakthrough capability for UVOIR space astronomy: Reaching the darkest sky

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Abstract

We describe how availability of new solar electric propulsion (SEP) technology can substantially increase the science capability of space astronomy missions working within the near-UV to far-infrared (UVOIR) spectrum by making dark sky orbits accessible for the first time. We present two case studies in which SEP is used to enable a 700 kg Explorer-class and 7000 kg flagship-class observatory payload to reach an orbit beyond where the zodiacal dust limits observatory sensitivity. The resulting scientific performance advantage relative to a Sun-Earth L2 point (SEL2) orbit is presented and discussed. We find that making SEP available to astrophysics Explorers can enable this small payload program to rival the science performance of much larger long development-time systems. Similarly, we find that astrophysics utilization of high power SEP being developed for the Asteroid Redirect Robotics Mission (ARRM) can have a substantial impact on the sensitivity performance of heavier flagship-class astrophysics payloads such as the UVOIR successor to the James Webb Space Telescope.

Keywords: solar electric propulsion, zodiacal light, space astronomy

1. Introduction

The Earth is imbedded in a cloud of dust grains that are produced by comet outgasing and impact fragmentation of asteroids that surround the inner planets.[1] This cloud occupies a disk-shaped region of interplanetary space encompassing much of the inner solar system. It extends from approximately the orbit of Venus to the asteroid belt, and its thickness extends roughly 0.5 AU above and below the ecliptic plane (Fig. 1). This interplanetary dust (IPD) cloud produces a UVOIR background light, known as the zodiacal light, through which all space observatories have had to observe. This background light (which is often brighter than the objects being observed) is a source of noise that typically limits the sensitivity of all space astronomy imaging systems that have operated within the near-UV to far-infrared spectrum.

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As development of UVOIR photon counting detectors advance in technology readiness for spaceflight application, sources of electrical noise become vanishingly small (cf: Mazin et al. 2013; Nikzad et al. 2012; Wen et al. 2006; Perryman et al. 1999; Romani et al. 1999). As a consequence, in the coming decade, photon noise from the IPD will become the primary limit on space observatory performance across the UVOIR spectrum for typical spectroscopic applications. In this paper, we discuss how this limit can be overcome through application of new in-space propulsion technology to astrophysics missions.
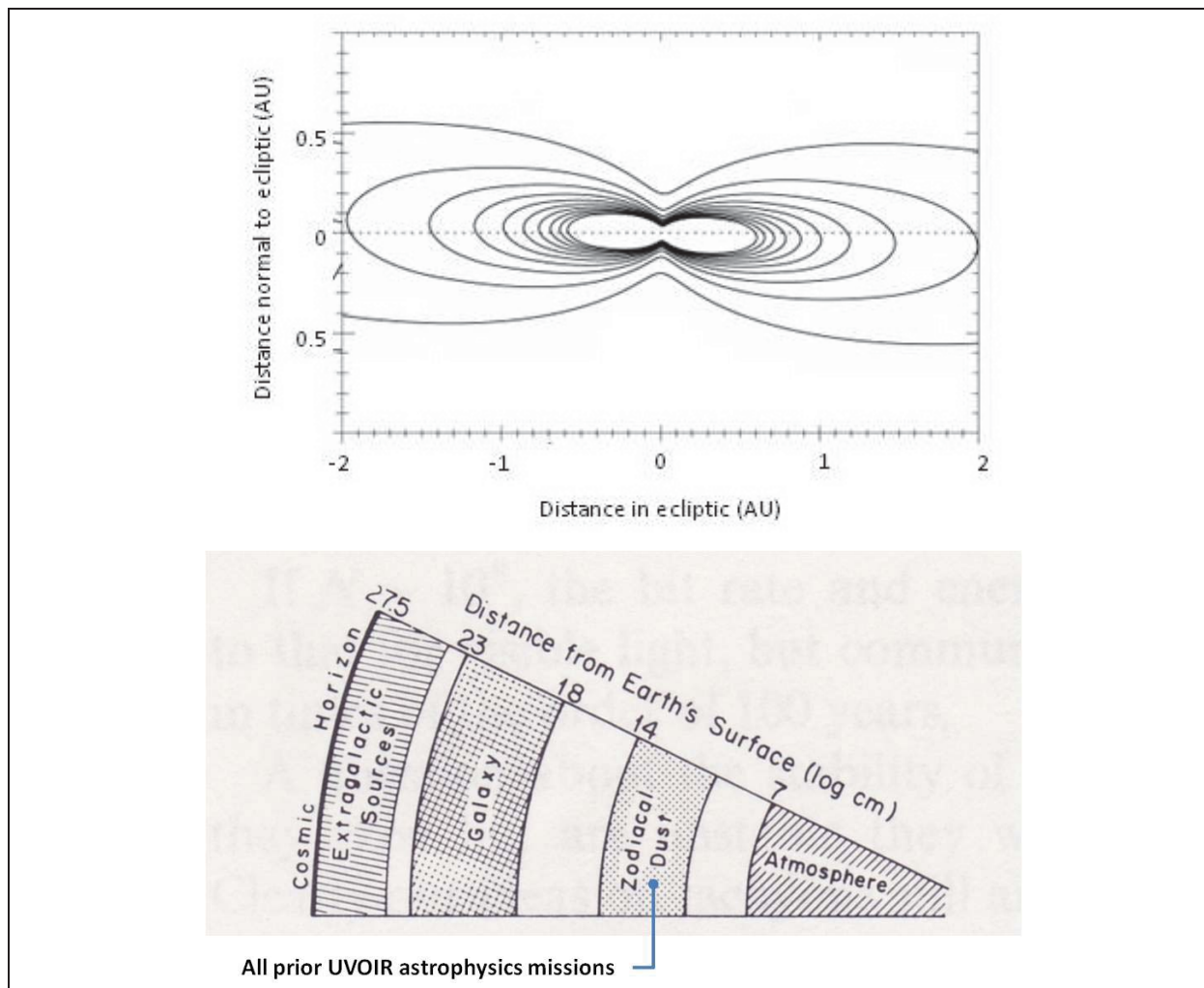

Fig. 1. Top: Isodensity contours of the interplanetary dust cloud on a plane perpendicular to the ecliptic plane from Kelsal, et. al. 1998; The outer most contour, in units of inverse mean free path, is 0.2×10^{-7} AU^{-1} and the contour interval is 0.2. In this paper we take IPD density $<0.4 \times 10^{-7}$ AU^{-1} as being "extra zodiacal". Bottom: Sources of natural background emission adapted from Harwit 1982. No UVOIR astrophysics mission has heretofore achieved an extra-zodiacal orbit.

