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. The solar array output for these trajectories is 9 kW at 1 AU except for the one with a launch date of 8/5/03 which has a power level of 9.5 kW at 1 AU.

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

Characteristics of some representative trajectories which rendezvous with comets are provided in Appendix A. The launch dates for these trajectories range from 2002 through 2004.

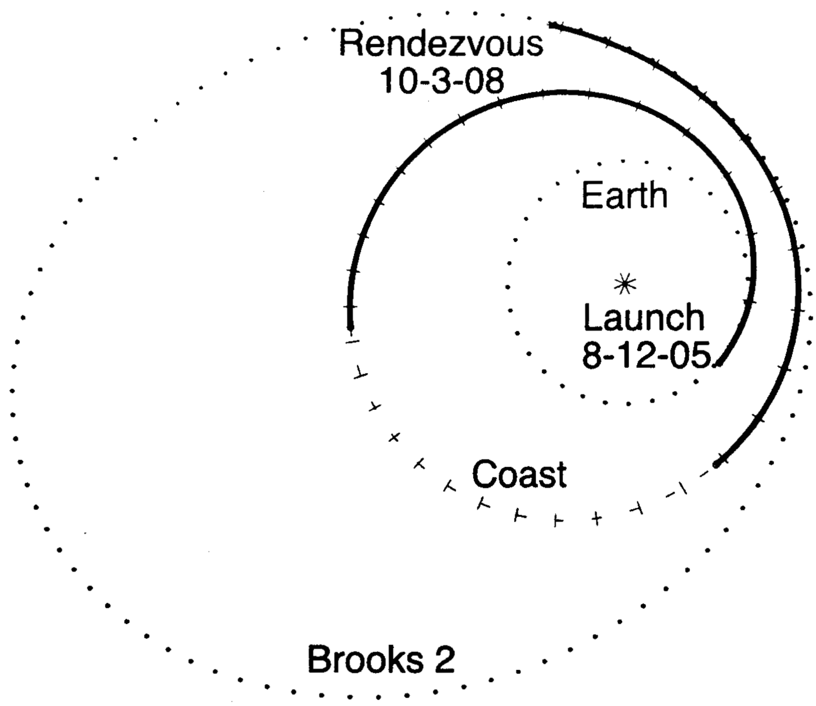

Figure 1 Brooks 2 Rendezvous with One Complete Revolution

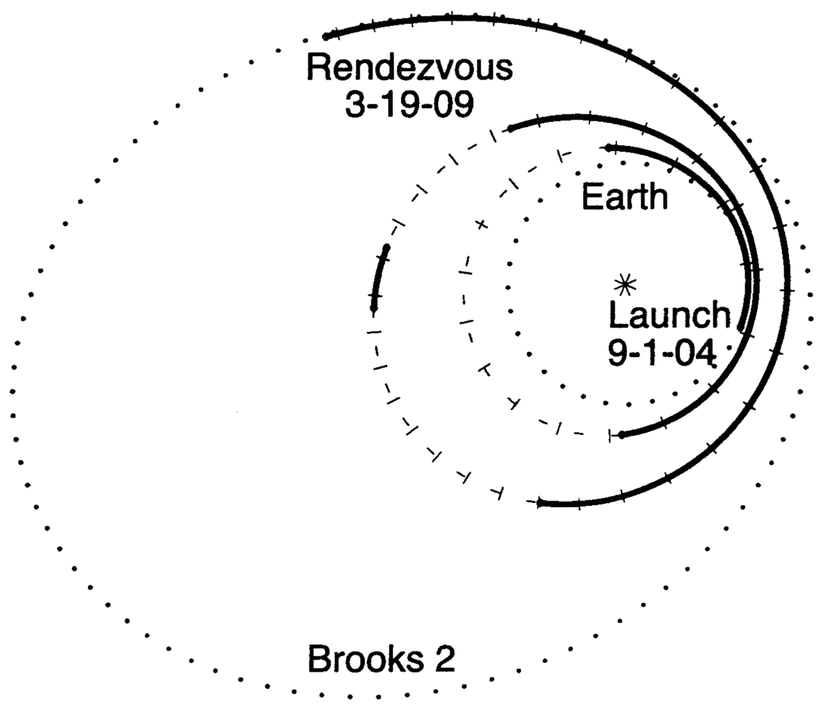

Figure 2 Brooks 2 Rendezvous with Two Complete Revolutions

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 many 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.

