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Fast Missions to Pluto Using Jupiter Gravity-Assist and Small Launch Vehicles

Michael A. Minovitch*
Phaser Telepropulsion, Inc., Los Angeles, California 90067

This paper gives a quantitative comparison of short trip time, direct transfer Earth–Pluto trajectories having launch windows in 1999, 2000, and 2001 that require Titan IV/Centaur launch vehicles with gravity-assist Earth–Jupiter–Plato trajectories having launch windows in 2002, 2003, and 2004 for the exploration of Pluto. It is shown that by utilizing fast, gravity-assist Earth–Jupiter–Pluto trajectories rather than fast, direct transfer Earth–Pluto trajectories, missions to Pluto can be accomplished with much larger spacecraft using much smaller launch vehicles. This will result in a major cost reduction and, at the same time, provide a major increase in scientific return.

Nomenclature

a	= semimajor axis of Earth–Pluto trajectory, a.u.
C_3	= launch energy, $V_{1\infty}^2$
DOCA	= distance of closest approach from Jupiter's surface, km
E	= orbital energy of Earth–Pluto trajectory, km^2/s^2
E_{12}	= orbital energy of Earth–Jupiter leg, km^2/s^2
E_{23}	= orbital energy of Jupiter–Pluto leg, km^2/s^2
e	= eccentricity of Earth–Pluto trajectory
R	= distance between Sun and spacecraft
R_j	= radius of Jupiter, 71,492 km
T	= Earth–Pluto trip time, yr
T_2	= Pluto arrival date of Earth–Pluto trajectory
T_3	= Pluto date of arrival of Earth–Jupiter–Pluto trajectory
T_{12}	= trip time of Earth–Jupiter leg, yr
T_{13}	= total trip time of Earth–Jupiter–Pluto trajectory, yr
T_{23}	= trip time of Jupiter–Pluto leg, yr
TDA	= trajectory deflection angle, deg
V	= heliocentric spacecraft velocity at distance R from Sun
$V_{1\infty}$	= departing hyperbolic excess velocity, km/s
$V_{2\infty}$	= arrival hyperbolic excess velocity at Pluto, km/s
$V_{3\infty}$	= arrival hyperbolic excess velocity at Pluto, km/s
ΔV	= gravity propulsion velocity increase, km/s
ϕ	= inclination of Earth–Pluto trajectory, deg
θ	= heliocentric transfer angle of Earth–Pluto trajectory, deg
θ_{12}	= heliocentric transfer angle of Earth–Jupiter leg, deg
θ_{23}	= heliocentric transfer angle of Jupiter-Pluto leg, deg

Introduction

ALTHOUGH chemical rocket propulsion is capable of generating high thrust-to-weight ratios, its relatively low specific impulse makes it very inefficient for accelerating a spacecraft to high velocities. Most of the chemical energy is wasted accelerating unburned propellant, which results in the well-known exponential increase in mass ratio. Thus, if a mission requires a high launch energy, the high mass ratio limits the possible payload mass to a very small fraction of the initial launch mass.

This situation is dramatically illustrated by the recently proposed direct "fast flyby" mission to Pluto.[1–4] Because Pluto is the most distant planet, it requires the most launch energy if direct transfer trajectories are used. Minimum energy Hohmann trajectories require an average C_3 launch energy of 135 km^2/s^2 but have an average trip time of 45 years. To decrease the trip time to 7 years for a launch in 1999, as proposed, requires increasing the launch energy to about 280 km^2/s^2. This launch energy is significantly higher than the highest launch energy of any previous mission. It would require the largest and most expensive unmanned launch vehicle in the U.S. inventory, a Titan IV/Centaur with an initial mass of nearly 10^6 kg (1,000 metric tons[5]) to launch a small 100-kg spacecraft on this trajectory. The plan proposes to send two 100-kg spacecraft directly to Pluto using two Titan IV/Centaur launch vehicles at a cost exceeding $1 billion.[1,2] (Because Pluto's rotational period is 6.39 days, two spacecraft with different times of arrival are required to photograph the planet's entire surface.)

The innovation of gravity propulsion (usually called "gravity-assisted" or "swingby" trajectories) is basically a propulsion concept for accelerating a spacecraft to a distant, hard-to-reach planet that ordinarily requires a high launch energy by sending the spacecraft to a nearby, easy-to-reach planet that requires relatively little launch energy, and letting the gravitational forces of this planet propel the spacecraft to the distant planet, either directly or via additional intermediate planets. After the spacecraft is launched to the nearby planet with relatively little launch energy, no additional onboard rocket propulsion is required. Because the planetary propulsive forces automatically increase with spacecraft mass as prescribed by the equivalence principle, it does not matter how massive the spacecraft is after it is launched to the initial planet. This propulsion concept not only enables every part of the solar system to be explored with spacecraft without using enormous launch vehicles or exotic propulsion systems (that have not yet been developed), it also allows the spacecraft to carry a relatively large payload of scientific instruments.

In view of the inherent performance characteristics of chemical rocket propulsion and gravity propulsion, it follows that one of the most inefficient applications of the former is represented by fast direct transfer Earth–Pluto trajectories, whereas one of the more efficient applications of the latter is represented by Earth–Jupiter–Pluto trajectories. The amount of free accelerating thrust generated by Jupiter in gravitationally catapulting a spacecraft to Pluto will increase a spacecraft's velocity far above that which could be achieved with any kick stage mounted on the launch vehicle. This velocity increase will significantly reduce the overall trip time to Pluto. Moreover, unlike rocket propulsion, this velocity increase is independent of the mass of the spacecraft.

It should also be noted that the launch energy required for reaching Jupiter can itself be significantly reduced by gravity propulsion generated by multiple encounters with the inner planets. Thus, the most efficient gravity-propelled trajectory for reaching Pluto will incorporate these encounters,[6–10] and the minimum launch energy will be essentially equal to that required for reaching Venus. Because the total trip times required for these minimum launch energy, gravity-propelled trajectories will range between 12 and 16 years, they will not be considered in this paper. However, they would be ideal for orbital missions to Pluto[9,10] after an initial flyby mission.

The primary aim of this paper is to present a detailed numerical analysis and comparison of short trip time, direct transfer trajectories to Pluto vs short trip time, gravity-propelled Earth–Jupiter–Pluto

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*President, 1888 Century Park East, Suite 1900.

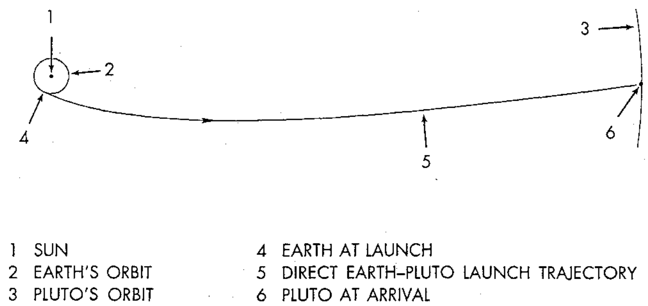

Fig. 1 Short trip time, rocket-propelled, Earth–Pluto trajectory.

