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New Opportunities for Outer Solar System Science using Radioisotope Electric Propulsion

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Summary

Today, our questions and hypotheses about the Solar System's origin have surpassed our ability to deliver scientific instruments to deep space. The moons of the outer planets, the Trojan and Centaur minor planets, the trans-Neptunian objects (TNO), and distant Kuiper Belt objects (KBO) hold a wealth of information about the primordial conditions that led to the formation of our Solar System. Robotic missions to these objects are needed to make the discoveries, but the lack of deep-space propulsion is impeding this science. Radioisotope electric propulsion (REP) will revolutionize the way we do deep-space planetary science with robotic vehicles, giving them unprecedented mobility. Radioisotope electric generators and lightweight ion thrusters are being developed today which will make possible REP systems with specific power in the range of 5 to 10 W/kg. Studies have shown that this specific power range is sufficient to perform fast rendezvous missions from Earth to the outer Solar System and fast sample return missions. This whitepaper discusses how mobility provided by REP opens up entirely new science opportunities for robotic missions to distant primitive bodies. We also give an overview of REP technology developments and the required next steps to realize REP.

Scientific Motivation and New Opportunities

Previous Decadal Survey contributions have summarized the science that can be addressed by robotic missions to small primitive objects [1]. The two broad issues are the role of primitive bodies in forming proto-planets and subsequently planets and their role as reservoirs of organic material, the precursors of life. The recent discovery of glycine amino acid in the Stardust sample from comet Wild 2 indicates that both in-situ measurement and sampling of primitive bodies will be essential to understand the early organic conditions on the planets and their moons. Developments in solar electric propulsion (SEP) have preceded the latest advancements of inner Solar System science as evidenced by the Hayabusa mission to asteroid Itokawa and the Dawn mission on route to Ceres and Vesta. But far from the Sun, the lack of deep-space propulsion and power for robotic vehicles is virtually crippling the process of discovery in the outer Solar System.

Comparatively little is known about objects beyond Saturn even though these worlds can tell us the most about conditions in the early Solar System. The planets Uranus (19 AU) and Neptune (30 AU) have yet to be visited by robotic orbiters. Some of their satellites include Kuiper belt objects (KBO) captured long ago which now orbit these gas giants. Unexplored minor planets, like the so-called Centaurs, are in various orbits between Jupiter and Neptune. Some of these objects display comet-like properties and likely contain primitive organics, such as Echeclus (11 AU) and Chiron (14 AU). The inner Kuiper belt is known to contain a huge population of primitive objects in orbits between 30 and 50 AU. The best known, Pluto, will be the subject of a brief fly-by in 2015 by New Horizons. Remarkably, the number of TNO's falls off dramatically beyond 50 AU, the so-called Kuiper Cliff. The region beyond, the scattered disk, seems to be made up of a few large objects in eccentric orbits, possibly deflected there by Neptune. Orbital observation, in-situ measurement, and sampling of even a few of these worlds with self-propelled, robotic craft would completely change our scientific understanding of primitive objects and the origin of our Solar System.

With so many objects available and a practical limit on the number of robotic vehicles we can send, a premium is placed on visiting *nearby, unique objects* and *distant collections of objects*. A key point is that visiting a collection of objects permits an incredible amount of science to be accomplished by one mission. Large bodies in the outer Solar System are gravitational repositories of primitive objects collected over eons. The planets Uranus and Neptune, the Pluto system, and large Kuiper objects will be very rewarding targets for robotic vehicles. Uranus has about 30 major satellites, at least eight of which are in retrograde orbits, suggesting they are captured objects (diameters 20 to 150 km). Neptune has at least 13 major satellites and four of these are probably captured objects in retrograde orbits, including its largest satellite, Triton (2700 km diameter). Like the inner giant planets, Uranus and Neptune are also expected to host a myriad of kilometer to sub-kilometer-size "moonlets". The Pluto system with its three satellites Charon, Nix, and Hydra represents a diverse sample of trans-Neptunian objects (TNO), all in a single location. Haumea, the fastest rotating large TNO (four-hour rotation period), and its two large satellites are probably the result of a collision and would tell us much about the formative stages of the outer Solar System.

