Extra-Zodiacal-Cloud Astronomy via Solar Electric Propulsion

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Scott W. Benson[*], Robert D. Falck[†] and Steven R. Oleson[‡]
NASA Glenn Research Center, Cleveland, Ohio, 44135, USA

Matthew A. Greenhouse[§], Jeffrey W. Kruk[#], Jonathan P. Gardner[**],
Harley A. Thronson[††] and Frank J.Vaughn[‡‡]
NASA Goddard Space Flight Center, Greenbelt, Maryland, 20771, USA

and

Dale J. Fixsen[§§]
University of Maryland, College Park, Maryland, 20742, USA

Solar electric propulsion (SEP) is often considered as primary propulsion for robotic planetary missions, providing the opportunity to deliver more payload mass to difficult, high-delta-velocity destinations. However, SEP application to astrophysics has not been well studied. This research identifies and assesses a new application of SEP as primary propulsion for low-cost high-performance robotic astrophysics missions. The performance of an optical/infrared space observatory in Earth orbit or at the Sun-Earth L2 point (SEL2) is limited by background emission from the Zodiacal dust cloud that has a disk morphology along the ecliptic plane. By delivering an observatory to a inclined heliocentric orbit, most of this background emission can be avoided, resulting in a very substantial increase in science performance. This advantage – enabled by SEP – allows a small-aperture telescope to rival the performance of much larger telescopes located at SEL2. In this paper, we describe a novel mission architecture in which SEP technology is used to enable unprecedented telescope sensitivity performance per unit collecting area. This extra-zodiacal mission architecture will enable a new class of high-performance, short-development time, Explorer missions whose sensitivity and survey speed can rival flagship-class SEL2 facilities, thus providing new programmatic flexibility for NASA's astronomy mission portfolio. A mission concept study was conducted to evaluate this application of SEP. Trajectory analyses determined that a 700 kg-class science payload could be delivered in just over 2 years to a 2 AU mission orbit inclined 15° to the ecliptic using a 13 kW-class NASA's Evolutionary Xenon Thruster (NEXT) SEP system. A mission architecture trade resulted in a SEP stage architecture, in which the science spacecraft separates from the stage after delivery to the

[*] NEXT Project Manager, Space Science Projects Office, Scott.W.Benson@nasa.gov
[†] Aerospace Engineer, Mission Design and Analysis Branch, Robert.D.Falck@nasa.gov
[‡] Research Engineer, Mission Design and Analysis Branch, Steven.R.Oleson@nasa.gov
[§] Astrophysicist, Observational Cosmology Laboratory, Matthew.A.Greenhouse@nasa.gov
[#] Research Astrophysicist, Observational Cosmology Laboratory, Jeffrey.W.Kruk@nasa.gov
[**] Chief, Observational Cosmology Laboratory, Jonathan.P.Gardner@nasa.gov
[††] Senior Scientist for Advanced Concepts, Astrophysics Science Division, Harley.A.Thronson@nasa.gov
[‡‡] Aerospace Engineer, Navigation and Mission Design Branch, Frank.J.Vaughn@nasa.gov
[§§] Senior Research Scientist, Department of Astronomy, Dale.J.Fixsen@nasa.gov

mission orbit. The SEP stage and science spacecraft concepts were defined in collaborative engineering environment studies. The SEP stage architecture approach offers benefits beyond a single astrophysics mission. A variety of low-cost astrophysics missions could employ a standard SEP stage to achieve substantial science benefit. This paper describes the results of this study in detail, including trajectory analysis, spacecraft concept definition, description of telescope/instrument benefits, and application of the resulting SEP stage to other missions. In addition, the benefits of cooperative development and use of the SEP stage, in conjunction with a SEP flight demonstration mission currently in definition at NASA, are considered.

Nomenclature

ΔV = velocity change
V_∞ = hyperbolic excess velocity

I. Introduction

SOLAR electric propulsion (SEP) is often considered as primary propulsion for robotic planetary missions, providing the opportunity to deliver more payload mass to difficult, high-ΔV destinations. However, SEP application to astrophysics has not been well studied. This research identifies and assesses a new application of SEP as primary propulsion for low-cost high-performance robotic astrophysics missions. The mission concept, designated Extra-Zodiacal Explorer (EZE), features use of SEP to deliver an Explorer-class spacecraft to an orbit outside the densest regions of the solar system zodiacal cloud. The study was in part formulated around the possibility of using the planned NASA SEP Flight Demonstration vehicle, in conceptual definition within the NASA Office of Chief Technologist (OCT), to serve as the SEP system. The implications of this approach are described throughout this paper.

II. Science Motivation

The goal of this study is to enable the NASA Astrophysics Explorer Program to access orbits that extend outside the zodiacal dust cloud in order to realize a dramatic increase in cosmic discovery potential and achieve major science goals with no increase in telescope aperture over that which is normally associated with this small payload program. This challenge is motivated by long-term downward budget pressure on space astronomy that precludes development of new large aperture flagship-class payloads for the foreseeable future. We find that for an Explorer Class-EX (700 kg) observatory, this goal can be realized today using solar electric propulsion technology that has reached sufficient maturity (Technology Readiness Level-6) for a Phase-A new start and flight during this decade.

