Multiple Encounter Missions with the Trojan and Main Belt Asteroids[†]

David F. Bender*, Paul A. Penzo**
Jet Propulsion Laboratory California Institute of Technology
4800 Oak Grove Dr.
Pasadena, California 91109

ABSTRACT

The clustering of asteroids, the Trojans, at the Jupiter liberation points L4 and L5 offer yearly launch opportunities for double flybys. In addition, passage through the main belt can add one and sometimes two additional flybys to make this an attractive mission for small spacecraft. Also, launch mass will double by using a 2-year Earth return gravity assist, as well as offer additional main belt flybys.

Introduction

The Trojan asteroids residing in the L4 and L5 regions of Jupiter (locations of 60 degree leading and lagging Jupiter in its orbit), represent important clusters of main-belt sized bodies. Their number, as detected from Earth, has increased significantly in the past few years, with improved telescopic sensitivity and interest (see Reference). Though further from the sun than main-belt asteroids, and so more difficult to reach, this is compensated somewhat by their clustering property, which allows higher probability for multiple encounters.

This clustering property is shown in Figure 1, which plots the ecliptic plane projection of their location on February 1, 1994. To avoid clutter on the Figure, only 80 asteroids have been plotted. As of November 1994 there are 114 numbered Trojans, and 70 unnumbered; and future observations should increase this number considerably. Figure 2 shows the same 80, as seen from 15 degrees to the ecliptic, and indicates that some Trojans can be highly inclined.

The purpose of this study is to explore the possibilities of multiple Trojan asteroid encounters, expecting that they would be more numerous because of their clustering property. This is indeed the case; and, in fact, since the spacecraft must pass completely through the main belt twice, opportunities exist to include one or two of these asteroids also.

Dual Trojan Flybys

A few double Trojan encounters have been generated in this exercise to get some understanding of their frequency of occurrence, and possible deep space maneuver requirements. The results are encouraging. Launch years from 1997 through 2001 have produced several. acceptable missions. The launch C_3

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*Retired, Jet Propulsion Laboratory
**Member of the Technical Staff, Systems Division, Jet Propulsion Laboratory

requirements for direct launch range from "18 to 86 km^2/sec^2. Flight times to the second Trojan range from 3.2 to 4.2 years, and the deep space Δv can be as little as none to 150 m/s.

Seven opportunities were found for the 5 years chosen, and more can certainly be discovered. The technique chosen was restrictive in the sense that Trojans with low orbital inclinations were tried first, and this worked quite well. One author (Bender), however, has developed a technique which finds favorable launch and arrival dates for each Trojan such that the arrival date is close to its nodal passage. This way, two which have similar launch dates (and trajectories) can be paired and used in MIDAS to compute the dual flyby possibility. Exercising this program will be left for future work.

Adding Main Belt Bodies

Missions beyond the Main Belt (as with Galileo) offer the opportunity of close encounters with these objects. A mission of Trojan flybys offer 2 passages through the belt., i.e., outbound and inbound. Perhaps more, in fact, if a second revolution about the Sun is considered. The typical period of the orbit. is about **6** years.

Once a trajectory for a double Trojan flyby is computed, it is propagated in the ASTENC program (or a MIDAS option) to see which other bodies it comes close to. Then, the closest candidates are included in the MIDAS program as flyby targets. More often than not, two bodies can be included, but usually with a maneuver penalty. Only those cases which have modest requirements (less than 300 m/s) have been selected. The final results are presented in Table 1.

Each pair of Trojans which results in favorable dual flyby encounters for a given launch opportunity is listed as the first mission of a possible set. This includes no Main Belt encounters and will yield the minimum total energy, or maximum payload.

The first set, for example, is a dual encounter of 1988 SK2 and 1988 RN11 (Trojans near L5) with a launch opportunity in 1997. The next two entries then also include the main belt asteroids 1971 WK1 (2nd mission) and 3146 T-2 (3rd mission). The encounter dates and flyby characteristics of the two Trojans do not change much, but there is usually a ΔV penalty to include the main belt asteroid. In this set, including 1971 WK1 requires 240 m/s, but including 3146 T–2 adds only 1 m/s to the dual flyby of 154 m/s. The penalties for the other 4 sets are greater.