Table 1: Largest known trans-Neptunian objects (TNO) and their satellites

Name	Distance AU	Diameter km	Density g/cc	Surface materials/ Albedo	Orbit/Period/ Inclination	Moons/Diameter
Eris	97	2400	2.3	tholins, methane 0.86	38 - 98 AU 557 yrs 44 degr	Dysnomia (150 km)
Pluto	33	2300	2	tholins, CO, methane, ethane 0.6	30 - 49 AU 248 yrs 17 degr	Charon (1200 km) Nix (50-140 km) Hydra (60-160 km)
Makemake	52	1500	2	tholins, methane, ethane 0.8	38 - 53 AU 310 yrs 29 degr	
Haumea	50	1500	3	water ice, silicate clays 0.7	35 - 52 AU 283 yrs 28 degr	Hi'iaka (310 km) Namaka (170 km)
Sedna	88	1500	2	tholins, methane 0.2	76 - 975 AU 12000 yrs 12 degr	
Quaoar	45	1200	2	tholins, water ice 0.2	42 - 44 AU 288 yrs 8 degr	one known (95 km)
Orcus	48	950	1.6	water ice, ammonia ice 0.2	30 - 48 AU 245 yrs 21 degr	one known (250km)

Table 1 summarizes the larger trans-Neptunian objects and their known satellites, as obtained from various data in the open literature. Surface compositions and albedos of TNO's and their satellites vary greatly. A key objective is to map the surface elemental composition of these bodies, including the abundance of the major rock-forming elements (O, Mg, Al, Si, Ca, Ti, and Fe), trace elements (Gd and Sm), long-lived radioactive elements (K, Th, and U), and light elements such as H, C, and N, which are the major constituents of ices and organics. In-situ measurement of the surface by a contacting vehicle will yield the most data short of actual sample return. The weak surface gravity of the smaller bodies (10^{-4} to 10^{-2} g for 3 to 300 km diameter objects) makes direct surface contact possible for a free-flying robotic vehicle using a combination of small chemical and Hall thrusters (no separate lander is needed). For objects with diameters of order a kilometer or less, gridded ion thrusters are adequate for contact and lift-off (~10^{-5} g), as demonstrated by the Hayabusa craft which made surface contact with asteroid Itokawa.

The typical instrumentation for orbital and in-situ measurements will include X-ray/gamma ray/neutron spectrometers, neutral gas/ion spectrometers, UV – IR imaging spectrographs, multi-spectral camera with imaging detector, laser rangefinder, and magnetometer. Today's asteroid/comet missions are power-limited to typically less than 100 W of power for scientific instruments. An important change occurs in the way deep-space science is done once radioisotope electric propulsion is on-board. Propulsive power will be at the kW level, and all of this power is available for science and communications when the thrusters are off. Future missions will no longer be power-constrained, but mass-constrained. REP missions will be able to carry more power-intensive instruments such as hundred-watt imaging radars and LIDAR (light detection and ranging) as well as more capable versions of other instruments. More power also means higher data transmission rates are possible during intensive scientific measurements.

Because of the high scientific pay-off, collections of primitive bodies at Uranus, Neptune, and Pluto, and special, nearby minor planets are high priority targets for rendezvous missions. Haumea, Orcus, and Quaoar are equally interesting collections but farther away (> 45 AU). Quaoar is only 14 AU from Pluto in the present era, making it a second target for a combined Pluto-Quaoar mission. Small TNO's offer special science opportunities since surface contact can be made by an electric propulsion vehicle for in-situ study. These are all distant and cold worlds where there is insufficient light for heat or solar electric power. We will need deep-space propulsion so our robotic vehicles can rapidly fly out, rendezvous with, and then maneuver in proximity with these objects. Ultimately we want to return kilogram size samples to Earth on a timescale relevant to investigators. This new robotic mobility will have far reaching implications for how we do space science in the future, including enhanced human exploration with compact, self-propelled robotic vehicles for in-situ science. As we discuss next, recent developments indicate that REP will soon enable robotic craft to explore these distant worlds.