Sunlight that impinges on the IPD is both scattered and absorbed. Near the Earth, at wavelengths shortward of ~3 microns, the zodiacal background light is dominated by the scattered component, and its spectral characteristics are that of the Sun. In the plane of the ecliptic, the space density of the grains decreases with distance from the Earth roughly as 1/r. So the scattered component decreases with distance as a result of both the decreasing grain space density and $1/r^2$ dilution of the sunlight itself. The sunlight that is absorbed by the grains heats them to a temperature of roughly 240 K at 1 AU (Fixsen and Dwek 2002) resulting in blackbody emission peaking at a wavelength of approximately 12 microns. Near the Earth, this blackbody component dominates the zodiacal background at wavelengths longward of ~3 microns. A minimum in the brightness of the total background emission occurs near 3 microns where scattering and self emission exchange roles as the dominant emission mechanism (Fig. 2). However, the grain temperature decreases with distance from the Sun causing the wavelength of this minimum to increase with distance beyond 1 AU reaching approximately 4.5 micron at 2 AU.
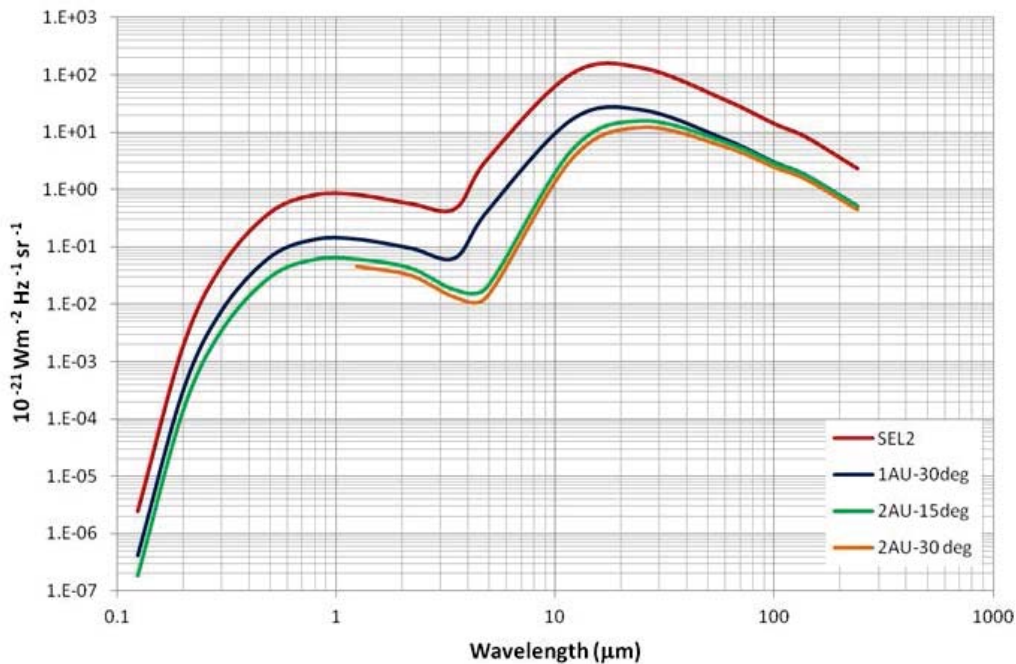

Fig. 2. The zodiacal background flux density toward the Ecliptic pole for four heliocentric orbit cases. The curves shown are a spline fit to ten filter bands of the COBE Diffuse Infrared Background Experiment (DIRBE) spanning the 1 – 240 micron spectrum. A 5600 K blackbody was used to extrapolate these data to the optical and near-UV spectrum.

Architecting a space astrophysics mission to operate in a low density region of the IPD and hence, reach the darkest sky, can follow two general approaches. One can design an orbit in the ecliptic plane with apogee in the outer solar system (Fig. 3), or one can take advantage of the disk morphology of the IPD (Fig. 1) and utilize

a lower apogee orbit that is inclined with respect to the ecliptic plane. There is a continuous trade space between them for optimization of a given astrophysics mission objective.
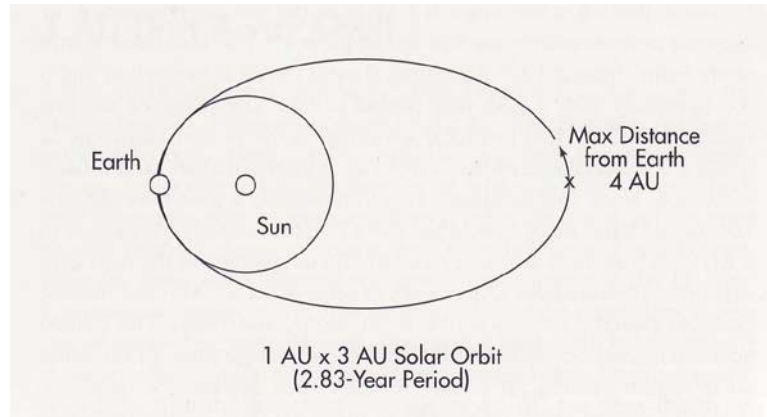

Fig. 3. An in-plane extra-zodiacal orbit option for the James Webb Space Telescope proposed by Lockheed Martin Corporation (see: The Next Generation Space Telescope; Visiting a Time When Galaxies Were Young, Ed: H.S. Stockman, 1997, Association of Universities for Research in Astronomy).

High apogee in-plane orbits (Fig. 3.) can reach an environment characterized by grain density and temperature that is low relative to a 1 AU orbit such as the Sun-Earth L2 point (SEL2); thus, yielding a very large gain in observatory sensitivity performance across the UVOIR spectrum. However, from a systems perspective, this performance advantage comes with challenges in electrical power generation and telecommunications bandwidth. Lower-apogee, high-inclination orbits ease these challenges but at the expense of propulsion energy needed to achieve them. In the following sections we discuss two case studies involving use of electric propulsion to enable an Explorer-class and Flagship-class astrophysics observatory to reach the darkest sky.

2. The Extra-Zodiacal Explorer (EZE)

The EZE refers to a detailed mission architecture study (Benson, et al. 2011; Greenhouse et al. 2012) that was conducted jointly by Goddard Space Flight Center and Glenn Research Center (GRC) using the GRC COllaborative Modeling for Parametric Assessment of Space Systems (COMPASS) facility to determine if and how a technically mature SEP system, such as the NASA Evolutionary Xeon Thruster (NEXT) shown in Fig. 4, can be used to enable astrophysics Explorer missions to operate in an IPD density environment that is very low relative to the SEL2 point in order to increase the scientific potency of this small payload program.
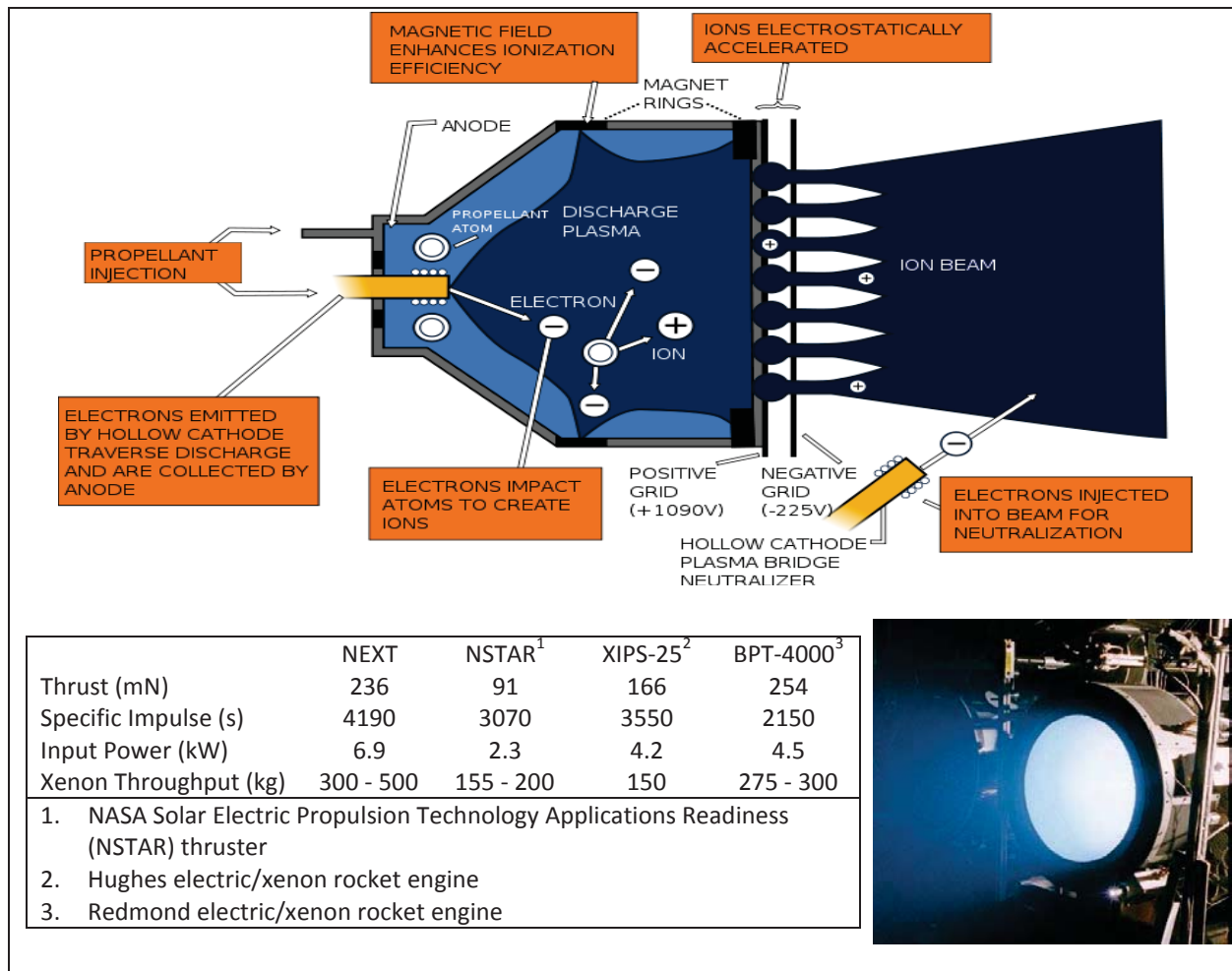
Fig. 4. NASA's Evolutionary Xenon Thruster (NEXT) uses electrical energy produced by solar panels to accelerate Xenon atoms producing thrust in a way that is much more efficient than conventional chemical thrusters (top). A NEXT is shown operating in a hot fire test (bottom right). NEXT has demonstrated lifetime in ground testing that is 2X that required for the mission applications discussed here. Performance properties achieved by NEXT along with those of other similar power SEP thrusters (bottom left).