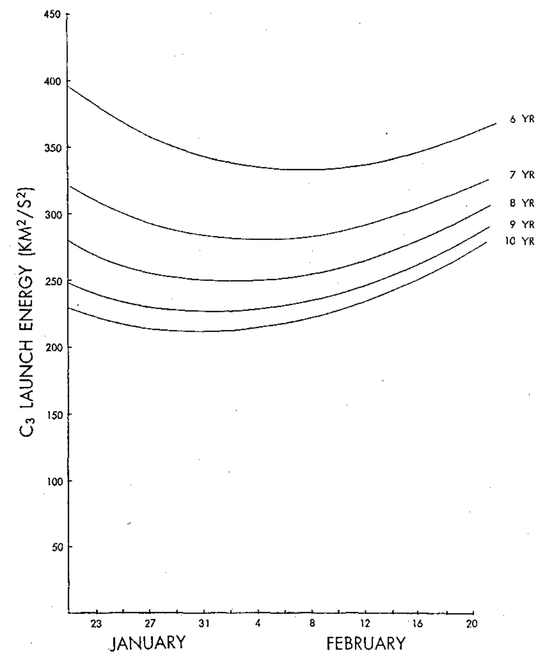

Fig. 2 1999 launch window for short trip time Earth–Pluto trajectories.

trajectories. It will be shown that by utilizing gravity-propelled trajectories it will be possible to increase the scientific return significantly while simultaneously reducing the cost. The paper is also intended to contribute to the relatively small database of Pluto mission analysis, which is necessary before any final mission profile is selected.

Launch Energy Requirements for Short Trip Time Direct Transfer Earth–Pluto Trajectories

Figure 1 illustrates a direct transfer, short trip time Earth–Pluto trajectory. For maximum efficiency, the trajectory is designed so that the departing asymptote is nearly parallel to the Earth's orbital velocity. Consequently, the launch windows are determined by the relative positions of Earth and Pluto. The time interval between successive windows is equal to the synodic period of these planets, which is 367 days. However, because the transfer trajectories are hyperbolic rather than elliptic, these windows do not correspond to the minimum launch energy windows. The trajectory parameters in each window are slightly different because the planetary orbits are eccentric and non-co-planar.

The transfer trajectories in three successive launch windows corresponding to direct fast flyby Pluto missions in 1999, 2000, and 2001 were determined numerically. Figures 2–4 are graphs of C_3 launch energy, V_∞^2, vs launch date corresponding to various trip times. Tables 1–3 give detailed trajectory parameters corresponding to the optimum 7-yr trip time launch date in each window of various trip times.

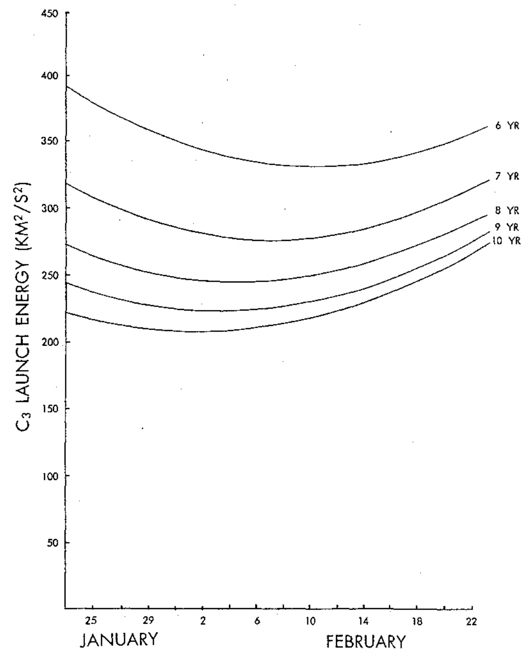

Fig. 3 Year 2000 launch window for short trip time Earth–Pluto trajectories.

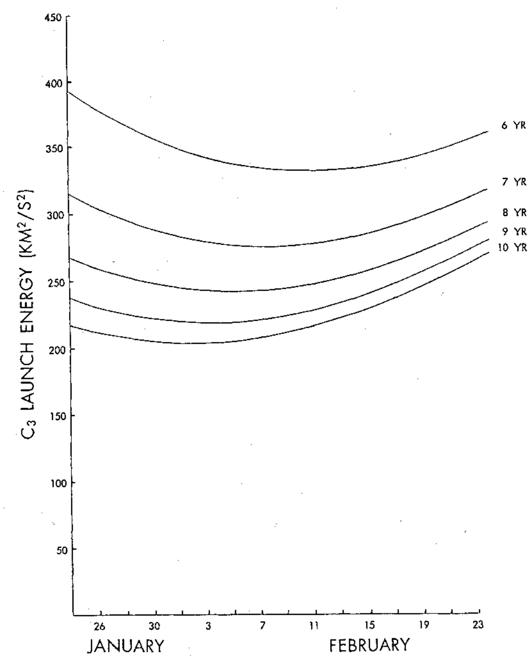

Fig. 4 Year 2001 launch window for short trip time Earth–Pluto trajectories.

Fast Gravity-Propelled Earth–Jupiter–Pluto Trajectories

Figure 5 illustrates a fast Earth–Jupiter–Pluto trajectory generated by relatively short Earth–Jupiter trip times. The optimum trajectories have departing asymptotes from Earth and Jupiter that are nearly tangent to the velocity vectors of these planets. The mass of Jupiter is sufficiently great to provide this characteristic at Jupiter with encounter trajectories that pass well outside the planet's atmosphere. Notice that because the orbit of Pluto is much larger than Jupiter's, the detour to Jupiter does not represent any significant increase in the total distance a spacecraft travels on the way to Pluto via Earth–Jupiter–Pluto trajectories. (The increase in distance is about 10% more than direct Earth–Pluto trajectories.) For optimum trajectories, the velocity increase generated by Jupiter's gravitational influence (the gravity propulsion ΔV) is about 11 km/s.

Because Jupiter's sidereal period is 11.86 yr, the gravity-propelled postencounter trajectories generated by initial Earth–Jupiter pre-

Table 1 High launch energy, direct transfer Earth–Pluto trajectories with launch date February 4, 1999

T	$V_{1\infty}$	C_3	θ	ϕ	a	E	e	$V_{2\infty}$	T_2
7.00	16.746	280.4	128.6	9.80	3.035	146.15	1.326	18.398	2/4/06
7.20	16.516	272.8	129.0	9.70	3.284	135.07	1.301	17.804	4/18/06
7.40	16.306	265.9	129.4	9.61	3.551	124.91	1.278	17.244	6/30/06
7.60	16.114	259.7	129.9	9.51	3.837	115.60	1.257	16.713	9/11/06
7.80	15.937	254.0	130.3	9.41	4.145	107.01	1.238	16.209	11/24/06
8.00	15.774	248.8	130.8	9.32	4.476	99.10	1.220	15.731	2/4/07
8.20	15.624	244.1	131.2	9.22	4.832	91.80	1.204	15.276	4/19/07
8.40	15.485	239.8	131.7	9.12	5.215	85.06	1.189	14.844	6/31/07
8.60	15.355	235.8	132.1	9.02	5.630	78.79	1.175	14.432	9/12/07
8.80	15.235	232.1	132.5	8.91	6.078	72.98	1.162	14.040	11/24/07
9.00	15.122	228.7	133.0	8.81	6.563	67.59	1.150	13.666	2/4/08

Table 2 High launch energy, direct transfer Earth–Pluto trajectories with launch date February 7, 2000

T	$V_{1\infty}$	C_3	θ	ϕ	a	E	e	$V_{2\infty}$	T_2
7.00	16.633	276.6	128.98	9.07	2.982	148.75	1.331	18.486	2/6/07
7.20	16.397	268.8	129.42	8.97	3.224	137.58	1.306	17.890	4/2/07
7.40	16.181	261.8	129.86	8.87	3.484	127.31	1.283	17.328	7/2/07
7.60	15.984	255.5	130.30	8.76	3.763	117.88	1.262	16.795	9/13/07
7.80	15.802	249.7	130.74	8.66	4.601	109.23	1.242	16.289	11/26/07
8.00	15.636	244.5	131.18	8.56	4.382	101.22	1.224	15.810	2/7/08
8.20	15.482	239.7	131.61	8.45	4.727	93.84	1.208	15.354	4/20/08
8.40	15.339	235.3	132.05	8.34	5.098	87.01	1.193	14.920	7/2/08
8.60	15.206	231.2	132.48	8.23	5.498	80.68	1.179	14.507	9/13/08
8.80	15.083	227.5	132.92	8.13	5.930	74.80	1.165	14.113	11/25/08
9.00	14.968	224.0	135.35	8.01	6.396	69.35	1.153	13.737	2/6/09