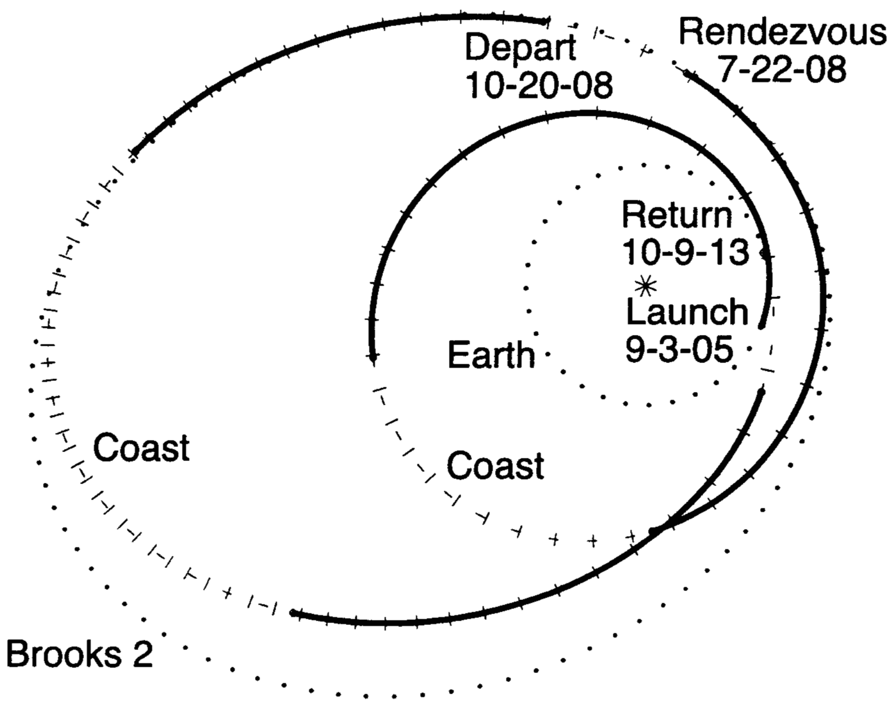

Figure 3 Brooks 2 Sample Return

Characteristics of some representative sample return trajectories are provided in Appendix B. We note that the flight times for these trajectories are pretty close to integer multiples of a year, since both the launch and return occur close to when the Earth crosses the longitude of the perihelion of the comet's orbit. We noted earlier that the launch can occur about one year earlier or later. Similarly, the return can often occur about one year earlier or later. The return date for the two trajectories to Tritton in Appendix B differ by about one year. The trajectory which returns in 2015 has a longer flight time, but the return V_∞ is lower and the spacecraft mass is higher. These options provide some flexibility in mission design.

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. Since the SEP engines would not be operated after the rendezvous, the solar arrays could be smaller and concerns of contamination of the engines and solar arrays from the dusty cometary environment would be eliminated. The optimum maneuver location is typically near aphelion of the comet's orbit, so the stay time at the comet can increase significantly, allowing more time for studying the comet and landing during a less active phase of the comet. 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

Previous Studies of Trajectories to Comets Using SEP

In the 1980s, Sauer[5,6,7] presented some SEP trajectories for missions to comets assuming the use of large launch vehicles and upper stages (Shuttle/IUS and Titan IV/Centaur). The SEP systems used a sizable amount of power (around 20-30 kW). The trajectories evolved from transfers of less than one complete revolution around the Sun, rendezvousing with the comet prior to perihelion, to those using an Earth gravity assist following an approximately 1-year Earth-to-Earth transfer. References 7, 8, and 2 present rendezvous trajectories which complete slightly more than one complete revolution, similar to the trajectory in Figure 1. The two references from the 1990s (8 and 2) assume Delta-class launch vehicles and SEP power in the range of 5 to 10 kW. Reference 2 presents characteristics for a few comet rendezvous trajectories and an all-SEP sample return trajectory similar to the one in Figure 3.