The high Earth-spacecraft distance, inherent to an in-plane orbit approach, such as shown in Fig. 3, would require solar array area and telecommunication system requirements that could not be met within the cost constraints of an Explorer project. Hence, inclined orbit cases were considered as a means to reach low zodiacal background power at reduced heliocentric radius and telecommunication range.

Two heliocentric circular orbit cases of radius 1 and 2 AU were considered in detail. The dependence of the zodiacal background on orbit inclination with respect to the ecliptic plane is shown in Fig. 5. Inclination angles of 30 and 15 degrees were chosen respectively to reach an IPD column density of $<0.4 \times 10^{-7}$ AU^{-1} (Fig. 1). Flight

dynamics analysis was conducted using MALTO (Benson, et al. 2011). In the 1 AU case, approximately 50% of the plane-change energy was achieved via a single gravity assist encounter with the Earth. Phasing with the Earth was achieved to yield a maximum telecommunications range of 0.7 AU over the orbit period. In the 2 AU case, a single gravitational assist from Mars was utilized. The transfer orbits for these two orbit cases are shown in Fig. 6.

In both cases, we found that acceptable science data down-link rates in the range of 0.7 – 3.5 Mbps can be enabled by conventional Ka-band (32 GHz) flight-ready technologies (Table 1). The cases shown in Table 1 utilize 200 W traveling wave tube amplifiers that were built for the Jupiter Icy Moons Mission (JIMO) and assume 3 db of link margin after 3 db of rain fade and 0.2 db of pointing loss. The rates shown in Table 1 are lower limits calculated at the maximum range. An Explorer-scale observatory would typically utilize a fixed (non-gimbaled) High Gain Antenna (HGA) necessitating interruption of observing for daily science data down-links. The rates shown in Table 1 would enable data volume capability that is sufficient for typical Explorers within several hours of ground contact per day.

Table 1. EZE science data down-link capability					
Orbit	Max Range (AU)	Space Terminal (55% efficiency)	Ka Band Power (W)	Ground Terminal	Data Rate (Mbps)
1AU 30^0	0.7	1.0 m HGA	200	DSN 36 m	3.5
2AU 15^0	3.0	1.5 m HGA	360	DSN 36 m	0.74
2AU 15^0	3.0	2.0 m HGA	200	DSN 36 m	0.74

We showed that Falcon-9, augmented by a SEP upper stage orbit transfer module utilizing two simultaneous firing NEXT thrusters (Fig. 7), can place a notional 700 kg (Class EX) Explorer payload (Fig. 8) into either of the above orbits -- thus enabling observatory performance gain shown in Fig. 9 relative to the low Earth orbit of the Hubble Space Telescope, the Earth-trailing orbit of the Spitzer and Kepler Space Telescopes, or the Sun-Earth L2 point orbit of the James Webb and Herschel Space Telescopes.
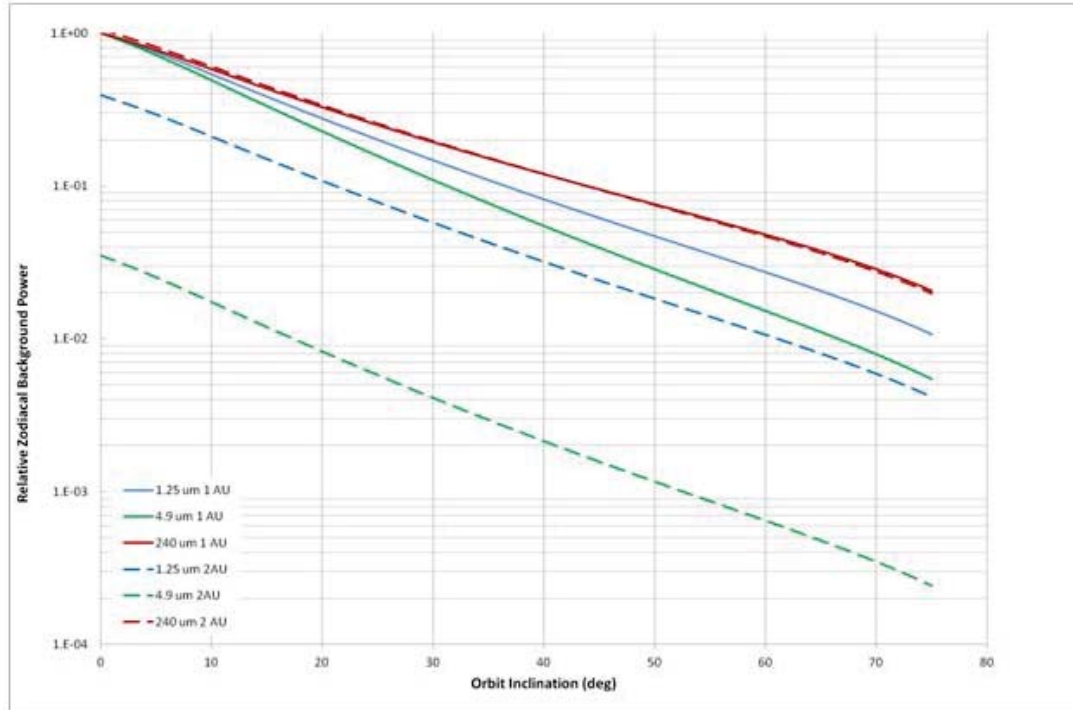
Fig. 5. Zodiacal background power toward the ecliptic pole relative to the SEL2 point vs inclination with respect to the ecliptic plane. Three DIRBE bands are shown for heliocentric radii of 1 (solid) and 2 AU (dashed).