As with Jupiter, favorable launch opportunities occur every 13 months, with those to L4 being two months after Jupiter launch dates, and L5 being two months before. In Table 1, mission sets 1-5 apply to L4, and mission sets 6, 7 to L5. Figure 3 shows a polar view of the trajectory for the 4 asteroid encounter of Set 2 in Table 1.

Mass Estimates

Also included in Table 1 is an estimate for spacecraft mass less on-board propulsion and AACS systems. The Medlite launch vehicle was chosen for this estimate. Using Figure 4, Medlite provides about 200 kg to an escape energy of 40 km^2/sec^2. Then, an advanced propulsion stage is used to increase this launch energy to 80 km^2/sec^2 (requiring about 1.6 km/s), in addition to performing deep space DV maneuvers of 200 m/s, the dry launch mass would be about 120 kg. Subtracting off the dry propulsion mass (with AACS) as shown in Figure 5, about 90 kg remains for science instruments and other spacecraft systems . This seems reasonable for the Millennium objectives.

Earth Gravity **Assist Option**

The use of gravity assist. is usually available, if necessary, to increase launch mass or decrease launch energy, C_3. For example, a 2 year Earth gravity assist (EGA) will reduce launch energy from about **80** km^2/sec^2 to about 25 km^2/sec^2 The Medlite injected mass would then be about_ 300 kg (Figure 4). Some of this will be lost because a mandatory DV of about 700 m/s is required a year after launch on the EGA trajectory. If, in addition, about 500 m/s is needed during the mission, the propulsion mass will be about 95 kg. Using Figure 5, the dry propulsion mass (with AACS) comes to about- 25 kg, leaving 180 kg for science and other spacecraft systems. Thus, although a 2-year flight Lime has been added to the mission, the payload available has been doubled.

An example 5-asteroid flyby has been generated by adding a 2-year EGA to the Set **6** (Table 1) mission. The launch year is then 1998 instead of 2000. In this trajectory search, it was possible to maintain the original two Trojan asteroids and their arrival dates, but the auxiliary main belt asteroids which were encountered changed. Also, on the 2--year Earth return, a fifth asteroid about 1 year after launch was found and included in the mission. Data for this mission may be found in Table 2 (called Set 8) . Total mission flight- time is 7.24 years.

Conclusions

Clustering of the Trojan asteroids allow double flyby launch opportunities every 13 months to either those at L4 or at 1,5. There is also a high probability that two main belt asteroid flybys can be included in the mission, one on the departure leg and the other on the return leg. Mission duration to the 4th asteroid ranges from 4.5 to 5 years, and provides about one flyby per year. The Medlite launch vehicle allows a launch mass of 80 to 100 kg for direct launch, excluding the propulsion and AACS systems.

Use of a two year Earth gravity assist can double the launch mass at the expense of flight, time. However, the average rate of about one flyby per year may be maintained if two additional flybys can be included on the Earth return segment . The probabilities for this are lower since the EGA only goes out to 2.2 AU and, if found, these flyby bodies will be smaller. Navigation requirements have not been computed for these missions, but it is felt that 100 m/s should be adequate. Finally, with respect to previous multiple asteroid flyby searches, including Trojans into the mission can yield science on a different class of asteroids as well as increase the number of bodies visited.

Reference

Bender, D. F., "Relative Motion Among the Trojan Asteroids, " Paper DPS 31.13-P, presented at the Division of Planetary Sciences Meeting, Washington, D.C., October 31 - November 4, 1994.