Table 3 High launch energy, direct transfer Earth–Pluto trajectories with launch date February 8, 2001

T	$V_{1\infty}$	C_3	θ	ϕ	a	E	e	$V_{2\infty}$	T_2
7.00	16.593	275.3	128.95	8.27	2.929	151.44	1.336	18.579	2/9/08
7.20	16.352	267.4	129.39	8.17	3.165	140.15	1.311	17.981	4/22/08
7.40	16.132	260.2	129.82	8.06	3.418	129.77	1.288	17.416	7/4/08
7.60	15.931	253.8	130.26	7.95	3.689	120.24	1.266	16.881	9/15/08
7.80	15.746	247.9	130.69	7.84	3.979	111.48	1.247	16.374	11/27/08
8.00	15.576	242.6	131.12	7.73	4.289	103.42	1.229	15.893	2/8/09
8.20	15.420	237.8	131.55	7.61	4.623	95.95	1.212	15.435	4/22/09
8.40	15.275	233.3	131.98	7.50	4.982	89.03	1.197	15.000	7/4/09
8.60	15.140	229.2	132.41	7.39	5.368	82.63	1.182	14.585	9/15/09
8.80	15.015	225.4	132.84	7.27	5.785	76.67	1.169	14.190	11/27/09
9.00	14.898	221.9	133.27	7.15	6.234	71.15	1.157	13.813	2/8/10

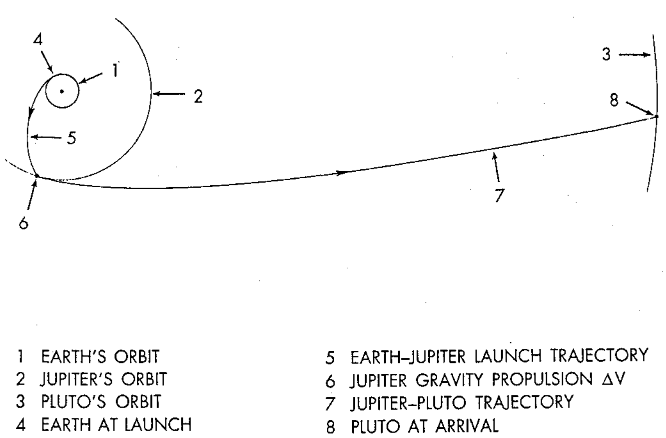

Fig. 5 Short trip time, gravity-propelled, Earth–Jupiter–Pluto trajectory.

encounter trajectories sweep 360 deg around the solar system every 11.86 yr. However, because these postencounter trajectories can have inclinations greater than ±90 deg, essentially any point in the solar system (including the Sun) can be reached by Jupiter-propelled postencounter trajectories with Earth–Jupiter launch energies significantly below the minimum required for direct transfer trajectories.

The time periods between optimum Earth–Jupiter–Pluto launch windows are approximately equal to the synodic period of Jupiter and Pluto, which is 12.46 yr. However, because the mass of Jupiter is so great, these optimum launch windows will always be surrounded by three additional launch windows. The four launch windows will be separated by time intervals equal to the synodic period of Earth and Jupiter, which is 399 days. The next group of Earth–Jupiter–Pluto launch windows occurs in 2002, 2003, 2004, and 2005. Because the group of favorable launch windows for Earth–Jupiter–Saturn–Pluto trajectories following these begins in 2016, they are not considered in this paper. However, these gravity-propelled trajectories would be ideal for future interplanetary missions to the outer planets. (The favorable launch windows for Earth–Jupiter–Uranus–Pluto trajectories are well beyond 2016.)

The Earth–Jupiter–Pluto trajectories corresponding to the 2002, 2003, and 2004 launch windows were numerically determined. Figures 6–8 are graphs of launch energy vs launch date corresponding to various trip times for these windows. The corresponding distances of closest approach to Jupiter's surface are shown in Figs. 9–11. The most favorable launch window occurs in 2003. Note that, for this window, the Earth–Jupiter–Pluto gravity-propelled

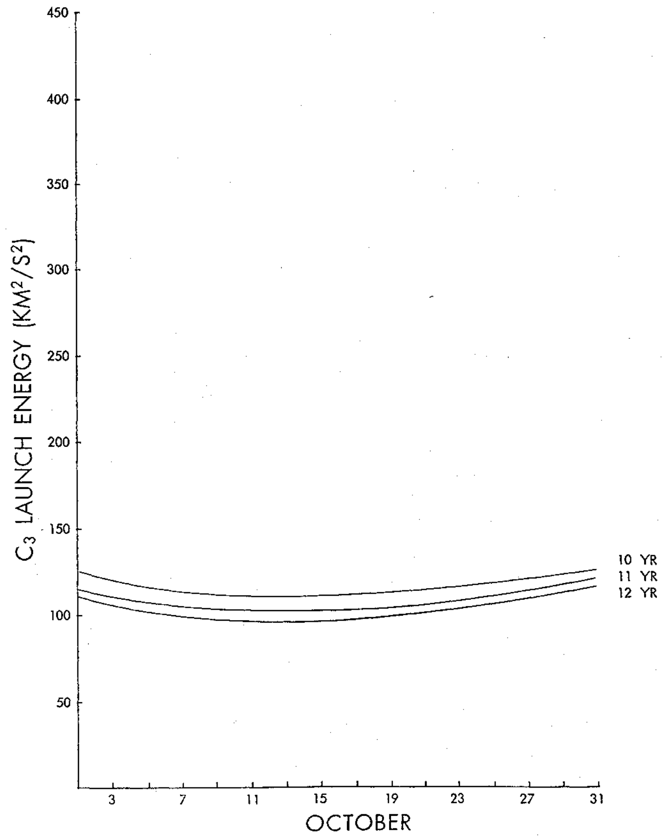

Fig. 6 Year 2002 launch window for Earth–Jupiter–Pluto trajectories.

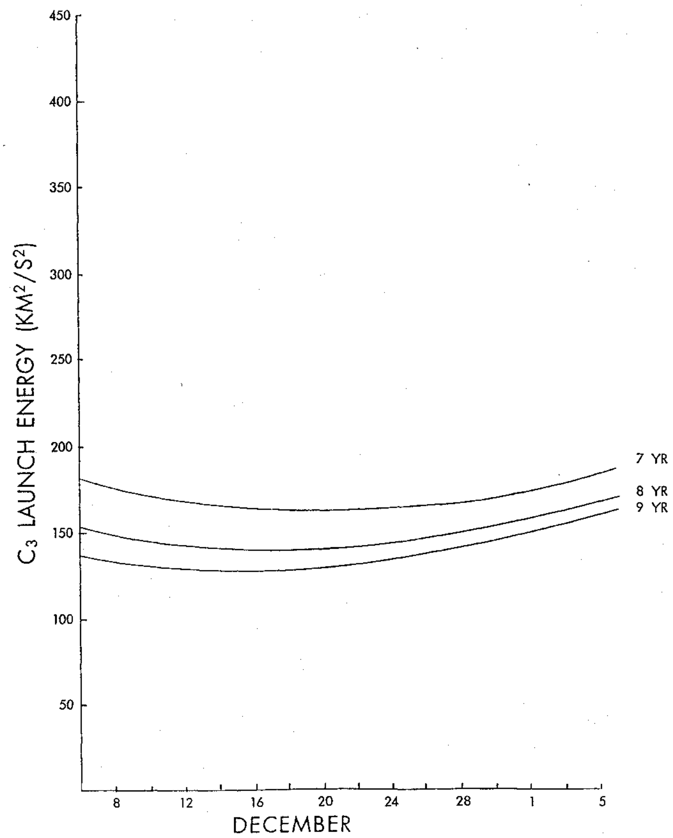

Fig. 8 Year 2004 launch window for Earth–Jupiter–Pluto trajectories.