We followed a mission architecture approach in which the SEP is implemented as an upper stage module that is controlled by the science payload spacecraft and ejected via a Lightband separation system (Holms 2004) when the payload is delivered to its operational orbit (Fig. 10). This approach has several advantages.

It enables a single module design to be applied to a wide range of community proposed missions spanning both astrophysics and planetary science applications. Provision of a standardized propulsion module, as government furnished equipment along with launch services, can enable the benefits of this technology to be realized with minimum non-recurring engineering cost and technical risk. In this light, we adopted a design approach involving a clean adiabatic systems interface (Fig. 11) between the propulsion module and science payload spacecraft that Explorer program proposers could design to following a user's manual. Ability to eject the SEP module after it is no longer needed can enable payloads with stringent pointing requirements to avoid the dynamic effects of large low frequency (~ 1 Hz) solar array structures. Top-level mass properties for the module shown in Figure 7 are given in Table 2.
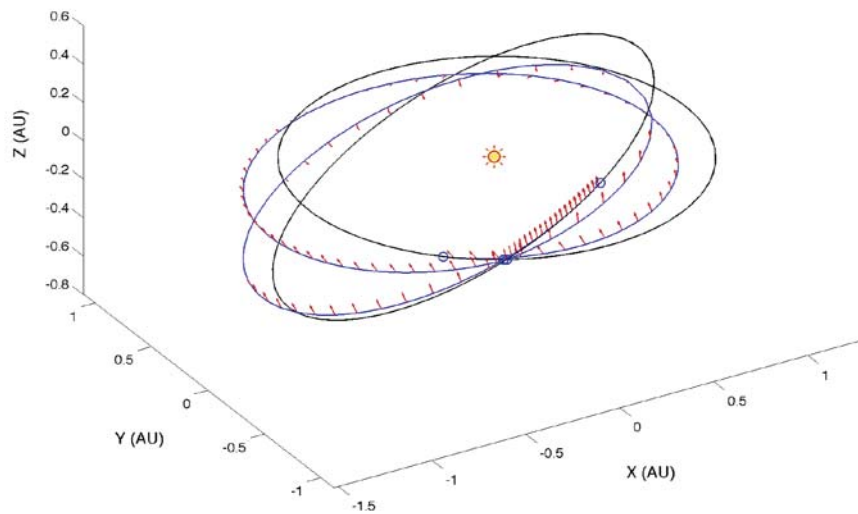
Date	Event	Location	Altitude (km)	C3 (km^2/s^2)	Mass (kg)
5/6/2019	launch	Earth		2.9	2020
5/23/2020	flyby	Earth	1000	106.9	1732
5/22/2021	flyby	Earth	1000	235.0	1521
6/24/2021	arrival	Science Orbit		0.0	1493
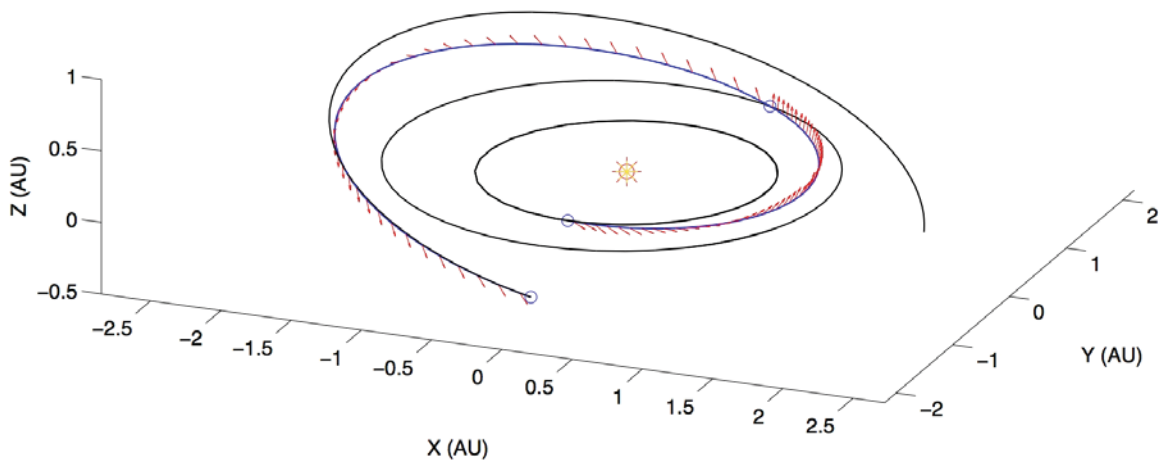
Date	Event	Location	Altitude (km)	C3 (km^2/s^2)	Mass (kg)
6/20/2020	launch	Earth		6.2	1823
1/16/2021	flyby	Mars	1000	12.3	1653
6/22/2022	arrival	Science Orbit		0.0	1439

Fig. 6. Transfer orbits for 1 AU 30 deg (top) and 2 AU 15 deg (bottom) circular science orbit cases. See Benson, et al., 2011 for orbit elements. Red arrows indicate the direction of SEP thrust.

Table 2: EZE Solar Electric Orbit Transfer Module Mass Properties			
Main Subsystem	Mass (kg)	Growth (%)	Total (kg)
Attitude Determination & Control	1	3	1
Remote Interface Unit	35	29	45
Communications & Tracking	4	30	5
Electrical Power	182	18	215
Thermal Control (non-propellant)	58	15	67
Propulsion & Propellant Management	168	8	181
Propellant (Xenon)	417	0	417
Structures & Mechanisms	91	18	107
Estimated Module dry mass with growth			622
Total Module wet mass with growth			1039

The EZE module concept is consistent with a wide range of solar array systems. Our study utilized Orion Ultraflex[i] arrays due to their high technical maturity. Of the 45 m^2 area afforded by two 6 m diameter Ultraflex arrays shown in Figure 7, we found it necessary to populate only 41 m^2 with 25% efficient triple junction GaAs solar cells, in order to provide (at 1 AU beginning of life) 12.5 kW to the SEP power processing units at 120 vdc and 577 W to housekeeping loads at 28 vdc. The 13 kW module design shown in Figs. 7 and 8, was sized to the fault tolerance requirements of a 700 kg medium Explorer payload, and is scalable to higher mass or higher reliability applications.