FIGURE 1 JUPITER AND 80 TROJAN ASTEROIDS FEB. 1, 1994

Ecliptic Plane Projection

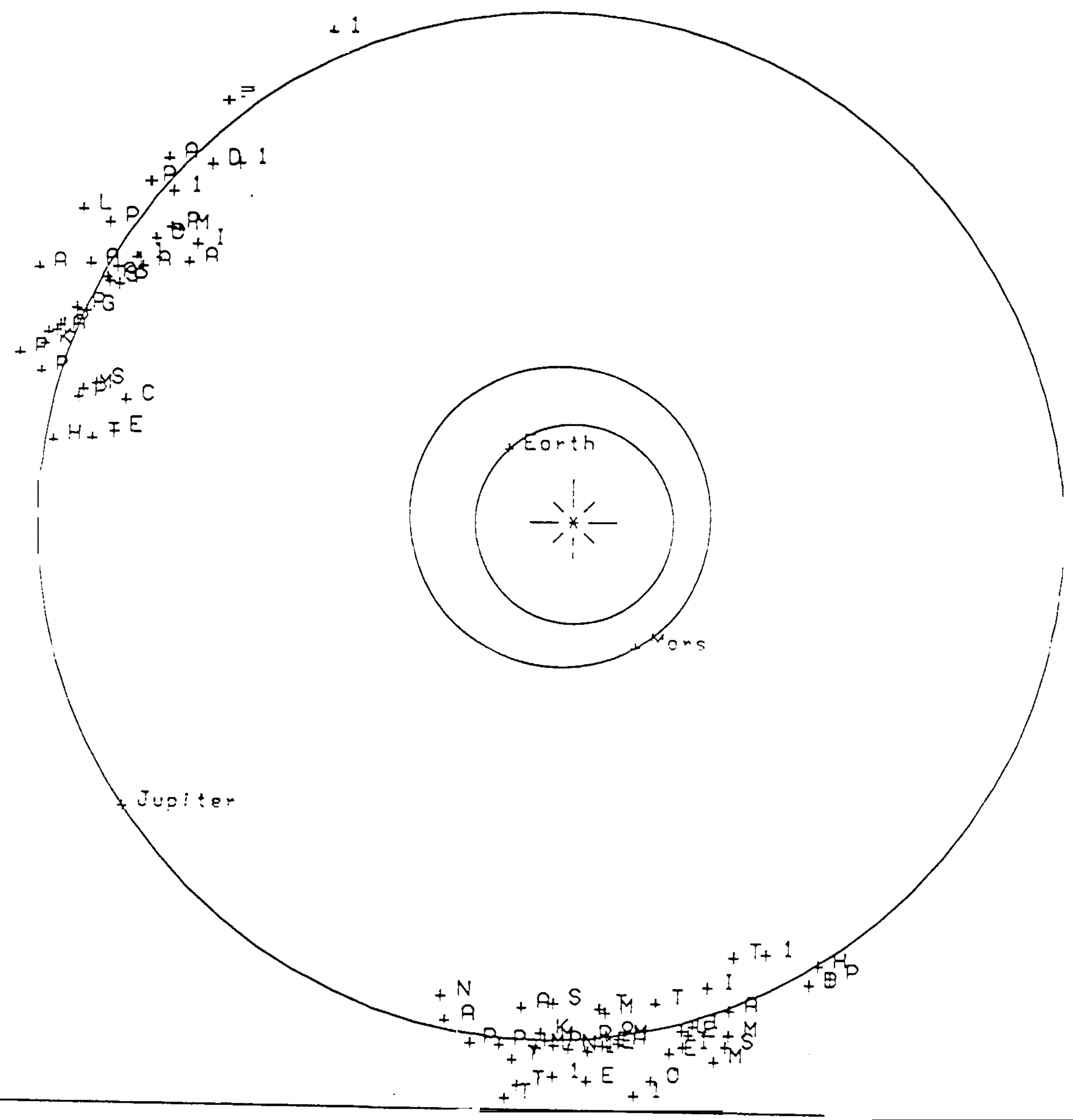

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FIGURE 2 JUPITER AND 80 TROJAN ASTEROIDS FEB. 1, 1994