REP Performance for Outer Solar System Missions

In this section we present an overview of REP for deep-space missions. A detailed discussion of REP performance for many outer Solar System missions is presented in the companion paper of Khan et al in these Decadal Survey proceedings [2]. Low-thrust, electric propulsion (EP), which expels ions at high velocity to attain a large momentum transfer with less propellant, is a recognized technology for high energy missions. Ion thrusters have been used on a number of inner Solar System missions powered by solar cells. Far from the Sun, solar electric propulsion is not usable, and a nuclear power source is needed. Nuclear reactors are efficient for 10 kW and higher powers, but robotic craft only require about a kilowatt of power (the maximum EP power for the 1200 kg Dawn craft is about 2 kW). These lower powers are well suited to the application of radioisotope electric propulsion. Plutonium-238 (87-yr half-life) has been commonly used as the heat source to generate electricity. Supplies are presently limited, but there is recognition that new Pu238 production is needed to continue deep-space science [3]. To convert heat to electricity, thermoelectric semiconductor unicouples have been used historically, but their 6% efficiency is too low for EP. Other options with no moving parts include advanced semiconductor multi-couples and infrared thermo-photovoltaic cells. Dynamic engines like the Stirling alternator are an option if lifetime can be assured. With any of these options, the specific mass of near-term REP systems is expected to be in the range of 100 to 200 kg/kW (5-10 W/kg).

The key reason that REP is useful for robotic science missions in the outer Solar System is that in a weak gravitational field, flight time τ and delta-v capability are only weakly dependent on a propulsion unit's specific mass α (ideally $\tau \sim \alpha^{1/3}$, $\Delta v \sim \alpha^{-1/3}$ for a free-space rocket). Initial REP feasibility studies demonstrated this was the case [4, 5], and later detailed mission studies by several workers confirmed the suitability of REP for robotic propulsion, especially for Uranus and Neptune orbiters and outer Solar System missions involving small bodies [6-8]. These analyses included the trade-offs in performance imposed by available launch vehicles. It was found that if one can afford a larger chemical rocket to provide a high excess velocity at Earth escape, then REP can be used almost exclusively for the deceleration and orbital maneuvers at the destination. This enables faster rendezvous missions to the outer planets (Figure 1) [6]. Recently a complete REP mission design was presented for a 10-year rendezvous with the Centaur object Thereus (11 AU), including vehicle design, science, power and mass budgets [9].

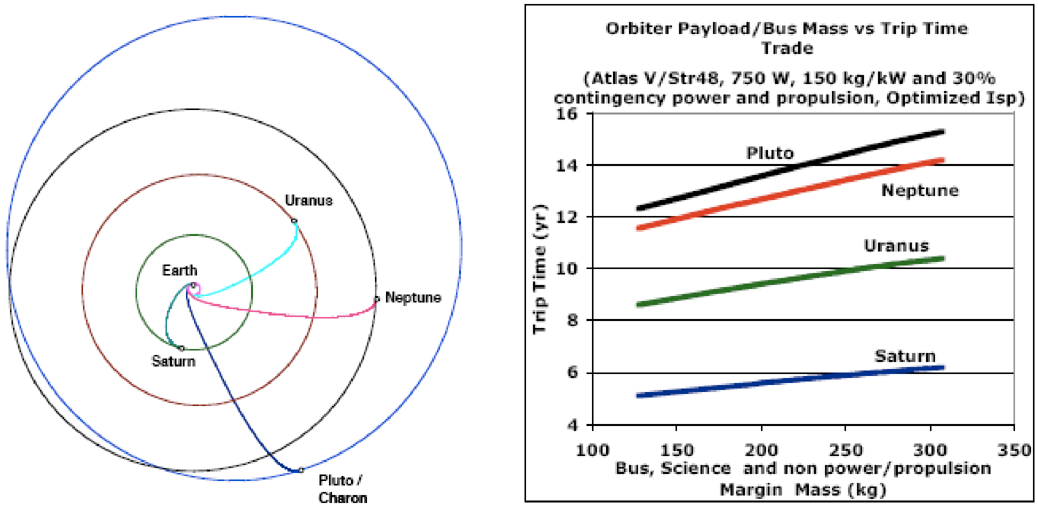

Figure 1: Rendezvous flight time to the outer planets with chemical rocket acceleration from Earth and REP deceleration at the destination (Ref. 6).

Some of the most challenging future missions will be sample return from primitive objects. Fast sample return from deep-space is prohibitive using chemical propulsion, but it becomes feasible with REP. Recently an initial study was made of REP performance for fast sample return from extreme distances of 30 to 100 AU [10]. Assuming that a parent robotic vehicle had already flown out to some distant object, this study calculated the return time for a dedicated REP, sample-return capsule. To permit a high-speed return, limited REP deceleration occurs prior to direct atmospheric entry at Earth. Return times are less than 14 years from as far away as 50 AU, as shown in Figure 2.