This study demonstrated that all enabling technologies for this propulsion module currently meet technology readiness for infusion into an Explorer mission solicitation during this decade. The module designed in this study represents a substantial step forward in capability over the prior SEP flight state of art demonstrated by the DAWN mission (Russel & Raymond 2011), for support of a wide range of Class-C[ii] astrophysics or heliophysics Explorer program mission applications, and is saleable to Class-B[i] planetary science Discovery program missions.
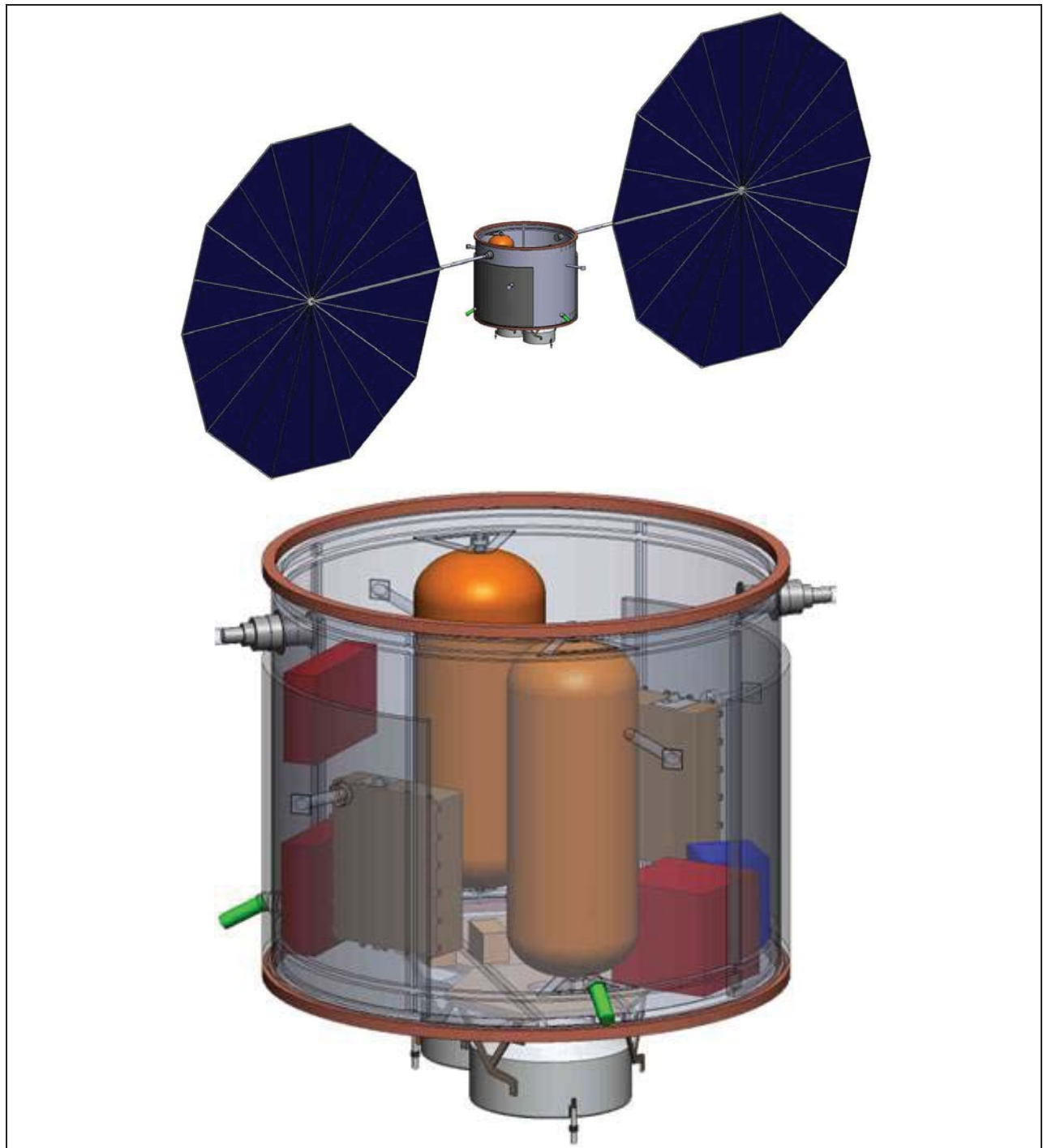
Fig. 7 The 13 kW EZE SEP orbit transfer module is shown in its cruse configuration with 6 m diameter Orion Ultraflex solar arrays deployed (top) and in detail (bottom). The cylindrical section of the module is 1.64 m in diameter and 1.41 m long. Further details of the module design are described in Benson, et al. 2011.
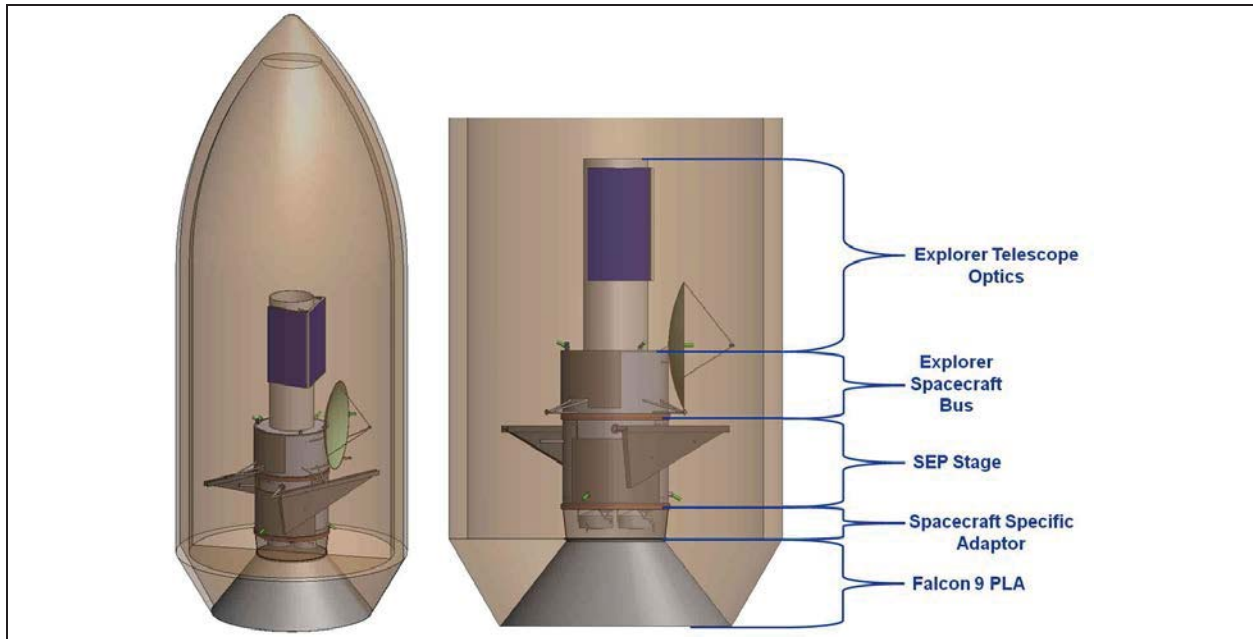
Fig. 8. Top: A notional 700 kg astrophysics Explorer integrated with the SEP module shown in Fig. 7 and encpsulated in a Flacon 9 faring.
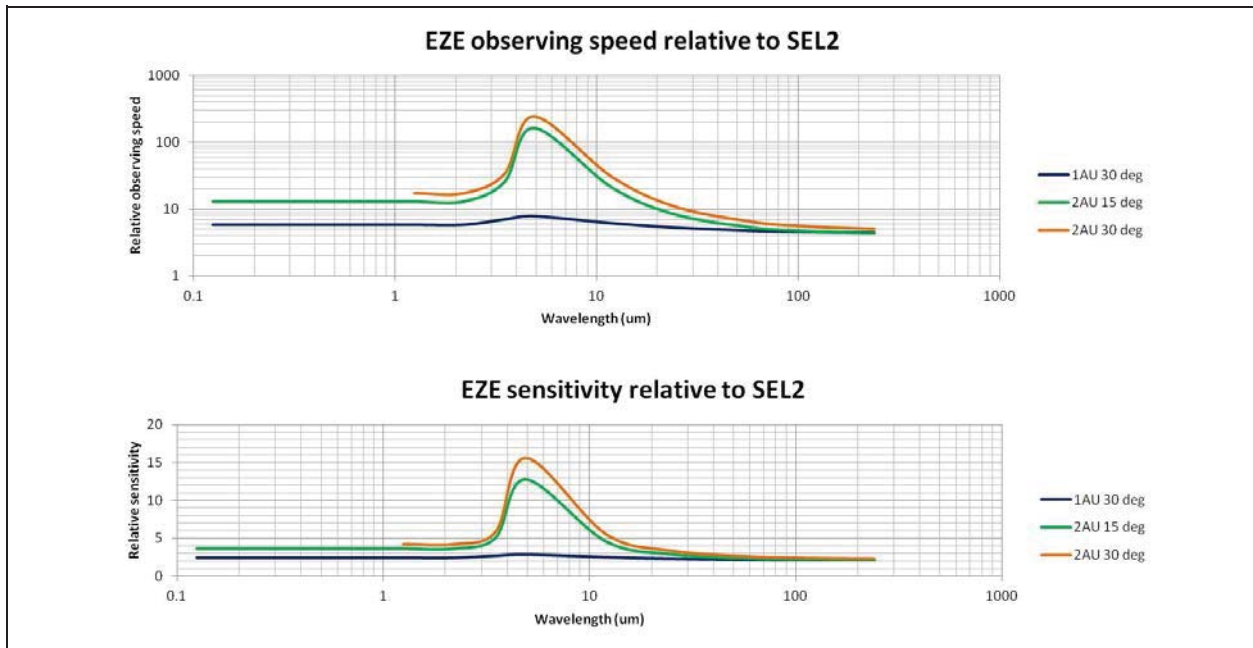