Inclined view 15 degree

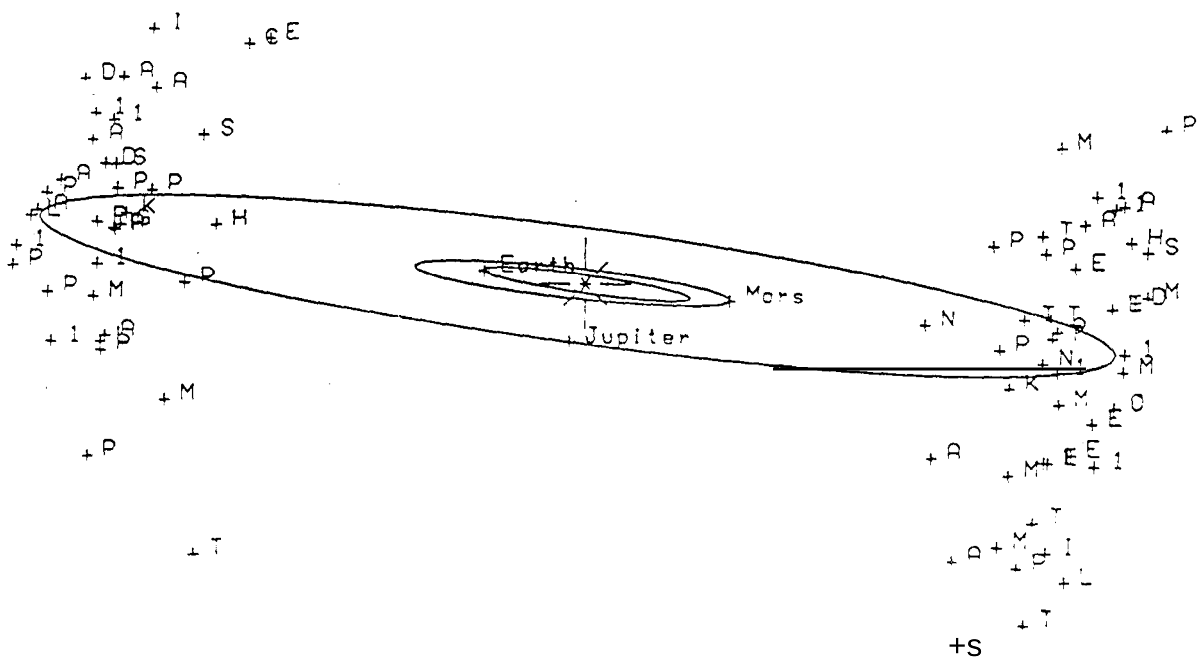
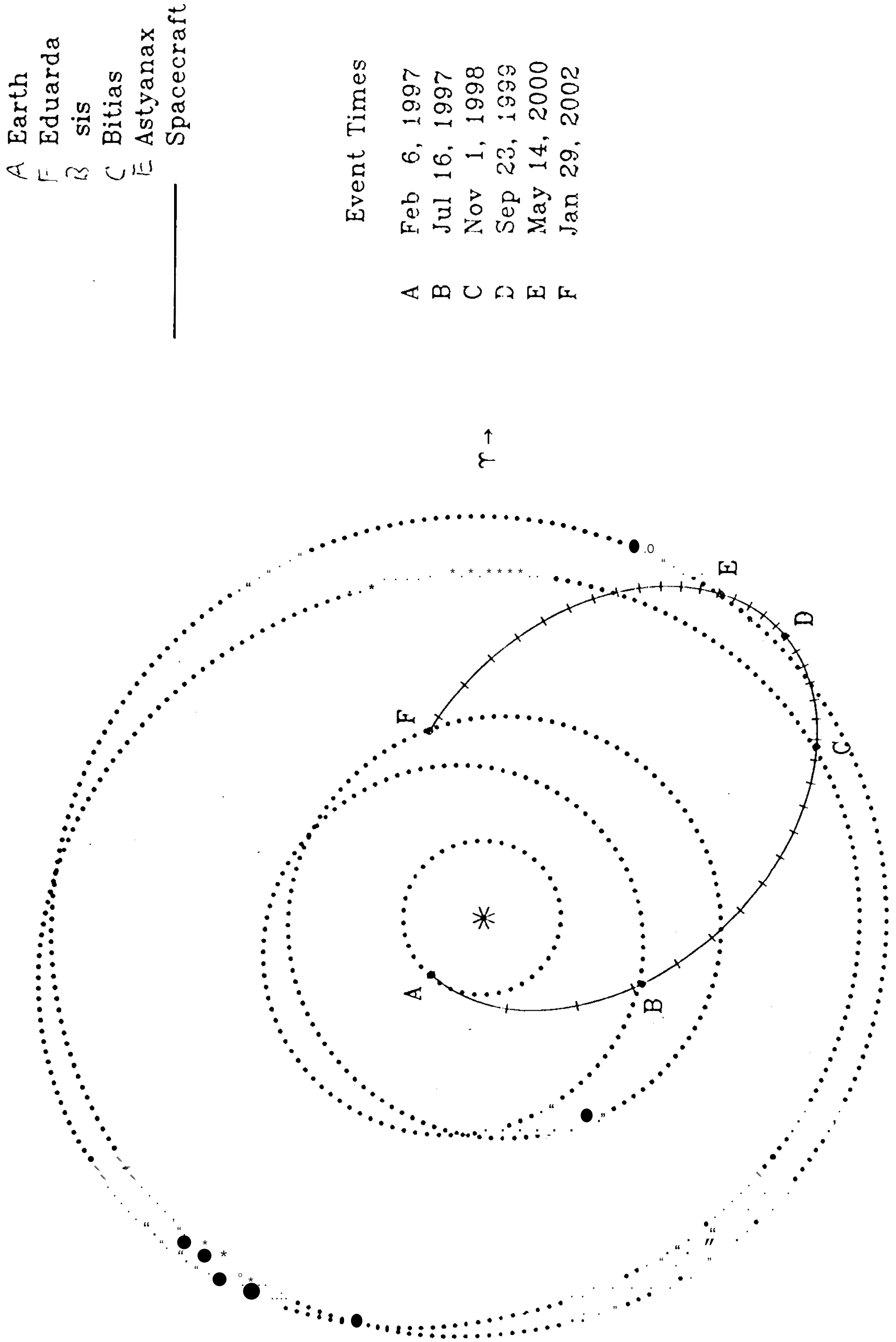


