TRAJECTORIES TO COMETS USING SOLAR ELECTRIC PROPULSION

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In situ analysis of a cometary nucleus and return of a sample are high priority scientific goals. Rendezvous and sample return trajectories to comets using low-thrust ion propulsion are presented. Several launch opportunities exist for each comet apparition, providing flexibility in mission design. Compared to chemical propulsion, ion propulsion is shown to reduce the propellant mass by over 60%, enabling the use of a smaller launch vehicle, while also reducing the flight time by several years.

INTRODUCTION

Comets are thought to have formed in the outer solar system, condensing from the ancient solar nebula at the same time as the outer planets and their satellites. Due to their small sizes and cold storage in the far reaches of the solar system, comets could have preserved the chemical mixture from which the giant planets formed. Composed of ices, dust, and carbon-based compounds, they also played an important role in the evolution of the terrestrial planets by delivering a significant fraction of the elements important to life. Hence, the in situ study and return of cometary samples are among the highest priority goals of the planetary program.

At least three missions are scheduled to fly by comets over the next several years. These flybys provide brief close-up glimpses of the comets, but they are unable to directly sample the pristine composition of the nucleus. Obtaining a meaningful sample requires rendezvousing with the comet; analyzing the sample thoroughly requires returning the sample to Earth. These types of missions are difficult to accomplish because of the high energy necessary to match the orbit of a comet – even those with relatively short periods (< 8 years). Missions using chemical propulsion alone require gravity assists and many years to rendezvous with a comet in order to deliver a reasonable mass using an affordable launch vehicle.

Highly efficient electric propulsion systems can be used to enable smaller launch vehicles and/or reduce the trip time over typical chemical propulsion systems. This technology has been demonstrated on the Deep Space 1 mission[1] – part of NASA's New Millennium Program validating technologies which can lower the cost and risk and enhance the performance of future missions. With the successful demonstration on Deep Space 1, future missions can consider electric propulsion as a viable propulsion option.

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In this paper, we present several trajectories to comets using solar electric propulsion (SEP). We describe the characteristics of both rendezvous and sample return trajectories and make a direct comparison with a trajectory using chemical propulsion.

APPROACH

The preliminary design software used in this study to discover and analyze the SEP trajectories simultaneously integrates the equations of motion and the costate or variational equations. A two-point boundary value problem is solved to satisfy terminal constraints and targeting conditions. A more detailed description of the program can be found in Reference 2.

The SEP engines are modeled by approximating the thrust and mass flow rate as polynomial functions of the power available from the solar arrays. Measurements of these characteristics for the NSTAR 30 cm ion thruster have been made at the NASA Lewis Research Center[3] and at the Jet Propulsion Laboratory[4] and have been estimated from the performance of Deep Space 1. We assume up to two thrusters operating simultaneously for rendezvous missions and up to three for sample return missions. During the thrusting periods, the engines are assumed to operate with a 90% duty cycle (on for 90% of the time). The remaining 10% of the time can be used for spacecraft operations which require the engines to be off.

We assume a Delta 7925 launch vehicle with a 5% contingency for rendezvous missions and a Delta IV Medium with a 10% contingency for sample return missions. The launch dates extend from 2002 to 2007. We typically optimize the spacecraft mass over a range of solar array power levels. Of the total power generated by the solar arrays, 450 Watts is dedicated to the spacecraft, and the remaining power is available to the SEP engines.

RESULTS

Rendezvous

The first step is to rendezvous with a comet by matching its position and velocity. A trade-off exists between using the launch vehicle to provide an initial velocity relative to the Earth and using the SEP system to provide the remainder of the ΔV. Since the SEP system is much more efficient in terms of specific impulse, the optimization tends to favor using the SEP system as much as possible. However, the ion engines have a maximum power, and hence a maximum thrust, at which they can operate. So orbital phasing, mission duration, and SEP operational conditions lead us toward particular types of trajectories.

A typical trajectory using SEP to rendezvous with a comet completes more than one revolution around the Sun and rendezvous shortly after the comet's perihelion passage. An example of this type of trajectory to the comet Brooks 2 is shown in Figure 1. The part of the trajectory drawn with a solid line in the figure indicates when the engines are thrusting. There is an optimal coasting period in this trajectory which lasts about one year between the initial and final thrusting arcs.

Launch from Earth occurs close to when the Earth crosses the longitude of the perihelion of the comet's orbit – about 2.7 years before the comet reaches perihelion in this case. Launch can occur about one year earlier or later with the same type of trajectory. Launching a year earlier requires the aphelion radius of the trajectory to be much larger to ensure proper timing with the comet. The larger aphelion radius requires a bigger boost from the launch vehicle. Since the launch vehicle is less efficient than the SEP system, the delivered spacecraft mass is smaller with an earlier launch date. Launching a year later doesn't give the SEP system much time to accumulate ΔV. Even with a locally optimal trajectory, the spacecraft is launched in an undesirable direction, the SEP system expends propellant to correct for the phasing, and rendezvous occurs further from the Sun where the thrusters are less efficient.