Fig. 9. The relative observing speed and point source sensitivity gain for background-limited observations in dark sky orbits enabled by the SEP module shown in Fig. 8. The relative speed and sensitivity are taken as proportional to the relative zodiacal background and square root of the relative background respectively.
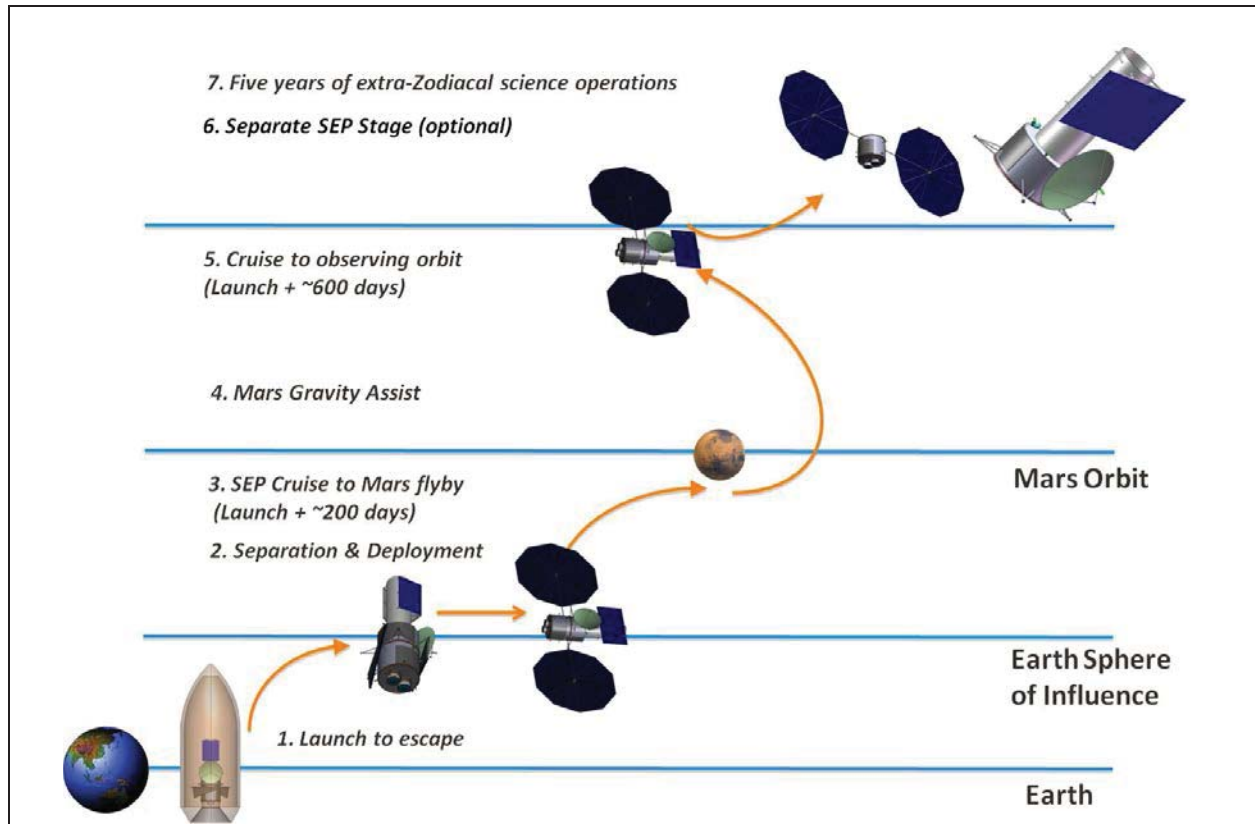
Fig. 10. The timeline sequence of events is shown for the EZE mission architecture.

During 2014, we revisited the above orbit trade space to consider a 2 AU 30 deg elliptical orbit case in order to increase the fraction of the orbital period that is spent outside of the 0.4×10^{-7} AU^{-1} contour of Fig. 1. In this case, the Evolutionary Mission Trajectory Generator (EMTG) described by Englander, et al. 2013 was used to find the transfer orbit shown in Fig. 12 using the same EZE space vehicle parameters described in our prior study (Benson et al. 2011). The zodiacal background as a function of mission time in this orbit is shown in Fig. 13 along with that of a circular orbit case with the same inclination. The science gain afforded by this orbit is included in Fig. 9.