Figure 3: Flybys Of Two Trojans Plus 2
50 day tics on s/c



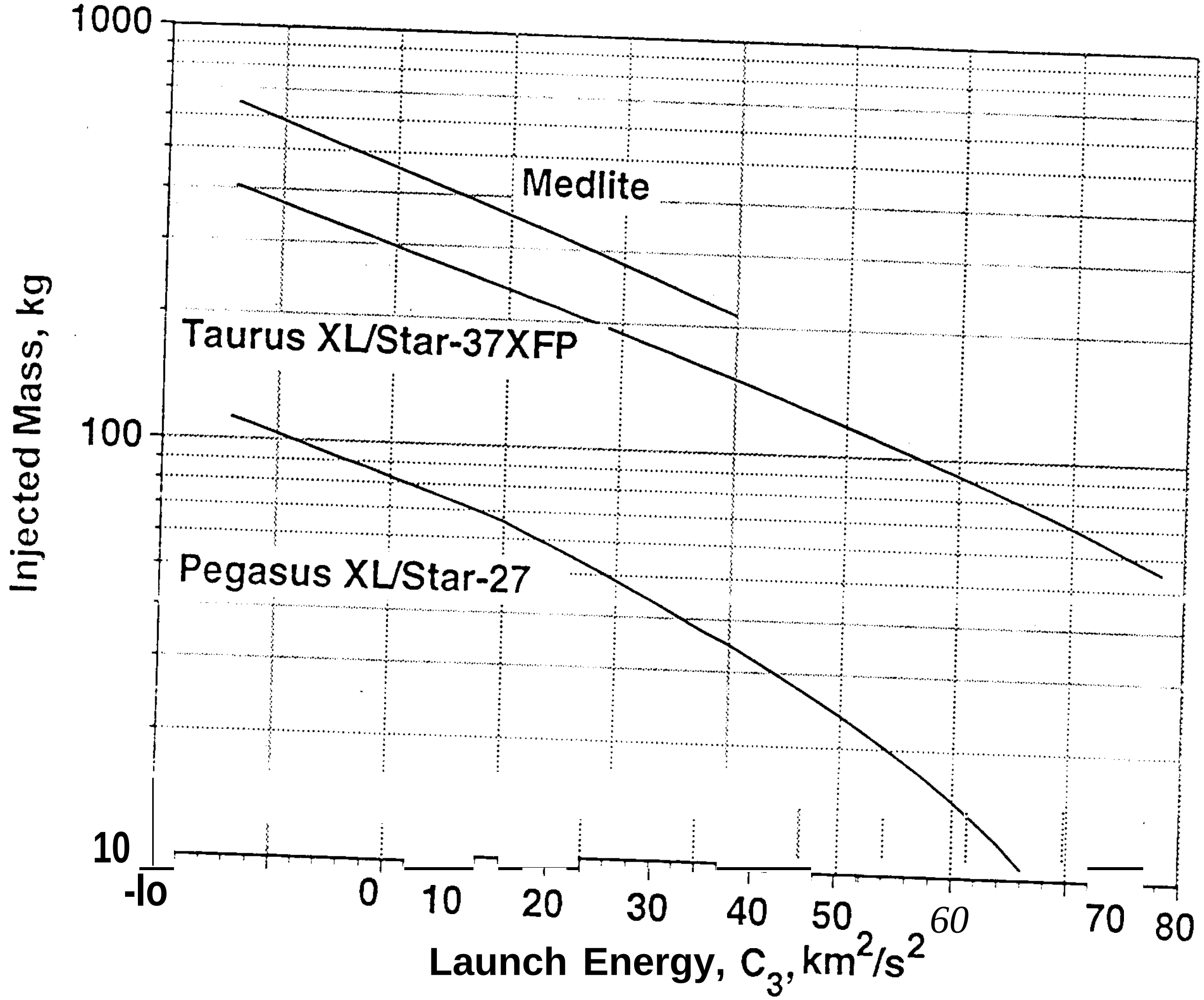


Figure 4: New Millenium Launch Vehicle Capability

Advanced Chemical Propulsion System
Rhenium MMH/NTO Engine, Includes Attitude Control
Clementine Like Components