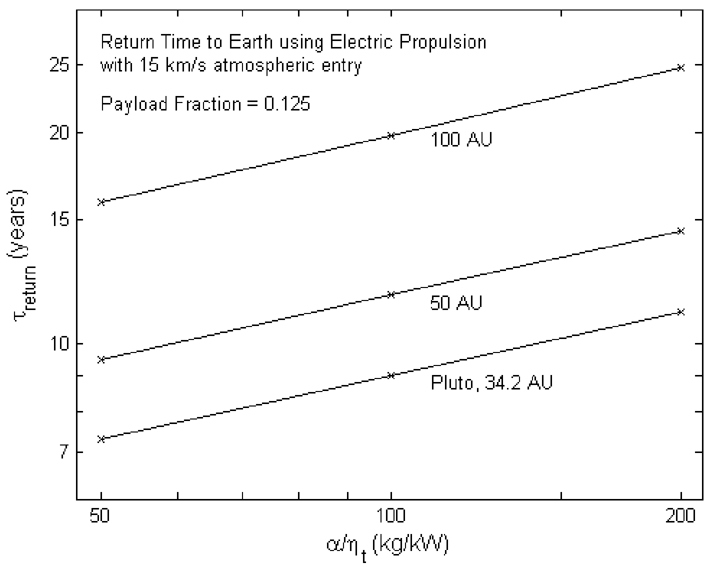

Figure 2: Return time to Earth from different distances as a function of powerplant specific mass. Near-term REP specific mass is in the range 100-200 kg/kW (Ref. 10).

REP Technology Status

Robotic science craft have low-power instruments requiring a kilowatt or less of power. This power range is well suited for REP spacecraft, whose electric power will be fully available for science when thrusters are off. REP hinges on two important technologies: (1) long lived, sub-kW to kW-class electric thrusters capable of several thousand seconds of specific impulse, and (2) high specific power Radioisotope Power Systems (RPS) [11].

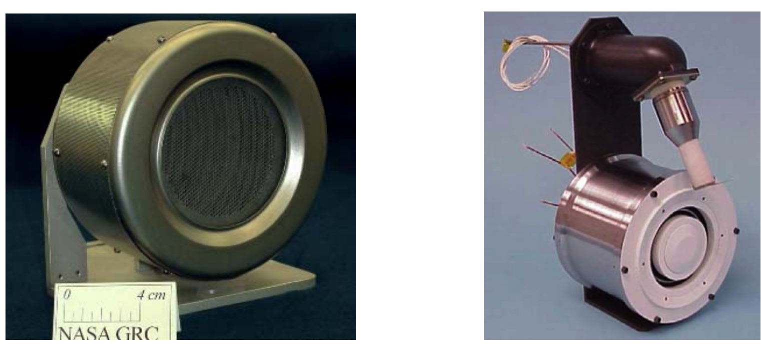

Figure 3: a) NASA 8-cm Ion Thruster and b) Busek BHT-600 Hall Thruster.

Electric Propulsion

Most REP studies have assumed the use of ion thrusters with power levels of about a kilowatt or less. Ion thrusters are best suited for specific impulses (Isp) above 3000 sec, as required for multi-year missions. The 30 cm, NSTAR thruster of Deep Space 1 operated for about 16,000 hours at the kilowatt level, but its mass is relatively high. A lightweight ion thruster that can operate continuously at the kilowatt to sub-kilowatt power level for many years does not yet exist. But recent thruster work makes such a development relatively straightforward. Until the early 2000's, NASA Glenn Research

Center had a project to develop a low-mass, sub-kilowatt ion propulsion system [12]. Fabrication and performance assessment of a 250 W, 8-cm beam diameter laboratory thruster (Fig. 3a) was completed in 1998. Fabrication of a second-generation thruster with a 100-500 watt throttling envelope was also performed [13,14]. All thrusters require an efficient power processing unit (PPU). Experience from flown EP units and new concepts are yielding low-mass PPU designs suitable for lightweight REP craft [15].