As illustrated on Fig. 13, choice of an elliptical orbit can yield long contiguous periods of dark sky performance (Fig. 9). However, as a matter of mission design, one must choose between favoring the north or south ecliptic hemisphere. In contrast, the circular cases are symmetric in this regard but afford shorter dark sky periods. In terms of compatibility with medium Explorer-class launch services, we found that the circular orbit case cannot be enabled with chemical propulsion alone.
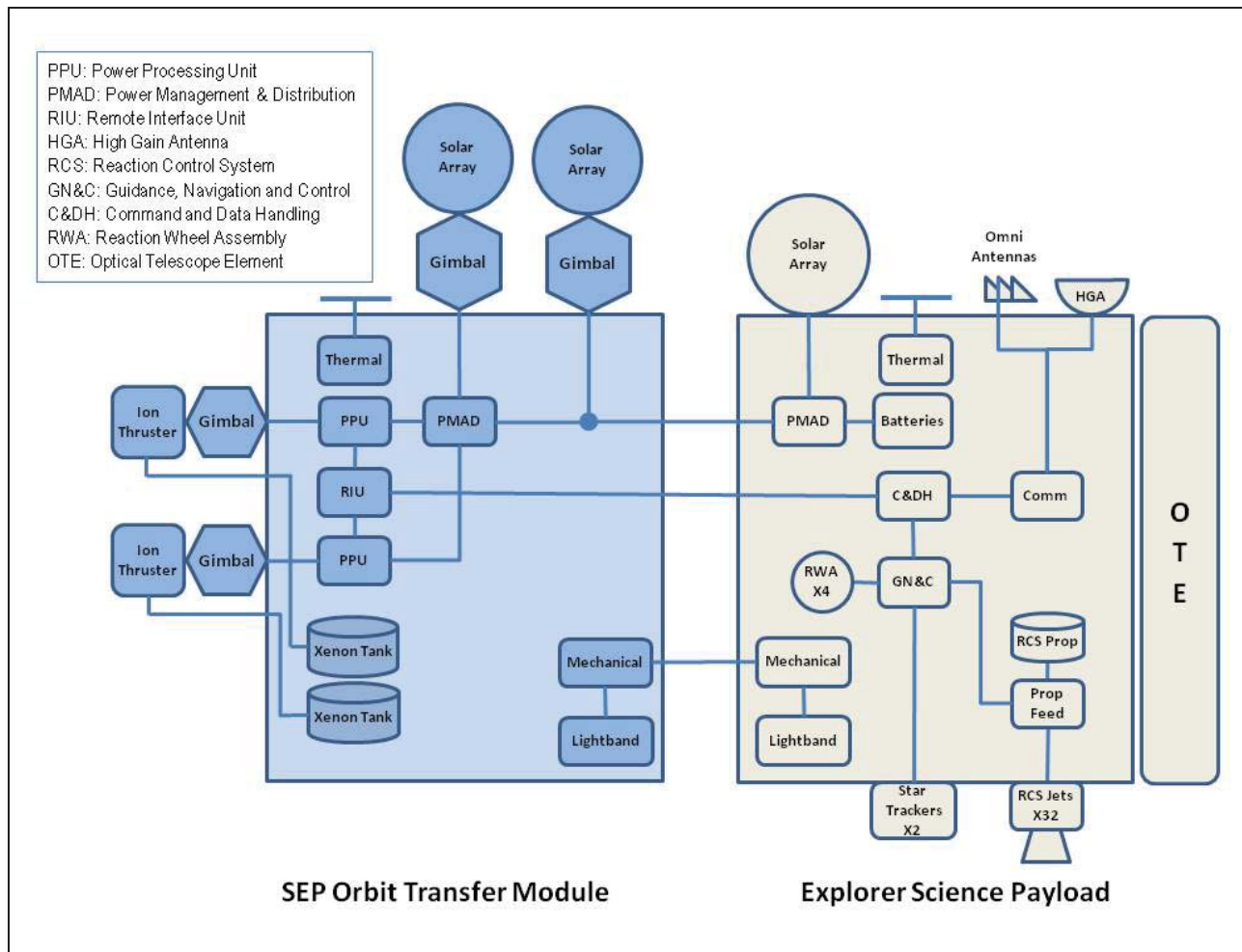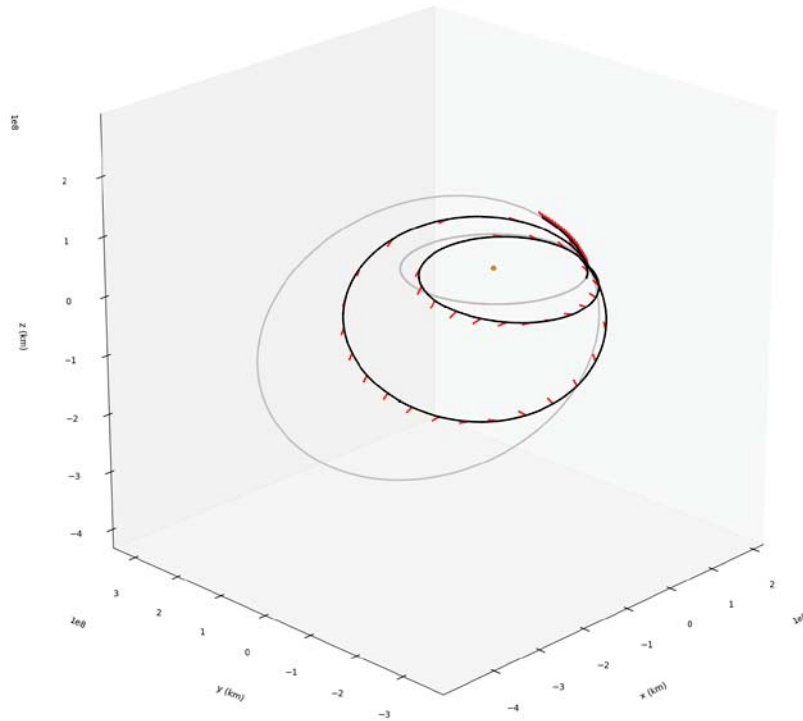
Fig. 11. The EZE SEP orbit transfer module (left) is controlled by its science payload spacecraft (right) yielding a clean systems interface to support a wide variety of community-proposed Explorer or Discovery program payloads.

Semi-major Axis (AU)	2
Eccentricity	0.56
Incination (deg)	30
Right Acention of the Acending Node (deg)	316
Argument of Periapsis (deg)	51
Period (years)	2.82
Flight Time to Arrival (years)	3.15

Date	Event	Location	Altitude (km)	DEC (^{0})	C3 (km^2/s^2)	Mass (kg)
7/21/2020	launch	Earth		28.5	12.5	2116
8/9/2021	flyby	Earth	300	26.1	137.3	1801
8/8/2023	flyby	Earth	300	54	379.6	1474
9/15/2023	arrival	Science Orbit		0	0	1439

Fig. 12. An elliptical dark sky orbit achieved using the Falcon 9 and SEP module shown in Fig. 8 for a 700 kg Explorer-class observatory payload. The science performance gain afforded by this orbit is shown in Fig. 9.
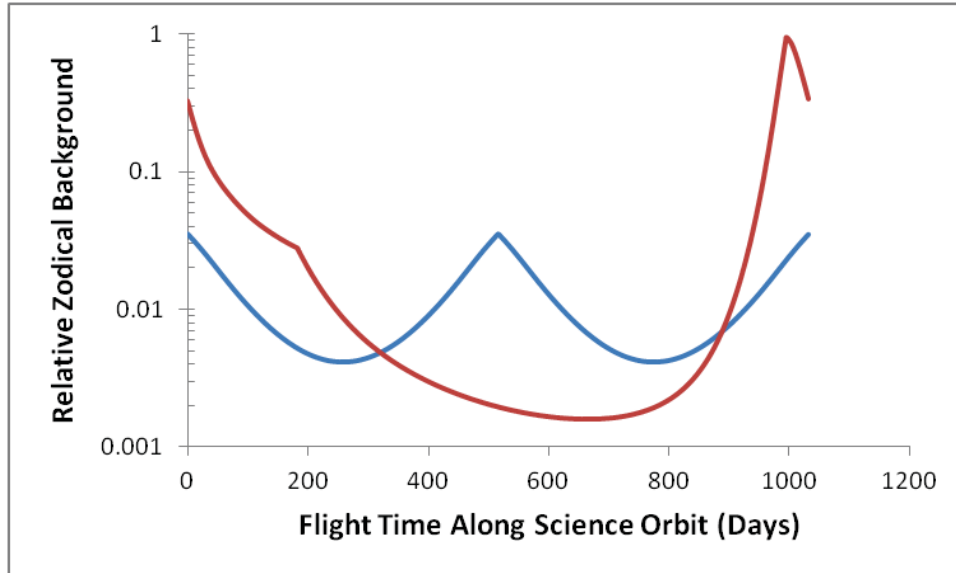
Fig. 13. The relative zodiacal background power toward the ecliptic pole as a function of orbital period is shown for the orbit of Fig. 12 (red) and a zero eccentricity orbit (circular) orbit of the same inclination and semi major axis (blue). The relative power shown is calculated toward the more favorable pole (north or south) depending on position with respect to the ecliptic plane.