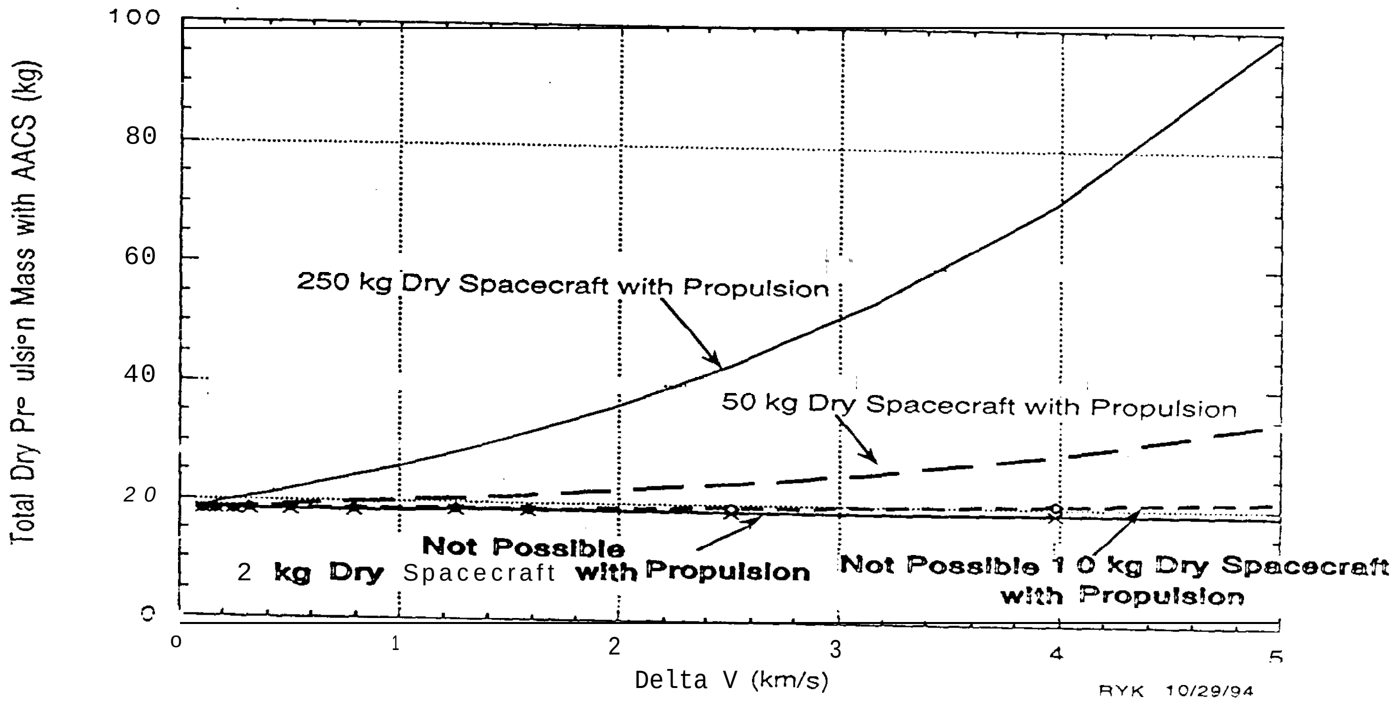


Figure 5: Chemical Propulsion Mass
Advanced Propulsion

Table 1. MISSION OPPORTUNITIES TO TWO TROJAN ASTEROIDS

						TARGET 3		TARGE	
DATE	C3 (km^2/s^2)	NAME	(NUMBER)	NAME	(NUMBER)	NAME	(NUMBER)	NAME	(NUMBER)
DLA	MASS S/C	TIME	FB SPEED	TIME	FB SPEED	TIME	FB SPEED	TIME	FB SPEED
INJ.DV	S/C DV	E-DIST	RADIUS	E-DIST	RADIUS	E-DIST	RADIUS	E-DIST	RADIUS
02-05-97	79 7	**1988 RS1°**	(5257)	**Astyanax**	(1871)	None		None	
-30.9 deg	102 kg	930 days	5.9 km/s	1172 days	6.3 km/s				
6,39 km/s	0 m/s	4.3 AU	9.0 km	5.6 AU	17.1 km				
02-05-97	80 3	**1981 EX38**	(10810)	**1988 RS10**	5257	**Astyanax**	(1871)	None	
-31.4 deg	98 kg	160 days	18.3 km/s	Same		Same			
6.45 km/s	40 m/s	1.7 AU	2.2 km						
02-05-97	80.5	**1981 EX38**	1°810	**1988 RS10**	5257	**Astyanax**	1871	**Kovalevskaya**	(1859)
-31.5 deg	92 kg	Same		Same		Same		1684 days	12.7 km/s
6.57 km/s	161 m/s							2.4 AU	24.3 km

LAUNCH (Set 2)		TARGET 1		TARGET 2		TARGET 3		TARGET 4	
DATE	C3 (km^2/s^2)	NAME	(NUMBER)	NAME	(NUMBER)	NAME	(NUMBER)	NAME	(NUMBER)
DLA	MASS S/C	TIME	FB SPEED	TIME	FB SPEED	TIME	FB SPEED	TIME	FB SPEED
INJ.DV	S/C DV	E-DIST	RADIUS	E-DIST	RADIUS	E-DIST	RADIUS	E-DIST	RADIUS
02-10-97	78.7	**Bitias**	(5120)	**Astyanax**	(1871)	None		None	