One way to alleviate the large aphelion radius required when launching a year earlier on this type of trajectory is to complete a second revolution around the Sun. The launch vehicle contribution is reduced, placing more of a burden on the efficient SEP system. An example of this type of trajectory to Brooks 2 is shown in Figure 2. Similarly to the single revolution trajectory type, we can launch a year earlier using two complete revolutions by increasing the aphelion radii of both revolutions. Since the increase can be split between the two revolutions, the trajectory alteration is less severe than when using only one complete revolution. A summary of trajectories to Brooks 2 is given in Table 1.

Table 1

TRAJECTORIES TO BROOKS 2

Launch Date	Number of Complete Revs	Launch C_3 (km^2/s^2)	Prop Mass (kg)	SC Mass (kg)	Flight Time (years)
8/5/03	2	1.2	340	863	4.93
9/1/04	2	1.2	341	862	4.54
8/23/04	1	18.4	170	671	3.78
8/12/05	1	9.7	237	769	3.14
6/30/06	1	12.2	320	634	2.81

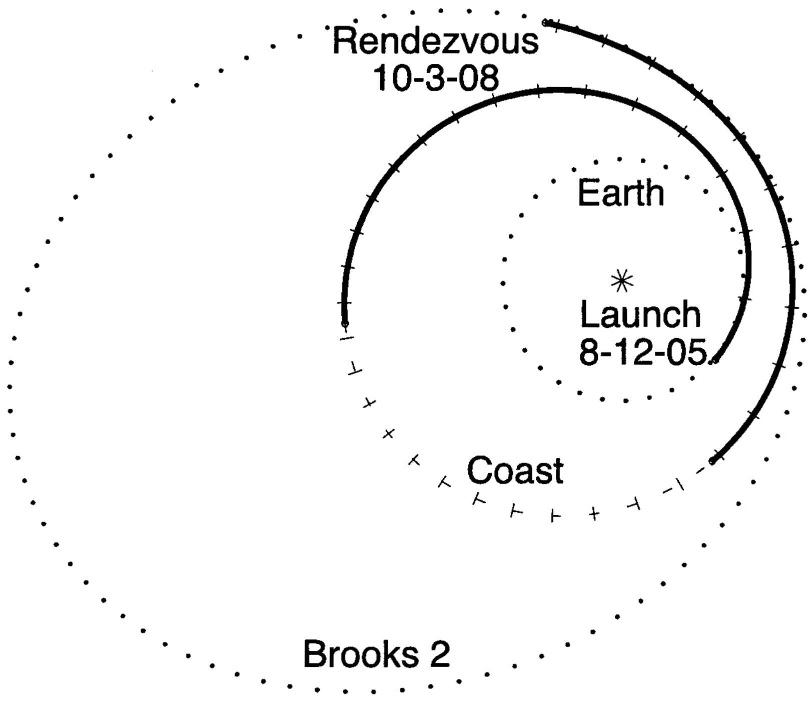

Figure 1 Brooks 2 Rendezvous with One Complete Revolution

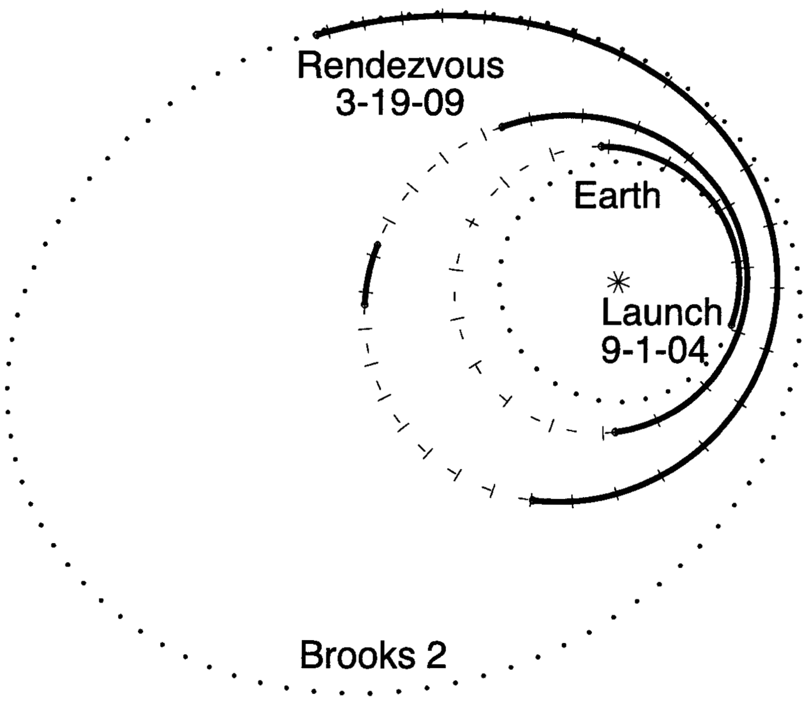

Figure 2 Brooks 2 Rendezvous with Two Complete Revolutions

Sample Return

To return a sample to Earth, we must depart the comet and intercept Earth. The best rendezvous trajectory as the first part of a sample return mission is not always the same as the best trajectory for a rendezvous mission. Again, there are lots of trade-offs. The ion engines require a minimum power (~500 Watts) to operate. The aphelion radii of comets are often 5 AU or more. So without extremely large solar arrays, the thrusters cannot operate on portions of the return trajectory, and the spacecraft must depart the comet at a reasonable distance from the Sun. Hence, trajectories which rendezvous earlier without much performance loss are better for sample return missions. For the same reasons, the optimal rendezvous date for a sample return mission is usually earlier than for a rendezvous mission.