The Earth is imbedded in a cloud of dust grains that are produced by comet outgassing and impact fragmentation of asteroids that surround the inner planets. The general morphology of the zodiacal cloud is illustrated in Figure 1. This zodiacal cloud imposes a dramatic limitation on the sensitivity of all space observatories that operate over the optical to far-infrared spectrum in near-Earth zero inclination orbits.

These zodiacal dust grains impact space astronomy observations by producing a background light through which all space observatories have observed. This zodiacal background adds photon noise to the detector signal from astronomical sources. This added noise entirely limits the sensitivity of observatories that are sited at near-Earth in-plane orbits such as the Sun-Earth L2 libration point (SEL2). This situation is analogous to ground-

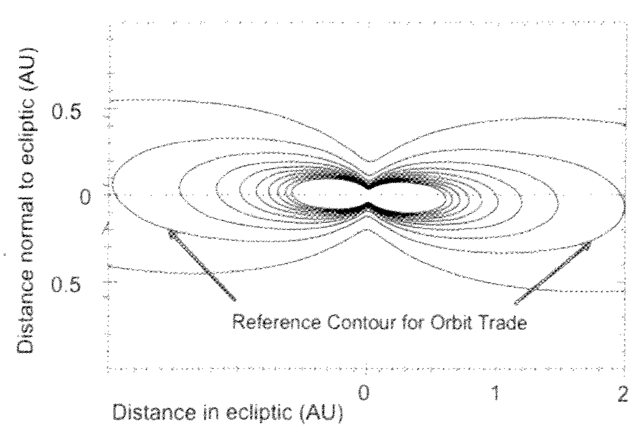

Figure 1. Isodensity contours of the Zodiacal cloud in a plane perpendicular to the ecliptic plane.[1]

based astronomers observing during daylight hours. In a very real sense, it has never been nighttime for optical and infrared space astronomers.

In this study, a mission architecture was developed to deliver an Explorer Class-EX astronomical observatory payload to an orbit outside the high-density region of the zodiacal cloud whose boundary is denoted by the isodensity reference shown in Figure 1.

III. Study Approach and Methodology

Initial analyses demonstrated that the desired spacecraft mass class and orbit could not be achieved, within the cost constraints of an Explorer mission, using chemical propulsion due to the very large mission ΔV's. Attention therefore focused on the use of electric propulsion. The consequent study had the following primary components: low thrust trajectory analyses, spacecraft concept definition, and characterization of science benefits.

A heliocentric target orbit, with semi-major axis of approximately 1.0 astronomical unit (AU) and inclination to the ecliptic plane of 30°, was established for initial low thrust trajectory analyses. Early in the study, a relatively large delivered observatory mass of 1500 kg was assumed. Trajectory searches were performed using available tools. Initial solutions resulted in use of the Atlas V 551 launch vehicle, two Earth gravity assists, and a 30 kW-class ion propulsion system to achieve the objective orbit. This class of mission was consistent with early planning for the SEP Flight Demonstration mission, but lower-cost solutions were sought. Subsequent analysis iterations generated a range of solutions. The team focused on the solution space that was achievable and consistent with Explorer CLASS EX mission payload mass and launch vehicle constraints. A reference case with a 700 kg observatory using an Atlas V 421 launch vehicle, two Earth gravity assists, and a 15 kW-class ion propulsion system provided a baseline with which to advance to the next stage of the study, spacecraft concept definition. Mission analyses further evolved during the concept definition phase as described below. A summary of the final mission analysis results is provided in Section 4.

Spacecraft concept definition was performed through use of the NASA Glenn Research Center (GRC) COllaborative Modeling for Parametric Assessment of Space Systems (COMPASS) team. The COMPASS team is a multidisciplinary concurrent engineering team whose primary purpose is to perform integrated vehicle systems analysis and provide conceptual designs and trades for both Exploration and Space Science Missions. COMPASS study pre-work consisted of mission analysis described above, validation of the 700 kg observatory mass, selection of the spacecraft/SEP architecture, and establishment of concept objectives. The 700 kg observatory mass target was validated by surveying a range of low-cost NASA observatory spacecraft and comparing their sizing and capabilities. The GRC and Goddard Space Flight Center (GSFC) study members reviewed this information and approved the 700 kg assumption as an input to the COMPASS study. The selected architecture consists of an observatory spacecraft with a separable SEP stage that is controlled by the spacecraft. The separated SEP vehicle was preferred for two primary reasons: 1) it is aligned with the general intentions of the SEP Flight Demo project, and 2) to minimize mass and momentum disturbances on the observatory for the science phase of the mission. Control of the SEP stage by the spacecraft reduces the SEP stage development and recurring cost. The primary objectives that influenced the COMPASS study included:

- Ensure that the observatory spacecraft would fit within the Explorer-EX class, including accommodating the impact of flying on the SEP stage assumed to be provided by the OCT project.
- Avoid low-TRL technologies in both the SEP stage and observatory; resulting in selection of the NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system and Orion-based UltraFlex solar arrays.
- Provide a capability that could be utilized by a variety of observatory missions, and thus is compatible with the competed Explorer-EX program approach.