3.0 The flagship-class UVOIR successor to the JWST

Most recently, we have used the EMTG to determine if and how the high power SEP system that is a primary technology development objective of the Asteroid Redirect Robotics Mission (ARRM) could be used in conjunction with the Space Launch System (SLS) to place a flagship class 7000 kg observatory into a 2 AU 30 degree dark-sky orbit. A potential application corresponding to this case would be the large UVOIR successor to the James Webb Space Telescope (JWST). A likely central science objective for this mission would be exoplanet imagery and spectroscopy[iii]. Although for many exoplanet mission designs the parent requirement on the telescope aperture is angular resolution, the brightness of an Earth-like exoplanet target (of order 30th magnitude) necessitates an extremely low noise spectroscopic sensor system that is limited by photon noise from the exoplanet's continuum emission and that from the exo-IPD that may surround it. As illustrated in Fig. 9, maximizing point source sensitivity for this application or others, such as deep cosmology imagery, is facilitated by choice of a dark sky orbit in which the noise contribution of our solar system's IPD is eliminated.

One specific case is shown in Figure 14, in which a 2 AU semi-major axis 30 deg inclined orbit is achieved with two Earth fly-bys within a SEP cruise phase of approximately 3 years. The zodiacal background power as a function of time after arrival in the operational orbit would be similar to that shown in Fig. 12 yielding performance gain shown in Fig. 9. The assumed properties for the ARRM-class SEP system are shown in Table 3.
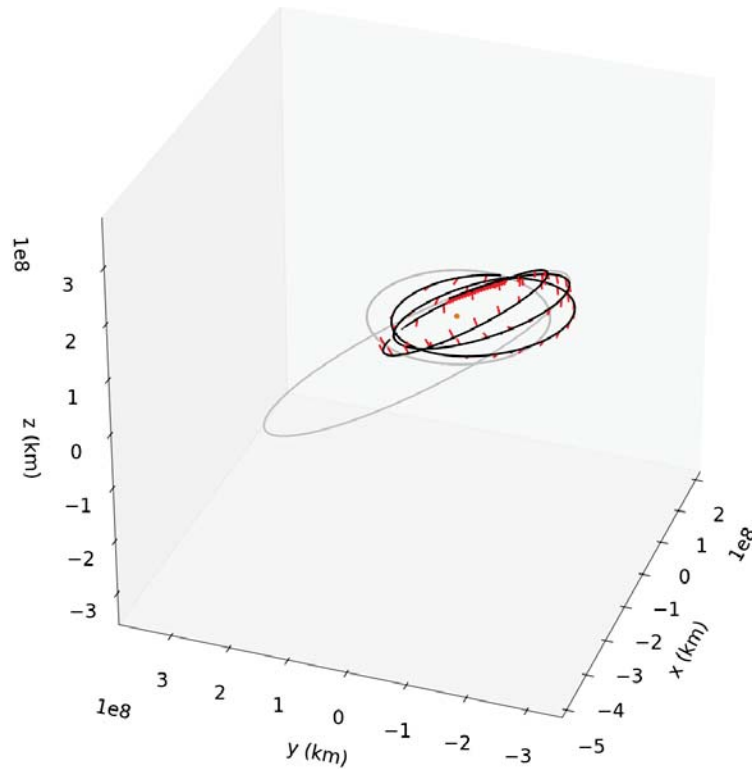
Semi-major Axis (AU)	2
Eccentricity	0.50
Incination (deg)	30
Right Acention of the Acending Node (deg)	165
Argument of Periapsis (deg)	190
True Anomoly (deg)	98
Period (years)	2.82
Flight Time to Arrival (years)	3.08

Date	Event	Location	Altitude (km)	DEC (^{0})	C3 (km^2/s^2)	Mass (kg)
9/14/2023	launch	Earth		-28.5	40.8	12427
9/7/2024	flyby	Earth	300	-17.8	124.7	11026
9/6/2025	flyby	Earth	300	-44.3	228.4	9610
9/7/2026	flyby	Earth	300	-74.4	315.1	8161
10/14/2026	arrival	free point		0		8000

Fig. 14. An elliptical dark sky orbit achieved using the SLS Block 1a and ARRM-class SEP system (Table 3) for a flagship-class 7000 kg science payload. The science performance gain afforded by this orbit is shown in Fig 9. The space vehicle arrival mass includes a 1000 kg dry mass allowance for the SEP system.

Table 3: ARRM-class SEP system parameters assumed for the mission case shown in Fig. 14.	
Array power	50 kW (10% margin)
Bus power during SEP cruise	1 kW
Hall thruster power	40 kW total (90% duty cycle)
ISP (s)	3000 (60% efficiency)
Dry mass	1000 kg

4.0 Discussion

Cost constraints on space science necessitate maximizing the performance of Explorer-class payload programs that can provide frequent access to space by university research teams. Provision of SEP-augmented launch services, such as described here, as government furnished equipment in Explorer and Discovery mission solicitations is a necessary step in ensuring the long-term scientific viability of these programs, and will serve as a key path finding step toward enabling UVOIR flagship successors to the JWST to achieve optimal science performance per unit telescope aperture.

Full return on investment in photon counting detector development can only be realized by enabling missions that utilize them to reach the darkest sky. Making SEP technology available to community proposed astrophysics missions in a cost effective way is the means to that end.

In the EZE study discussed above, we found that provision of SEP through development of an orbit transfer module that is infused into NASA's Explorer and Discovery programs as part of government furnished launch services is practical and cost effective – particularly from the perspective of minimizing cost to support mission applications spanning all NASA space science disciplines. We demonstrated that this approach can offer a clean systems interface to Explorer and Discovery program proposers -- thus enabling build-to-print duplication of a common design for minimization of both non-recurring engineering cost and risk through successive flight heritage of a common design.

We adopted a design approach that accommodates ejection of the module upon orbit insertion in order to support missions with pointing requirements that cannot tolerate low frequency solar array structures (such as high slew rates with low settling time). However, we note that most mission applications would not require separation. Those cases would benefit from several advantages. The NEXT thrusters are gimbal-mounted, and can be used to de-spin reaction wheels in the science payload spacecraft, thus eliminating need for reaction control thrusters. After orbit insertion, excess power from the modules solar arrays can be utilized to achieve higher science data telecommunication rates than those shown in Table 1.

Long cruise time to science operations is the norm in planetary science; however, it is new to astrophysics and inherent to low thrust propulsion. We note that, in a low cost program such as Explorers, the telescope and SEP thrusters cannot be pointed independently beyond the angular range of the thruster gimbals. Hence, ability to do astronomical science requiring pointing over a large field of regard would be restricted during this phase. However, this pointing restriction would not apply to a flagship-class dark sky mission involving a gimbal-mounted or boom-deployed telescope. Design concept examples of boom-deployed configurations include ATLAST (Postman 2012) and SAFIR (Lille & Dailey 2005).

Application of SEP to space science was designated as a priority in the NRC Decadal Survey *Vision and Voyages for Planetary Science in the Decade 2013-2022* (NRC 2011). It is a key enabling technology for human exploration of Mars. The work described in this paper illustrates the potential of this technology toward enabling very high performance UVOIR astrophysics missions. In a literal sense, it has never been "dark time" for UVOIR space astronomers. Application of SEP to astrophysics can change that. In this paper, we illustrate an orbit transfer module design approach that can enable small payload programs across all NASA space science disciplines to benefit from this technology. We further illustrate that launch vehicle and high power SEP systems under development for NASA's Human Exploration Program can be utilized to enable a UVOIR flagship-class JWST successor mission to reach dark sky and thus achieve optimal performance per unit telescope aperture.

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[iii] http://science.nasa.gov/media/medialibrary/2013/12/20/secure-Astrophysics_Roadmap_2013.pdf