A trajectory for a sample return mission to the comet Brooks 2 is shown in Figure 3. The rendezvous portion of the trajectory is very similar to the trajectory in Figure 1, but note that the optimal rendezvous occurs more than two months earlier for the sample return mission. In this particular case, we are constrained to stay at the comet for at least 90 days. The total propellant mass for the ion engines for this trajectory is 558 kg and the remaining spacecraft mass at launch is 1279 kg.

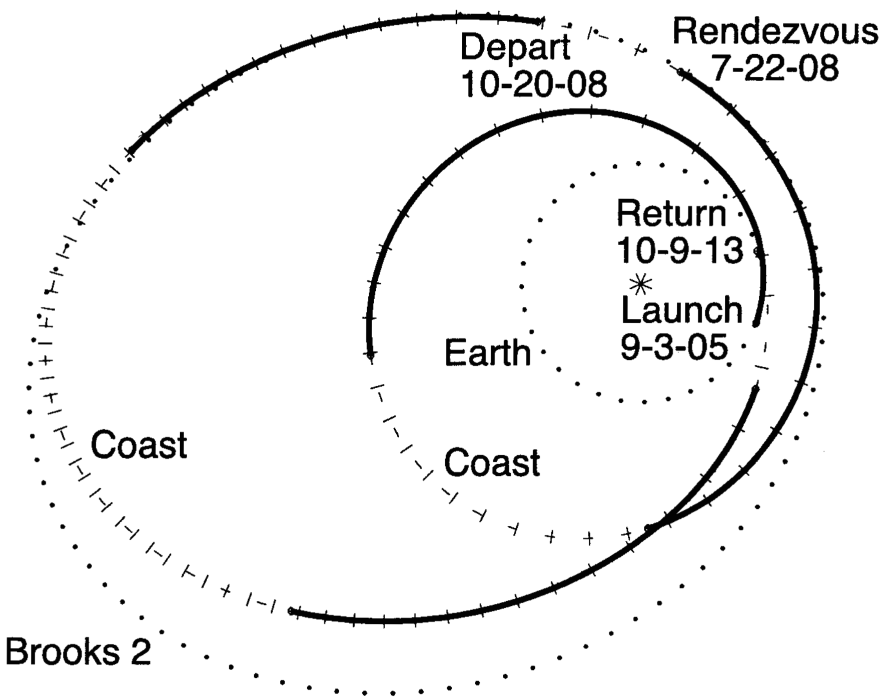

Figure 3 Brooks 2 Sample Return

The amount of ΔV required on the return leg can vary substantially for missions to different comets. Several missions have much lower requirements than the one to Brooks 2 shown in Figure 3. Using a chemical engine to achieve the Earth-intercept trajectory on the return leg can have several operational advantages. The required propellant mass is much greater using a chemical engine; however, for missions with low ΔV requirements on the return leg, a return using chemical engines may be viable.

Comparison between Missions Using SEP and Chemical Propulsion

Trajectories which rendezvous with comets require substantial ΔV – on the order of 10 km/s. Using highly efficient ion propulsion instead of chemical propulsion can result in tremendous advantages in terms of spacecraft mass, flight times, and launch vehicle. A comparison of trajectories to the comet Wirtanen is shown in Table 2. The example using chemical propulsion is based on the Rosetta mission.

Table 2

MISSION TO WIRTANEN

	Rendezvous	**Rendezvous**	**Sample Return**
Launch Vehicle	Ariane 5	Delta IV Medium	Delta IV Medium
Spacecraft Propulsion	Chemical	Ion	Ion
Trajectory Type	Mars-Earth-Earth Gravity Assist	SEP with One Complete Rev	SEP
Flight Time (years)	9.1	2.6	7.1
Injected Mass (kg)	2900	1830	1830
Propellant Mass (kg)	1600	510	540
Spacecraft Mass (kg)	1300	1320	1290

CONCLUSION

Low-thrust, highly efficient ion propulsion allows several launch opportunities for each comet apparition. Rendezvous trajectories which complete two revolutions around the Sun generally take longer than those that complete only one, but they often result in a higher spacecraft mass. The numerous trajectory opportunities provide flexibility in the overall mission design. Sample return trajectories require a small amount of additional propellant.

Compared to chemical propulsion, ion propulsion has been shown to significantly reduce the required propellant mass and flight time to rendezvous with a comet, allowing the use of a small launch vehicle.

ACKNOWLEDGMENT

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