-6.4 deg	102 kg	630 days	9.7 km/s	1192 days	6.5 km/s				
6.42 km/s	71 m/s	5.0 AU	24.8 km	5.2 AU	17.1 km				
02-06-97	79.1	**Isis**	(42)	**Bitias**	5120	**Astyanax**	(1871)	None	
-5.6 deg	94 kg	160 days	19.5 km/s	Same		Same			
≤.51 km/s	142 m/s	1.7 AU	53.5 km						
02-07 -97	79.3	**Isis**	(42)	**Bitias**	(5120)	**Astyanax**	(1871)	**Eduarda S**	(340)
-5.6 deg	90 kg	Same		Same		Same		1819 days	12.9 km/s
≤.62 km/s	254 m/s					3.1 AU	16.1 km		

Table 1. MISSION OPPORTUNITIES TO **TWO** TROJAN ASTEROIDS

LAUNCH (Set 3)		**TARGET 1**		**TARGET 2**		**TARGET 3**		**TARGET 4**	
DATE D LA INJ . DV	C3 (km^2/s^2) MASS s/c s/C DV	NAME T IME E-DIST	(NUMBER) FB SPEED RADIUS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUIS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS
32-17-97 -13.7deg 6.50 km/s	78.6 95 kg 154 In/s	1988 SK2 713 days 6.0 AU	(11569) 6.6 km/s 10.8 km	1988 **RN11** 1199 days 5.3 AU	(12205) 6.3 km/s 10.8 km	None		None	
02-16-97 -15.5 deg 6.57 km/s	78.3 92 kg 240 m/ s	**1971 WK1** 188 days 2.3 AU	(3421) 14.2 km/s 4.1 km	1988 SK2 Same	(11569)	1988 **RN11** Same	(12295)		None
02-18-97 -12.0 deg 5.53 km/s	79.3 94 kg 155 m/s	3146 T-2 190 days 2.3 AU	(14235) 14.9 km/s 1.7 km	1988 SK2 Same	(11569)	1988 **RN11** Same	(12205)		None