Tan-Wang and Sims[9] describe several trade studies for a comet sample return mission. They examine the sensitivities of the trajectory characteristics to several spacecraft and trajectory parameters and their effect on the overall mission design.

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 smaller launch vehicle.

ACKNOWLEDGMENT

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APPENDIX A COMET RENDEZVOUS TRAJECTORIES

Comet	Launch Date	Flight Time (yr)	Power (kW)	C_3 (km^2/s^2)	Prop Mass (kg)	SC Mass (kg)
Wild 2	1/15/02	2.85	10	11.11	312	666
Vaisala 1	1/24/02	2.89	9	22.27	289	487
Chernykh	1/27/02	4.75	9	22.86	298	468
Singer Brewster	3/1/02	4.70	9	3.04	444	713
Lovas 2	3/18/02	5.17	9	0.40	357	866
Tempel 1	4/16/02	3.50	9	16.10	211	670
Russell 1	4/24/02	5.03	9	4.34	438	688
Forbes	4/27/02	4.30	9	1.00	444	764
Forbes	5/16/02	3.68	9	15.01	230	671
Tempel 1	5/17/02	4.23	9	1.76	383	806
Schwassmann-Wachmann	5/20/02	4.95	9	3.76	350	790
Tempel 2	6/21/02	3.74	9	11.70	254	711
Reinmuth 2	6/21/02	6.15	9	21.57	186	600
Howell	6/29/02	2.84	9	7.39	278	778
d'Arrest	7/1/02	6.25	9	4.65	404	715
McNaught-Hughes	7/5/02	3.46	9	11.80	282	682
Wiseman-Skiff	7/15/02	5.18	9	21.14	306	488
Johnson	7/17/02	3.40	9	17.90	277	572
Reinmuth 2	7/21/02	5.51	10	1.84	372	815
Forbes	7/21/02	4.07	9	2.40	405	768
Holmes	7/28/02	5.67	9	2.19	450	728
Jackson-Neujmin	7/28/02	2.35	9	25.22	282	448
Slaughter-Burnham	7/29/02	3.34	9	35.04	239	356
Brooks 2	8/1/02	5.81	9.5	2.00	328	855
Lovas 2	8/5/02	4.69	9	1.18	333	870
Neujmin 3	8/7/02	2.86	9	31.60	184	455
Shajn-Schaldach	8/8/02	6.30	9	1.32	387	812
Wilson-Harrington	8/13/02	3.04	10	15.15	173	726
Shoemaker 2	8/17/02	6.26	9.5	4.39	459	666
Finlay	8/21/02	5.96	9	7.12	295	768
Harrington	8/23/02	5.92	9.5	2.44	348	824
Tsuchinshan 2	8/28/02	4.38	9	9.55	341	668
Lovas 1	8/29/02	6.15	9	1.48	412	784
Arend	9/4/02	5.78	9	2.36	455	718
Shoemaker-Levy 7	9/7/02	3.87	9	11.26	274	700
Denning-Fujikawa	9/7/02	3.50	9	16.63	254	618
Kohoutek	9/8/02	5.67	10	0.99	374	833
Wilson-Harrington	9/18/02	3.58	9	1.83	373	814
Haneda-Campos	9/18/02	2.71	12	5.57	402	695
Shoemaker-Levy 6	9/20/02	4.48	9.5	3.68	401	740
Faye	9/24/02	4.79	9.5	1.59	385	808
Boethin	9/25/02	6.40	9	6.32	298	782
Giacobini-Zinner	9/30/02	3.63	9	14.59	431	478
Giclas	10/2/02	4.91	9	1.09	396	810
Bus	10/2/02	6.12	10	0.52	436	784