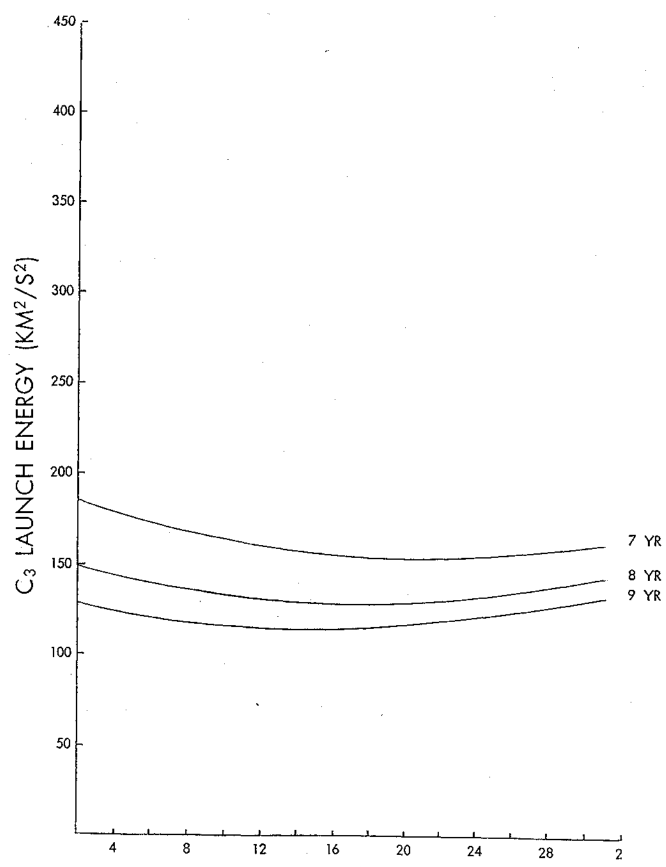

Fig. 7 Year 2003 launch window for Earth–Jupiter–Pluto trajectories.

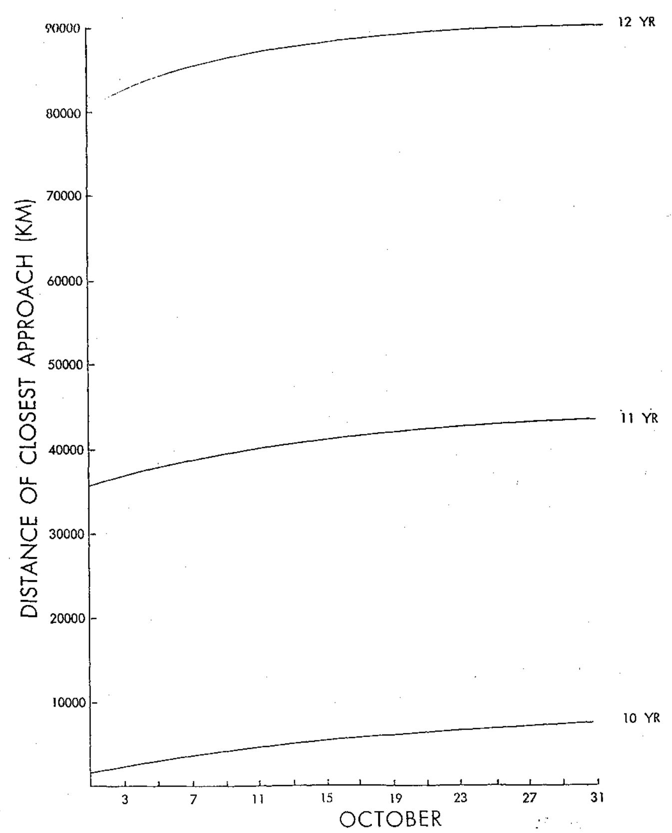

Fig. 9 Distances of closest approach corresponding to the year 2002 Earth–Jupiter–Pluto launch window.

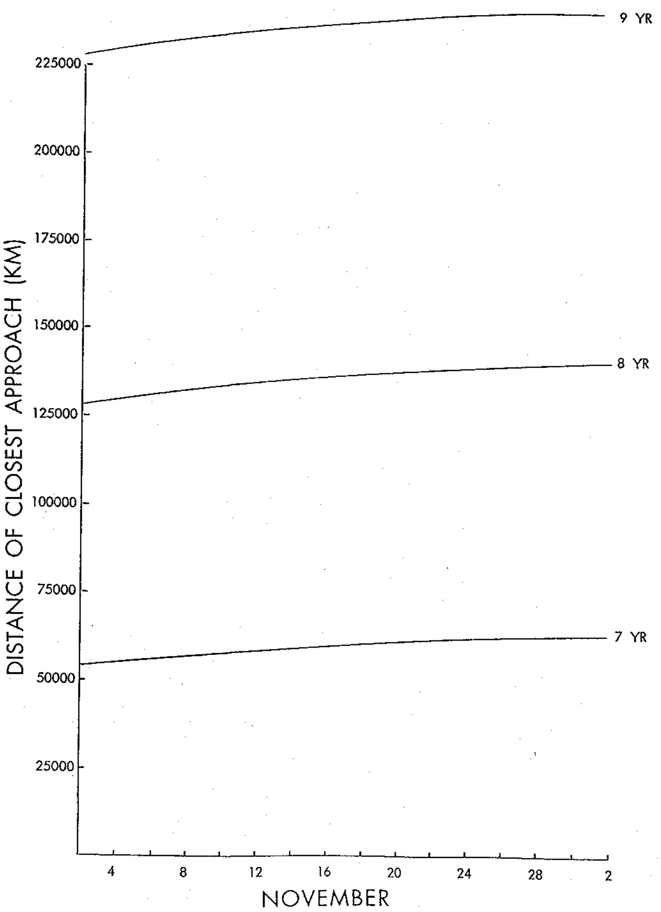

Fig. 10 Distances of closest approach corresponding to the year 2003 Earth–Jupiter–Pluto launch window.

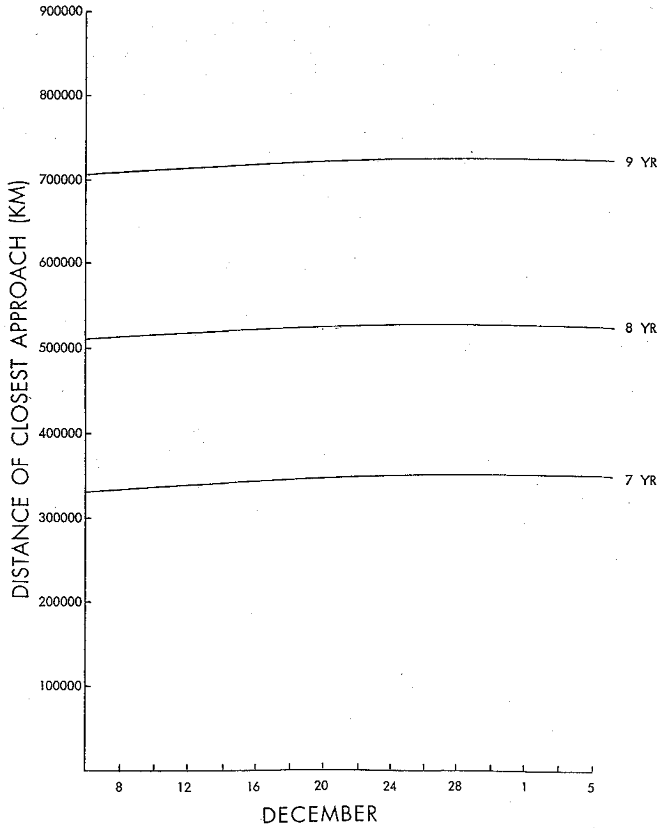

Fig. 11 Distances of closest approach corresponding to the year 2004 Earth–Jupiter–Pluto launch window.

trajectories have launch energies about one-half that of direct transfer Earth–Pluto trajectories with approximately the same trip times.