The COMPASS study generated mission concepts for two destination orbits and performed a top-level comparison study with the representative 700 kg observatory in a more traditional near-Earth orbit. As the study evolved, the second destination orbit with semi-major axis of approximately 2.0 AU and 15° inclination to the ecliptic plane was developed in detail and provided a more favorable result. In addition, collaborative, iterative analyses allowed the team to baseline the Falcon 9 launch vehicle and still meet the mission trajectory objectives. This was a key accomplishment in fitting the resulting mission into an Explorer-EX mission class. The results of the COMPASS concept definition study are described in Section 5 of this paper.

A key element of the overall effort was to characterize the benefits provided by performing science in the resulting mission orbits; however, detailed description of the methods to quantify these benefits are outside the scope of this paper and will be reported in other technical forums. The general results of this assessment are presented in Section VI.

IV. Mission Analysis

The EZE Mission study developed two possible science orbits; a highly inclined (~30°) heliocentric orbit with a semi-major axis of 1 AU, and a less inclined heliocentric orbit (~15°) with a semi-major axis of 2 AU. The major figures of merit for mission performance were the time required to reach the science orbit, the flux of the Zodiacal dust as the spacecraft operates in its science orbit, and the communications distance from the spacecraft to Earth during science orbit operations. The 1 AU/30° case is designed to keep the communication distance to the spacecraft at a minimum, while the 2 AU/15° case reduces the interference of the Zodiacal dust cloud without requiring such a large plane change. Following the analysis of the two options, the 2 AU/15° case is baselined, and further reported here, due to its superior science performance.

Mission analysis is conducted using MALTO 5.2.6[2]. The launch opportunity is mid-2020 based on the expected release year of an Explorer-EX announcement of opportunity, and the exact optimal launch date will be shown in the results below. This launch window provides the opportunity for a Mars flyby, which provides a significant benefit to the mission. Based on the dry mass of the spacecraft, MALTO is operated to minimize the total mission flight time while delivering no less than 1439 kg of mass, including the observatory spacecraft and dry SEP stage, to the target orbit.

The launch vehicle is modeled as a Falcon 9 Block 2, with a vehicle adapter mass of 40 kg and a mass contingency of 10%. To ensure that the launch vehicle performance curve is not applied to high declination departures, the declination of the Earth departure asymptote is limited to +/-28.5°. Before accounting for contingency and adapter mass, the launch vehicle performance is modeled using the following equation:

$$2490.88 - 72.1167 \cdot V_\infty + 0.614262 \cdot V_\infty^2 - 0.00280389 \cdot V_\infty^3$$

The nominal power generation of the solar arrays at 1AU is 13 kW. Of that, 500 W is dedicated to the non-propulsion aspects of spacecraft operation during thrusting periods. A propulsion duty cycle factor of 90% is used to model periodic coast periods for communications, navigation, and other functions best performed when the engines are not firing. The solar array model used is the "Lockheed UltraFlex" model as given in MALTO GUI v2.5.7.

The propulsion system utilizes two NEXT thrusters assuming a "P10 High Thrust" throttle table[3]. The thruster switching strategy is set to run as many thrusters as possible given the current power. In general, ion thrusters tend to run at higher specific impulses at higher input power, so dividing the power between two thrusters will reduce the specific impulse but increase the thrust, reducing the trip time.

The science mission orbit for EZE only has a few loose constraints on its parameters. For this analysis, we assumed a circular orbit of approximately 2 AU in semi-major axis with zero eccentricity. The 15° inclination is chosen based on what seemed to be an achievable goal in approximately 2 years of flight time. With zero eccentricity, the argument of perihelion of the orbit is effectively irrelevant, so a value of 0° is used. Two elements of the orbit are thus undefined; the right ascension of the ascending node and the mean anomaly.

The elements of the optimal target orbit are given in Table 1. Table 2 summarizes some of the key features of the resulting trajectory. Not only is the vehicle capable of getting to the science orbit in just over two years, but the propellant throughput is less than the capacity of a single NEXT thruster[4].

Table 1. EZE Science Orbit Elements

Semi-major axis (km)	300 000 000
Eccentricity	0
Inclination (deg)	15
Right ascension of the ascending node (deg)	73.0813
Argument of periapsis (deg)	0
Mean anomaly (deg)	-66.0805

Table 2. Trajectory summary

Earth departure date	June 20, 2020
Earth departure mass (kg)	1823
Earth departure hyperbolic velocity (km/s)	2.48
Mars flyby altitude (km)	1000
Mars flyby hyperbolic velocity (km)	3.51
Science orbit arrival date	June 22, 2022
Science orbit arrival mass (kg)	1439 kg
Total Time of Flight (days)	731
Total xenon propellant expenditure (kg)	384

Figure 2 shows the trajectory inclination history as a function of time. The Falcon 9 at launch provides about three degrees of the inclination change, and roughly four degrees comes from the Mars flyby maneuver, which is the