Chernykh	10/2/02	4.06	9	27.45	213	484
Urata-Niijima	10/10/02	4.94	9	3.74	463	677
Ciffreo	10/11/02	5.40	9	1.99	401	782
Schuster	10/17/02	4.94	9	3.02	438	719
Churyumov-Gerasimenko	10/18/02	6.45	9	5.71	296	799
Gehrels 2	10/28/02	3.07	9	19.35	235	589
Hartley 2	11/3/02	2.40	9	18.13	278	567
Wirtanen	11/4/02	5.38	9.5	4.68	329	789
Tritton	11/12/02	6.80	9	4.59	310	810
Harrington-Abell	11/13/02	4.76	9	1.28	448	753
Kowal 2	11/25/02	2.45	9	18.77	283	550
Tsuchinshan 2	11/28/02	3.92	9	12.28	244	710
Wolf-Harrington	11/28/02	2.34	9	25.56	271	453
Wiseman-Skiff	11/29/02	4.66	9	2.59	429	739
Harrington-Abell	11/29/02	4.44	9	18.00	227	620
West-Kohoutek-Ikemura	12/1/02	4.70	9	7.39	473	584
Comas Sola	12/3/02	3.29	9	15.26	285	612
Kohoutek	12/4/02	5.03	9.5	2.01	362	820
Arend-Rigaux	12/14/02	2.88	9	14.69	291	617
Taylor	12/26/02	3.02	9	20.80	282	518
Tsuchinshan 1	12/29/02	2.94	9	8.25	307	731
Takamizawa	1/3/03	4.15	9	9.13	383	636
Kojima	1/4/03	5.84	9	0.61	452	766
Tsuchinshan 2	1/7/03	4.08	9.5	4.04	427	706
Kohoutek	1/8/03	4.77	9.5	7.17	350	711
Kojima	1/10/03	5.01	9.5	1.54	385	809
Neujmin 2	1/21/03	5.79	9	4.18	284	846
Shoemaker-Levy 7	1/26/03	3.57	9.5	6.90	419	648
Bus	1/29/03	5.63	9	23.83	200	551
Clark	2/20/03	4.41	9	0.27	440	787
Bus	2/26/03	5.23	9	0.83	384	828
du Toit-Hartley	2/27/03	5.38	9	3.80	269	870
duToit-Neujmin-Delporte	3/6/03	6.50	9	0.94	360	849
Tuttle-Giacobini-Kresak	3/7/03	4.31	10	17.35	198	661
Singer Brewster	3/18/03	3.81	10	6.62	321	752
Tuttle-Giacobini-Kresak	3/26/03	4.09	9	1.97	390	793
Russell 1	3/26/03	4.11	9	21.37	252	538
Grigg-Skjellerup	3/29/03	5.14	9	6.08	396	690
Tempel 1	4/22/03	2.88	9	7.58	296	756
Kopff	4/29/03	6.34	9	2.63	334	833
Clark	4/30/03	4.15	9	14.64	216	693
Russell 1	5/3/03	4.00	9	15.11	390	509
Peters-Hartley	5/9/03	4.05	9	31.76	249	388
Takamizawa	5/13/03	3.52	9	12.28	271	683
Schwassmann-Wachmann	5/18/03	3.19	9	19.32	194	630
Wirtanen	5/21/03	5.75	10	0.72	421	794
Takamizawa	5/21/03	3.79	9	7.38	457	599
Peters-Hartley	5/28/03	4.28	9	9.93	458	544