When a spacecraft moves from one planet to another, its motion is determined primarily by the Sun's gravitational field. Hence, its trajectory is nearly equal to a conic section with constant orbital energy. This orbital energy E is equal to $\mp(\mu/2a)$, where μ is equal to the Sun's gravitational constant, 1.327×10^{11} km^3/s^2, and a is equal to the trajectory's semimajor axis. The negative or positive sign is chosen if the trajectory is elliptical or hyperbolic, respectively. Parabolic trajectories have zero orbital energy. The velocity of a spacecraft at any point on its orbit is given by

$$V = ((2\mu/R) + 2E)^{1/2} \tag{1}$$

Consequently, to obtain short trip times, E should be as high as possible.

Figure 12 is a graph of the orbital energies E of direct transfer, short trip time Earth–Pluto trajectories vs launch hyperbolic excess velocity V_∞ corresponding to the optimum February 4, 1999, launch date. The orbital energies of postencounter Jupiter–Pluto trajectories generated by Earth–Jupiter pre-encounter trajectories having launch hyperbolic excess velocities V_∞ corresponding to the optimum November 17, 2003, Earth–Jupiter–Pluto launch date are also plotted on Fig. 12 for comparison. Figure 13 displays graphs of total trip time vs launch V_∞ for Earth–Pluto and Earth–Jupiter–Pluto trajectories corresponding to these launch dates. These graphs clearly demonstrate the significant propulsion advantages that can be obtained for missions to Pluto by using gravity-propelled Earth–Jupiter–Pluto trajectories instead of direct transfer Earth–Pluto trajectories.

Tables 4–6 describe the detailed Earth–Jupiter–Pluto trajectory parameters corresponding to the optimum launch date in the 2002, 2003, and 2004 windows for various trip times. In studying these tables, we note that the C_3 launch energies are well within the capabilities of the relatively small commercial Atlas IIAS/Centaur launch vehicle equipped with a Star 48B kick stage.[11] Figure 14 gives the payload mass vs C_3 for this vehicle corresponding to a medium

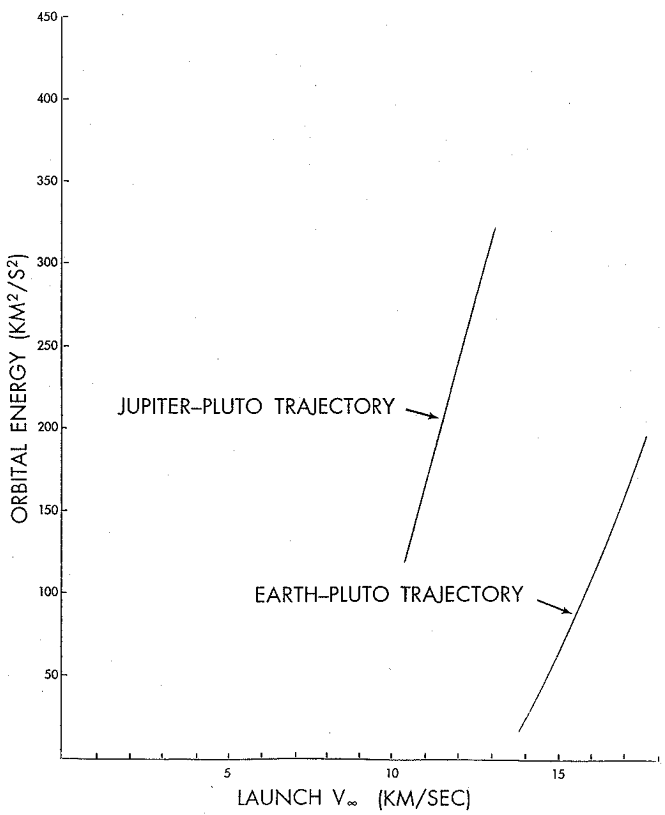

Fig. 12 Orbital energy vs launch V_∞ of gravity-propelled Jupiter–Pluto trajectories and rocket-propelled Earth–Pluto trajectories.

Table 4 Gravity propelled Earth–Jupiter–Pluto trajectories with launch date October 15, 2002

T_{12}	V_{1_∞}	C_3	M_s	θ_{12}	E_{12}	DOCA, km	TDA, deg	ΔV	E_{23}	T_{23}	θ_{23}	V_{3_∞}	T_{13}	T_3
1.45	10.701	114.5	445	144.69	−71.56	0	66.21	10.598	128.52	8.35	112.29	16.342	9.81	8/5/12
1.46	10.677	114.0	450	144.85	−72.57	1,193	65.86	10.611	127.00	8.39	112.21	16.256	9.85	8/20/12
1.47	10.637	113.1	459	145.13	−74.25	3,248	65.26	10.631	124.46	8.45	112.07	16.110	9.92	9/5/12
1.48	10.598	112.3	463	145.41	−75.89	5,339	64.67	10.648	121.91	8.51	111.94	15.963	9.99	10/11/12
1.49	10.560	111.5	466	145.69	−77.48	7,509	64.07	10.667	119.47	8.57	111.81	15.821	10.06	11/6/12
1.50	10.524	110.8	474	145.97	−79.04	9,745	63.47	10.685	117.06	8.63	111.68	15.680	10.13	12/2/12
1.51	10.489	110.0	480	146.25	−80.56	12,035	62.88	10.704	114.71	8.70	111.54	15.541	10.21	12/28/12
1.52	10.454	109.3	483	146.53	−82.03	14,395	62.28	10.721	112.40	8.76	111.41	15.403	10.28	1/24/13
1.53	10.421	108.6	486	146.80	−83.47	16,818	61.67	10.738	110.13	8.82	111.28	15.266	10.35	2/19/13
1.54	10.389	107.9	491	147.08	−84.88	19,318	61.07	10.754	107.88	8.61	111.15	15.130	10.42	3/18/13
1.55	10.358	107.3	497	147.36	−86.25	21,874	60.46	10.771	105.70	8.95	111.02	14.996	10.50	4/13/13
1.56	10.328	106.7	506	147.64	−87.58	24,508	59.86	10.786	103.54	9.01	110.89	14.864	10.57	5/10/13
1.57	10.298	106.1	509	147.92	−88.88	27,218	59.25	10.801	101.42	9.07	110.76	14.732	10.64	6/6/13
1.58	10.270	105.5	511	148.20	−90.15	30,003	58.64	10.815	99.33	9.14	110.63	14.601	10.72	7/3/13
1.59	10.242	104.9	514	148.47	−91.39	32,867	58.02	10.829	97.28	9.20	110.50	14.472	10.79	7/30/13
1.60	10.215	104.4	520	148.75	−92.60	35,812	57.41	10.842	95.26	9.27	110.83	14.343	10.87	8/27/13
1.61	10.189	103.8	526	149.03	−93.78	38,852	56.79	10.854	93.26	9.33	110.25	14.215	10.94	9/23/13
1.62	10.164	103.3	531	149.31	−94.93	41,954	56.18	10.867	91.32	9.40	110.12	14.089	11.02	10/21/13
1.63	10.140	102.8	534	149.58	−96.05	45,166	55.56	10.877	89.39	9.46	110.00	13.963	11.09	11/18/13
1.64	10.116	102.3	537	149.86	−97.14	48,447	54.94	10.889	87.50	9.53	109.88	13.839	11.17	12/16/13
1.65	10.093	101.9	543	150.14	−98.21	51,842	54.31	10.899	85.62	9.60	109.75	13.715	11.25	1/13/14
1.66	10.071	101.4	546	150.42	−99.25	55,315	53.69	10.908	83.79	9.67	109.63	13.592	11.33	2/10/14
1.67	10.049	101.0	547	150.69	−100.26	58,904	53.06	10.917	81.97	9.73	109.51	13.469	11.40	3/11/14
1.68	10.029	100.6	549	150.97	−101.26	62,578	52.43	10.926	80.19	9.80	109.39	13.348	11.48	4/9/14
1.69	10.008	100.2	551	151.25	−102.22	66,373	51.80	10.933	78.41	9.87	109.27	13.227	11.56	5/8/14
1.70	9.989	99.8	552	151.53	−103.16	70,202	51.17	10.938	76.65	9.94	109.16	13.105	11.64	6/7/14