Another form of electric propulsion suitable for REP systems is the Hall thruster. These operate at lower Isp than ion thrusters, but are simpler and less expensive. Commercial Hall thrusters exist today that fit the general power level and many of the performance requirements for small REP spacecraft. Hall thrusters have been considered in only a few REP studies because of their limited lifetime (~2,000 hrs), arising from erosion of the thruster's insulating channel. NASA Glenn is currently developing a technology to increase lifetime and Isp. This has been verified through wear testing of a 3.5 kW laboratory Hall thruster (the NASA-103M.XL), for more than 4,700 hours with an Isp of up to 2,800 sec [16,17]. NASA Glenn and Busek are incorporating this improvement into the BHT-600 thruster under NASA's Innovative Partnership Program (Fig. 3b).

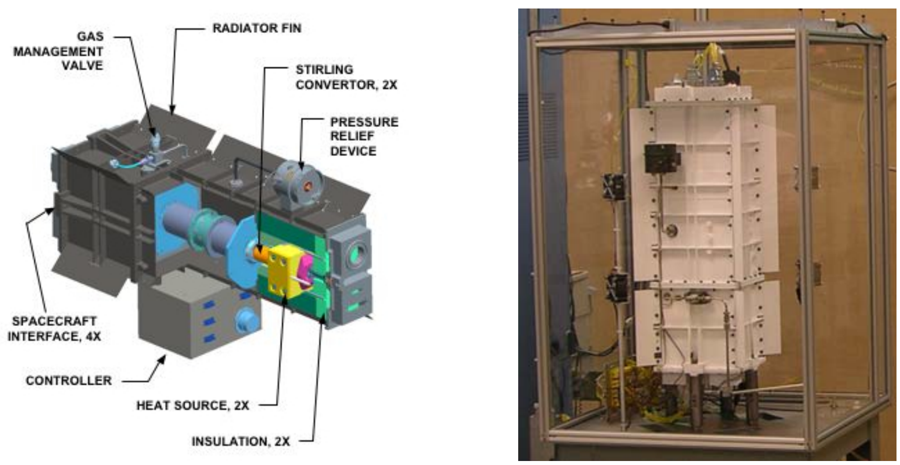

Figure 4: Advanced Stirling Radioisotope Generator (ASRG) and Engineering Unit.

Advanced Radioisotope Power

A major technical challenge to realize REP is the development of advanced RPS with a high specific power ≥8 We/kg, a significant advancement over the General Purpose Heat Source (GPHS)-RTG used since 1989 (~5.2 We/kg). DOE and NASA are developing the ASRG Engineering Unit (EU), an advanced RPS prototype (Fig. 4) [18, 19]. The ASRG employs a dynamic Stirling conversion cycle with an efficiency of over 30%, about five times higher than thermoelectric generators. The ASRG-EU uses two opposed Advanced Stirling Convertors (ASC) and will produce about 140 We at 6 We/kg. System-level testing of the ASRG-EU began in early 2008, followed by extended duration testing at NASA Glenn starting in fall 2008. A higher temperature ASC is under study to reach higher specific power. The project is making progress to achieve a Technology Readiness Level (TRL) of 6 (system demonstration in relevant environment) and provide flight-qualified units for a possible 2013 Discovery mission. After first demonstration, the 150

We ASRG will become the building block for New Frontiers-class missions. A 500 We building block is under study for REP Flagship missions. The ASRG's high efficiency can enable an REP Pluto orbiter with the same amount of Pu238 as used for the New Horizons flyby and Neptune or Kuiper-belt orbiters with the same amount as Cassini.

Next Steps

Radioisotope electric propulsion opens up new science opportunities for rendezvous and sample-return missions to small primitive bodies and planet satellites. Like all deep-space science missions, REP needs a reliable supply of radioisotope, and Pu238 production must be restarted. Mission studies have determined the RPS and EP requirements to realize REP, but an adequately funded, coordinated program is needed to develop an REP prototype. This would become the basis for an off-the-shelf, multi-mission REP module. The next steps for advanced RPS are to increase specific power to ≥8 We/kg, construct a prototype with heater head and controller, flight test a 150 We unit, qualify the new technology's lifetime for 15-20 year missions, develop larger heat sources for advanced 500 We generators, and reduce radiator mass. The critical next steps for thrusters are to increase efficiency to 65-75% at powers below 3 kW, improve lifetime for >600 kg mass throughput, and reduce PPU mass. Only if resources are provided can development remain on track to provide radioisotope power generators and lightweight propulsion systems for missions in the 2013-2023 decade. To guide these efforts and provide clear goals, a dialogue must begin between the science and technology communities to define the first generation of REP science missions.

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