LAUNCH (Set 4)		**TARGET 1**		**TARGET 2**		**TARGET 3**		**TARGET 4**	
DATE DLA INJ. DV	C3 (km^2/s^2) .%ss s/c S/C DV	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS	NAME T IME E-DIS T	(NUMBER) FB SPEED RADIUIS	NAME T I ME E-DIST	(NUMBER) FB SPEED RADIUS
03-26-98 -15.6 deg 6.61 km/s	84.2 89 kg 69 m/s	**Pandarus** D 787 days 5.9 AU	(2674) 6.3 km/s 51.0 km	1988 **RN11** 1535 days 5.3 AU	(12205) 5.9 km/s 10.8 km	None		None	
03-30-98 -17.0 deg 6.66 km/s	83.9 87 kg 123 m/s	Parvati 126 days 1.1 AU	(2847) 15.1 km/s 5.4 km	**Pandarus** D Same	(2674)	1988 **RN11** Same	(12205)	None	
03-30-98 -17.0 deg 6.74 km/s	83.9 83 kg 219 m/s	**Parvati** Same		Pandarus D Same	(2674)	1988 **RN11** Same	(12205)	**Fanatica** 2134 days 1.9 AU	(1589) 16.8 km/s 6.8 km

Table 1. MISSION OPPORTUNITIES TO TWO TROJAN ASTEROIDS

LAUNCH [Set 5)		TARGET 1		TARGET 7		TARGET 3		TARGET 4	
DATE DLA INJ. DV	C3 (km^2/s^2) MASS S/C S/C DV	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUIS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS
04-01-98 -19.0 deg 6.47 km/s	78.8 97 kg 110 m/s	Phereclos 885 days 4.4 AU	D (2357) 5.7 km/s 51.5 km	1988 RN11 1331 days 4.2 AU	(11074) 5.8 km	None 7.8km/s		None	
03-31-98 -16.3 deg 5.55 km/s	78.7 91 kg 196 m/s	1976 QP 128 days 1.1 AU	(10267) 17,2 km/s 1.7 km	Phereclos D Same	(2357)	1988 RN11 Same	(11074)	None	
03-31-98 -16.3 deg 6.57 km/s	78.7 91 kg 215 m/s	1976 QP Same		Phereclos D Same	(2357)	1988 RN11 Same	(11074)	Graz 1894 days 3.3 AU	(2806) 15.0 km/s 10.1 km

Table 1. MISSION OPPORTUNITIES TO TWO TROJAN ASTEROIDS

DATE DLA INJ.DV	$C3\ km^2\ s^2$ MASS S/C S/C DV	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS
10-31-00 10.3 deg 6.56 km/s	81.4 91 kg 108 m/s	**4523 P-L** 797 days 5.6 AU	(11925) 6.9 km/s 15.6 km	**Kalchas** 1399 days 5.6 AU	(4138) 6.3 km/s 29.8 km	None		None	
10-31-00 8.3 deg 6.66 km/s	80 9 86 kg 228 m/s	**Korolev** 150 days 1.5 AU	(1855) 16.5 km/s 5.4 km	**4523 P-L** Same	(11925)	**Kalchas** Same	(4138	None	
10-31-00 8.3 deg 6.84 km/s	80.9 78 kg 413 m/s	**Korolev** Same	1855	**4523 P-L** Same	(11925	**Kalchas** Same	(4138	**Bavaria** 1995 days 2.4 AU	(301) 14.8 km/s 27.8 km
LAUNCH (Oct …)		TARGET 1		TARGET 2		TARGET 3		TARGET 4	
DATE DLA INJ.DV	$C3 (km^2/s^2$ MASS S/C S/C DV	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUIS	NAME TIME E-DIST	(NUMBER) FB SPEED RADIUS
11-05-01 28.4 deg 6.62 km/s	[illegible].3 [illegible]9 kg 0 m/s	**Kalchas** 814 days 5.4 AU	(4138) 6.6 km/s 29.8 km	**Philoctetes** 1304 days 4.5 AU	(1869 5.7 km/s 17.1 km	None		None	
11-07-01 26.2 deg 6.82 km/s	85 7 80 kg 220 m/s	**Ostara CS** 212 days 2.7 AU	(343) 10.4 km/s 10.3 km	**Kalchas** Same	(4138	**Philoctetes** Same	1869	None	
11-06-01 26.2 deg 6.89 km/s	85 9 76 kg 290 m/s	**Ostara CS** Same	(343	**Kalchas** Same	4138	**Philoctetes** Same	1869	**Phaeton F** 2218 days 0.2 AU	(3200) 44.0 km/s 3.5 km