Table 5 Gravity propelled Earth–Jupiter–Pluto trajectories with launch date November 17, 2003

T_{12}	V_{1_∞}	C_3	M_s	θ_{12}	E_{12}	DOCA, km	TDA, deg	ΔV	E_{23}	T_{23}	θ_{23}	V_{3_∞}	T_{13}	T_3
1.17	12.501	156.3	229	134.18	6.99	58,708	61.74	11.226	276.84	5.81	86.53	23.280	6.98	11/9/10
1.18	12.403	153.9	240	134.45	3.11	62,971	61.22	11.221	270.44	5.87	86.39	23.021	7.05	12/3/10
1.19	12.310	151.5	249	134.73	−0.65	67,357	60.69	11.216	264.21	5.92	86.25	22.767	7.11	12/27/10
1.20	12.218	149.3	257	135.00	−4.31	71,891	60.17	11.210	258.09	5.98	86.12	22.514	7.18	1/21/11
1.21	12.130	147.1	266	135.28	−7.87	76,579	59.64	11.204	252.09	6.04	85.98	22.263	7.25	2/15/11
1.22	12.044	145.1	274	135.56	−11.32	81,414	59.11	11.197	246.21	6.10	85.85	22.016	7.32	3/12/11
1.23	11.961	143.1	283	135.83	−14.68	86,401	58.58	11.189	240.46	6.16	85.72	21.771	7.38	4/6/11
1.24	11.881	141.2	293	136.11	−17.94	91,554	58.04	11.181	234.83	6.22	85.59	21.528	7.45	5/1/11
1.25	11.803	139.3	300	136.38	−21.11	96,871	57.50	11.171	229.13	6.28	85.45	21.287	7.52	5/27/11
1.26	11.727	137.5	313	136.66	−24.19	102,363	56.96	11.161	223.88	6.34	85.32	21.049	7.59	6/21/11
1.27	11.654	135.8	322	136.93	−27.19	108,034	56.42	11.149	218.52	6.40	85.20	20.811	7.67	7/18/11
1.28	11.583	134.2	327	137.21	−30.10	113,888	55.87	11.138	213.31	6.46	85.07	20.577	7.74	3/18/11
1.29	11.514	132.6	337	137.48	−32.94	119,937	55.32	11.125	208.19	6.52	84.94	20.344	7.81	9/8/11
1.30	11.447	131.0	343	137.76	−35.69	126,182	54.77	11.112	203.16	6.59	84.82	20.114	7.88	10/5/11
1.31	11.383	129.6	354	138.04	−38.37	132,632	54.22	11.098	198.23	6.65	84.70	19.885	7.96	11/2/11
1.32	11.320	128.1	360	138.31	−40.98	139,295	53.66	11.083	193.38	6.72	84.58	19.658	8.03	11/29/11
1.33	11.259	126.8	367	138.59	−43.52	146,187	53.10	11.068	188.61	6.78	84.46	19.432	8.11	12/27/11
1.34	11.201	125.5	374	138.86	−45.99	153,305	52.54	11.051	183.93	6.85	84.34	19.207	8.19	1/24/12
1.35	11.144	124.2	383	139.14	−48.39	160.647	51.98	11.034	179.33	6.92	84.22	18.985	8.26	2/21/12
1.36	11.088	123.0	387	139.41	−50.73	168,261	51.41	11.016	174.79	6.99	84.11	18.763	8.34	3/21/12
1.37	11.035	121.8	397	139.69	−53.01	176.095	50.84	10.997	170.35	7.06	84.00	18.543	8.42	4/19/12
1.38	10.983	120.6	403	139.96	−55.22	184,212	50.27	10.977	165.97	7.13	83.89	18.324	8.50	5/19/12
1.39	10.933	119.5	413	140.24	−57.38	192,602	49.69	10.956	161.66	7.20	83.78	18.106	8.59	6/18/12
1.40	10.884	118.5	418	140.51	−59.48	201,278	49.11	10.935	157.41	7.27	83.67	17.889	8.67	7/18/12
1.41	10.837	117.4	425	140.79	−61.53	210,254	48.53	10.912	153.22	7.35	83.57	17.672	8.75	8/18/12

3.3-m-diam payload fairing. By using this payload mass vs C_3 performance data, the possible spacecraft mass M_s corresponding to the various Earth–Jupiter–Pluto trajectories given in Tables 4–6 can be determined for this launch vehicle. These spacecraft masses are included in these tables. Notice that these spacecraft masses are significantly greater than 100 kg. Hence, by using a gravity-propelled Earth–Jupiter–Pluto trajectory, a mission to Pluto could be accomplished with a relatively small $120 million Atlas IIAS/Centaur launch vehicle with a spacecraft approximately three times the mass of a spacecraft that could be launched to Pluto directly using a very large $400 million Titan IV/Centaur. The resulting mass ratio (total launch mass/injected spacecraft mass) would be decreased by about one order of magnitude. The trip time would be about the same. Because the payload of an Earth–Jupiter–Pluto spacecraft could be significantly greater, it could carry much more instrumentation, and this instrumentation could be used for exploring two different planetary systems instead of one, giving a large increase in scientific return.

Radiation Hazard

Tables 4–6 show that fast Jupiter accelerated trajectories to Pluto will require close passing distances. During this time the spacecraft will be exposed to Jupiter's radiation belts. If the spacecraft cannot be sufficiently hardened to withstand this radiation, such trajectories must be ruled out. But this is not the case.

Table 7 is a list of all previous spacecraft that were gravitationally accelerated by jupiter showing the distances of closest approach (DOCA, km) and the radiation effects. All of the

Table 6 Gravity propelled Earth–Jupiter–Pluto trajectories with launch date December 21, 2004