Forbes	5/31/03	3.19	9	7.55	301	751
Schwassmann-Wachmann	6/9/03	3.83	9	2.58	432	737
Harrington	6/16/03	5.85	9.5	1.00	371	837
Lovas 2	7/8/03	4.32	9	1.35	396	803
d'Arrest	7/9/03	5.33	9	3.97	412	723
Reinmuth 2	7/10/03	5.39	9	0.96	395	814
Reinmuth 2	7/13/03	5.71	9	27.20	179	522
Kohoutek	7/15/03	5.38	9	0.53	395	825
Shoemaker-Levy 2	7/18/03	6.56	9	1.29	400	801
Shoemaker-Levy 6	7/19/03	4.13	9.5	2.20	500	678
Tempel 2	7/24/03	2.65	9	11.64	300	667
Lovas 2	7/28/03	3.53	9	15.95	182	702
Brooks 2	8/5/03	4.93	9.5	1.19	340	863
Harrington	8/5/03	5.79	9.5	25.62	151	573
Harrington-Abell	8/7/03	4.03	9	9.68	354	653
Holmes	8/8/03	4.85	9	23.14	245	516
Holmes	8/11/03	4.85	9	3.93	457	678
Shoemaker 1	8/13/03	3.55	10	21.63	297	489
Shajn-Schaldach	8/16/03	5.37	10	0.99	392	816
Giclas	8/16/03	4.01	9	11.29	266	708
Finlay	8/20/03	5.05	9	4.76	314	802
Tsuchinshan 2	8/21/03	3.40	9	11.63	336	631
Wilson-Harrington	8/31/03	2.97	10	6.64	261	812
Shoemaker-Levy 6	9/5/03	3.54	9	19.91	247	567
Faye	9/10/03	3.96	9	14.38	239	674
Wiseman-Skiff	9/11/03	4.02	9	16.50	315	559
Lovas 1	9/24/03	5.16	9	1.71	430	760
Boethin	9/25/03	5.54	9	4.80	316	799
Giacobini-Zinner	9/27/03	2.64	9	31.09	275	371
Bus	9/29/03	5.13	10	0.80	439	773
Wiseman-Skiff	9/29/03	3.97	9	5.33	496	607
Ciffreo	10/1/03	4.23	9	20.05	223	589
Faye	10/10/03	4.14	9.5	3.08	443	713
Schuster	10/11/03	3.89	9	22.72	242	526
Urata-Niijima	10/11/03	3.42	9	24.77	243	493
Churyumov-Gerasimenko	10/12/03	5.54	9	3.79	316	823
Lovas 1	10/14/03	5.10	9	23.54	200	555
Urata-Niijima	10/18/03	4.02	9	6.39	466	612
Denning-Fujikawa	10/18/03	2.42	9	21.68	260	526
Kohoutek	10/24/03	4.49	9	19.56	194	626
Honda-Mrkos-Pajdusakova	10/24/03	3.45	9	17.19	247	615
Schuster	10/27/03	4.40	9	3.48	454	692
Ciffreo	10/28/03	4.73	9	2.05	415	767
Tritton	11/8/03	5.88	9	2.95	329	830
Wirtanen	11/10/03	4.48	9	3.61	338	806
Kojima	11/19/03	4.83	9	18.26	214	629
Wiseman-Skiff	11/21/03	3.83	9	17.26	266	594
Kohoutek	11/26/03	4.55	9.5	1.31	371	829