T_{12}	$V_{1\infty}$	C_3	M_s	θ_{12}	E_{12}	DOCA, km	TDA, deg	ΔV	E_{23}	T_{23}	θ_{23}	$V_{3\infty}$	T_{13}	T_3
1.12	12.691	161.1	209	127.85	20.46	338,255	37.94	8.974	232.79	5.83	59.90	21.570	6.95	12/4/11
1.13	12.589	158.5	220	128.13	16.04	354,094	37.44	8.919	224.75	5.92	59.82	21.220	7.05	1/8/12
1.14	12.490	156.0	229	128.40	11.75	370,558	36.94	8.862	216.87	6.01	59.74	20.872	7.15	2/13/12
1.15	12.394	153.6	241	128.68	7.59	387,709	36.43	8.804	209.15	6.10	59.67	20.525	7.25	3/20/12
1.16	12.301	151.3	249	128.96	3.55	405,545	35.93	8.745	201.59	6.19	59.59	20.180	7.35	4/26/12
1.17	12.212	149.1	257	129.24	−0.36	424,043	35.42	8.685	194.22	6.28	59.53	19.839	7.45	6/3/12
1.18	12.125	147.0	260	129.52	−4.17	443,411	34.90	8.624	186.94	6.38	59.47	19.496	7.56	7/13/12
1.19	12.041	145.0	273	129.79	−7.87	463,578	34.39	8.562	179.80	6.48	59.41	19.154	7.67	8/22/12
1.20	11.960	143.0	286	130.07	−11.46	484,537	33.87	8.498	172.82	6.58	59.36	18.814	7.78	10/2/12
1.21	11.882	141.2	291	130.35	−14.95	506,365	33.35	8.434	165.98	6.69	59.31	18.475	7.90	11/14/12
1.22	11.806	139.4	297	130.63	−18.33	529,148	32.83	8.368	159.26	6.80	59.27	18.136	8.02	12/27/12
1.23	11.732	137.6	310	130.91	−21.62	552,887	32.30	8.301	155.66	6.91	59.24	17.798	8.14	2/10/13
1.24	11.661	136.0	318	131.18	−24.82	577,643	31.78	8.232	146.19	7.03	59.22	17.460	8.27	3/29/13
1.25	11.593	134.4	326	131.46	−27.92	603,469	31.24	8.163	139.83	7.15	59.20	17.122	8.40	5/16/13
1.26	11.527	132.9	336	131.74	−30.94	630,426	30.71	8.092	133.59	7.28	59.19	16.784	8.53	7/4/13
1.27	11.462	131.4	343	132.02	−33.87	658,566	30.18	8.020	127.45	7.41	59.19	16.445	8.68	8/24/13
1.28	11.400	130.0	351	132.30	−36.73	687,935	29.64	7.946	121.43	7.54	59.20	16.106	8.82	10/16/13
1.29	11.340	128.6	359	132.58	−39.50	718,615	29.10	7.872	115.51	7.68	59.22	15.776	8.97	12/10/13
1.30	11.282	127.3	362	132.86	−42.20	750,705	28.56	7.796	109.68	7.83	59.25	15.424	9.13	2/6/14
1.31	11.226	126.0	366	133.13	−44.82	784,207	28.01	7.718	103.96	7.98	59.29	15.082	9.29	4/6/14
1.32	11.171	124.8	383	133.41	−47.37	819,240	27.46	7.640	98.33	8.14	59.35	14.738	9.46	6/7/14
1.33	11.118	123.6	387	133.69	−49.86	855,902	26.91	7.560	92.79	8.31	59.42	14.392	9.64	8/11/14
1.34	11.067	122.5	391	134.97	−52.28	894,296	26.36	7.478	87.34	8.49	59.51	14.044	9.83	10/18/14
1.35	11.018	121.4	400	134.25	−54.63	934,433	25.81	7.396	81.98	8.67	59.61	13.693	10.02	12/29/14
1.36	10.970	120.3	405	134.53	−56.92	976,502	25.25	7.312	76.70	8.87	59.73	13.339	10.23	3/14/15

Table 7 Spacecraft survivability passing through Jupiter's radiation belts

Spacecraft	DOCA, R_j	Radiation damage
Pioneer 10	1.8	Saturated two cosmic ray detectors No critical damage
Pioneer 11	0.6	No critical damage
Voyager 1	3.9	No critical damage
Voyager 2	9.1	No critical damage

spacecraft survived.[12–18] The Ulysses and Galileo spacecraft will have distances of closest approach of approximately $5R_j$ and $3R_j$, respectively.[19,20] It is also important to note that Jupiter's maximum radiation intensity inside approximately $12R_j$ remains about the same.[16]

The spacecraft shown in Table 7 were hardened with techniques and technology developed many years ago. Since that time, this field has been significantly advanced.[21,22] The Strategic Defense Initiative program also contributed to this field.[23,24] For these reasons it is submitted that future spacecraft can be designed to withstand Jupiter's radiation belts easily for any distance of closest approach. Close passing distances to Jupiter's surface can, in fact, be regarded as an important benefit, because they will provide excellent opportunities for detailed scientific measurements.

Pluto's Atmosphere

Launch windows for direct Earth–Pluto trajectories occur every 367 days (the synodic period between Earth and Pluto), whereas the launch windows for Earth–Jupiter–Pluto trajectories are less frequent. The time interval between these windows can range from 399 days to 11 yr, as described above. However, from a practical point of view, this situation is relatively unimportant because it usually requires roughly a decade of lead time between mission conception and actual launch.

In the case of the proposed fast flyby missions to Pluto, it has been suggested by Terrile[25] and others[2,4,26] that a spacecraft should be launched as soon as possible so as to reach Pluto near perihelion passage (October 11, 1989) before the atmosphere condenses and falls to the surface as snow.[2,4] But this possibility is unlikely for several reasons. Recent observations show that methane, CH_4, is the main constituent of Pluto's atmosphere.[27–30] Methane has a triple point of 90.6 K. Because the maximum temperature of Pluto's surface is about 60 K and reaches a low of about 45 K, it is already well below the triple point. The atmosphere is created by vapor pressure equilibrium between the solid and gaseous phases. Thus,

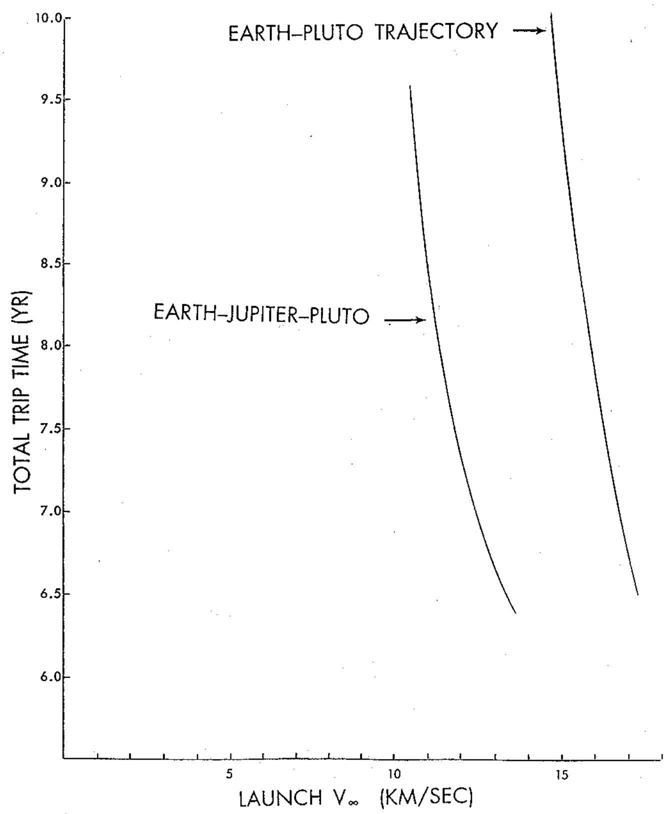

Fig. 13 Total trip time vs launch V_∞ of Earth–Jupiter–Pluto and Earth–Pluto trajectories.

Pluto will always have an atmosphere. However, a large fraction of methane always remains on the surface in the solid state. This is graphically illustrated by the Pressure-Temperature Phase Diagram shown in Fig. 15. This diagram gives the physical state of methane (and hence, the physical state of Pluto's atmosphere) for any given temperature.[31,32]

There is also strong evidence indicating that, as is common in most atmospheres, Pluto's atmosphere is being heated by infrared absorption, which will continue when the planet reaches aphelion.[28,30] This possibility will introduce complicated thermodynamics, the analysis

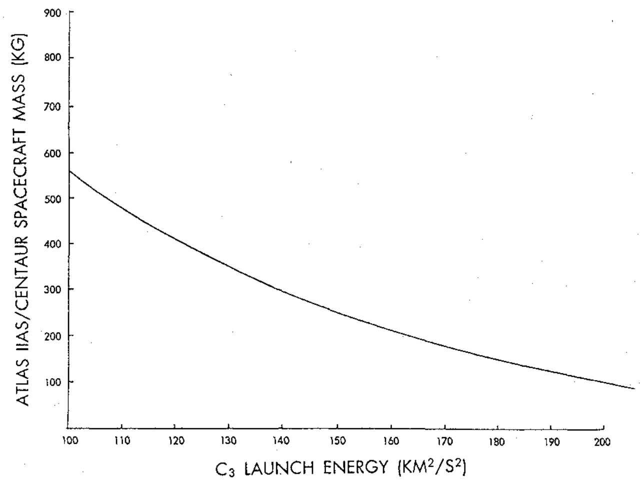

Fig. 14 Injected spacecraft mass vs launch C_3 for the commercial Atlas IIAS/Centaur/Star 48B launch vehicle.