West-Kohoutek-Ikemura	11/26/03	3.41	9	30.85	247	402
Shoemaker-Levy 7	12/5/03	2.66	9	16.89	273	595
West-Kohoutek-Ikemura	12/7/03	3.99	9	11.17	454	523
Harrington-Abell	12/9/03	3.67	9	10.56	289	700
Honda-Mrkos-Pajdusakova	12/17/03	3.26	9	12.22	402	554
Kopff	1/12/04	5.87	9.5	0.83	360	852
Neujmin 2	1/17/04	4.92	9	2.47	302	868
Tsuchinshan 2	1/22/04	2.98	9	12.82	270	674
Bus	1/31/04	4.62	9	13.87	235	688
Shoemaker 1	2/20/04	3.49	10	13.77	423	502
du Toit-Hartley	2/22/04	4.54	9	1.97	291	892
Tuttle-Giacobini-Kresak	3/10/04	3.30	10	9.15	267	751
Kojima	3/19/04	4.77	10	1.41	397	800
Bus	3/19/04	4.66	10	3.60	386	757
Kohoutek	3/19/04	4.83	10	0.27	463	764
Spacewatch	4/7/04	4.45	9	0.88	382	829
Grigg-Skjellerup	4/10/04	4.02	9	5.26	426	678
Russell 1	4/22/04	3.03	9	24.31	256	488
Clark	5/6/04	3.21	9	6.12	307	777
Peters-Hartley	5/16/04	3.15	9	27.96	274	416
Schwassmann-Wachmann	5/23/04	2.94	9	9.84	299	705
Wirtanen	6/12/04	4.42	9	0.70	446	769
Takamizawa	7/9/04	2.65	9	18.95	241	590
Lovas 2	8/2/04	3.07	9	7.80	252	795
Holmes	8/2/04	3.87	9	17.49	284	573
Tuttle-Giacobini-Kresak	8/10/04	2.67	10	17.55	342	513
Brooks 2	8/23/04	3.78	9	18.40	170	671
Shoemaker 1	8/23/04	2.99	10	20.32	329	478
Brooks 2	9/1/04	4.54	9	1.21	341	862
Lovas 1	9/22/04	4.09	9	15.40	262	632
Shoemaker-Levy 6	9/22/04	2.70	9	15.29	285	611
Ciffreo	10/3/04	3.62	9	12.97	277	664
Giclas	10/14/04	2.88	9	17.18	272	590
Kohoutek	10/15/04	3.82	9	11.83	247	716
Schuster	10/17/04	3.43	9	17.07	288	576
Faye	10/18/04	3.06	9	10.70	291	695
Urata-Niijima	10/18/04	3.02	9	18.54	311	527
Wirtanen	11/5/04	3.38	9	18.39	200	640
Honda-Mrkos-Pajdusakova	11/13/04	2.40	9	22.10	260	518
Wirtanen	11/26/04	3.95	9	2.50	387	784
West-Kohoutek-Ikemura	12/4/04	3.00	9	26.57	295	415
Kojima	12/6/04	3.92	9	10.72	272	714
Wiseman-Skiff	12/7/04	2.78	9	16.07	293	589
Kohoutek	12/11/04	4.03	9.5	4.71	415	702

APPENDIX B COMET SAMPLE RETURN TRAJECTORIES

Comet	Launch Date	Rendezvous Date	Return Date	Flight Time (yrs)	Return V_∞ (km/s)	Launch C_3 (km^2/s^2)	Prop Mass (kg)	S/C Mass (kg)
Finlay	2005, Aug 12	2008, Sept 25	2014, Sept 20	9.11	10.12	16.0	449	1193
Brooks 2	2005, Sept 3	2008, July 22	2013, Oct 9	8.10	8.38	11.9	558	1279
Wirtanen	2005, Nov 17	2008, June 4	2012, Dec 14	7.08	11.14	12.1	535	1293
Kopff	2006, June 23	2009, June 9	2015, July 14	9.06	8.45	16.3	550	1079
Churyumov-Gerasimenko	2006, Oct 26	2009, July 27	2014, Nov 16	8.06	9.73	11.4	541	1320
Tritton	2006, Dec 8	2009, Aug 16	2014, Jan 10	7.09	11.75	13.3	559	1211
Tritton	2006, Nov 13	2009, Oct 16	2015, Jan 4	8.14	9.33	11.8	585	1257
Kowal 2	2007, Nov 17	2010, Jul 16	2014, Nov 18	7.00	10.37	14.0	500	1235
Kowal 2	2007, Oct 28	2010, Nov 7	2015, Nov 21	8.07	11.14	12.6	516	1284

Solar array: 17 kW (1 AU, beginning of life)
Solar array degraded with time

Stay time at comet: 90 days
100 kg "dropped" at comet