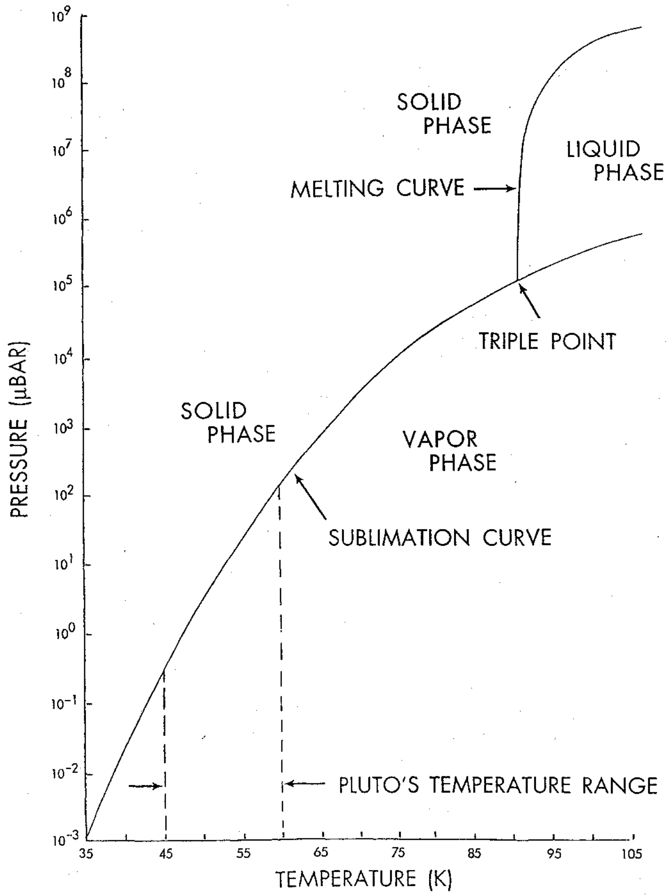

Fig. 15 Pressure–temperature phase diagram of methane.

of which is beyond the intended scope of this paper.[27,28,30] However, because Pluto's orbital period is 248 yr, a 4-yr delay in reaching Pluto will correspond to an average temperature change ΔT of approximately $(60\text{ K} - 45\text{ K}) \times (4/124) = 0.5\text{ K}$. (Vaning has shown that by incorporating regiolith thermal lag, Pluto's surface temperature can actually increase a few degrees after perihelion passage, while moving farther from the Sun.[33]) Consequently, the atmosphere of Pluto will be essentially unchanged during this time interval. Therefore, the atmosphere observed by a spacecraft launched in 1999 on a 7-yr direct transfer Earth–Pluto trajectory arriving at Pluto in 2006 will be essentially identical to the atmosphere observed by a spacecraft launched in 2003 on a 7-yr gravity-propelled Earth–Jupiter–Pluto trajectory arriving at Pluto in 2010. This will be true for any spacecraft launched in any of the six launch windows described in Figs. 2–4 and Figs. 6–8.

Concluding Remarks

The recently proposed 7-yr direct fast flyby missions to Pluto require a C_3 launch energy of about 280 km²/s². This is more than twice the launch energy of any previous mission. If conventional chemical rocket propulsion is used (which is the only viable option) the well-known exponential increase in mass ratio that limits the performance capabilities of this type of propulsion system becomes very evident. In particular, it would require a very large $400 million Titan IV/Centaur launch vehicle with a mass of nearly 1,000 metric-tons to send to small 100-kg spacecraft to Pluto on these trajectories. The plan proposes to send two of these 100-kg spacecraft directly to Pluto with these launch vehicles near the end of this decade at a total cost exceeding $1 billion.[2]

If the missions to Pluto were carried out by gravity-propelled Earth–Jupiter–Pluto trajectories, the $400 million Titan IV/Centaur launch vehicles could be replaced with relatively small commercial Atlas IIAS/Centaur launch vehicles at one-fourth the cost, and the spacecraft mass could actually be increased by a factor of three without increasing the trip time. Most of the propulsive energy required to accelerate the spacecraft to high velocities for short trip times is taken from Jupiter's orbital energy via gravitational forces, which, unlike rocket propulsion, are independent of spacecraft mass. The spacecraft could be similar to the Pioneer 10 and 11 spacecraft that were sent to Jupiter by Atlas/Centaur launch vehicles in 1972 and 1973 and accelerated by that planet into deep interstellar space. In the case of Pioneer 11, Jupiter accelerated the spacecraft to Saturn via an Earth–Jupiter–Saturn trajectory. However, the amount of scientific instrumentation could be significantly increased by using state-of-the-art electronics and miniaturization. As in the Pioneer 11 mission, the Earth–Jupiter–Pluto trajectory profile also enables the instrumentation to be used for exploring two different planetary systems (Jupiter and Pluto), thereby obtaining a much greater scientific return. The total cost of the missions involving two separate Atlas/Centaur launches would be about one-third the cost of the proposed plan. A savings of this magnitude (spread over a longer time interval) would enable the exploration of Pluto to proceed without drawing significant funding form other important space exploration missions, thereby allowing all of the previous missions to continue as originally planned.[34]

Because the Atlas IIAS/Centaur could launch a significantly greater payload on a 7-yr Earth–Jupiter–Pluto trajectory than a Titan IV/Centaur could on a 7-yr direct transfer Earth–Pluto trajectory, the cost could be reduced another 50% by simply launching two (or three) 115-kg proposed spacecraft close to the original design,[2] but radiation hardened, with one Atlas IIAS/Centaur, and giving them slightly different velocities after release. (The hardening is assumed to increase the spacecraft mass by 15 kg, which is probably much more than required.) The time of arrival at Pluto for each spacecraft would be a few days different so that together the spacecraft could photograph Pluto's entire surface. Because only one relatively small launch vehicle is used, the overall cost of the mission would be reduced to about one-fifth the cost of the proposed plan.

In view of the fact that the atmosphere of Pluto will not disappear by condensing and falling to the surface as snow in the near future (if ever), a delay of 4 yr in reaching that planet will have essentially no effect on the observational conditions. But it will have a major beneficial effect on cost and scientific return because Earth–Jupiter–Pluto trajectories could be used instead of energy-consuming direct transfer Earth–Pluto trajectories with no increase in trip time. In view of the Jet Propulsion Laboratory's outstanding success with the more complicated Voyager 2 Earth–Jupiter–Saturn–Uranus–Neptune mission, the Laboratory would find the Earth–Jupiter–Pluto trajectory profile relatively easy. As an alternative, the Earth–Jupiter–Pluto missions could also be undertaken by NASA's Ames Research Center with a much lower budget, as was demonstrated by the successful Pioneer 10 and the Earth–Jupiter–Saturn Pioneer 11 missions.

There is another advantage to using gravity-propelled Earth–Jupiter–Pluto trajectories for missions to Pluto. The orbital energy after the Jupiter encounter will be significantly higher than that of direct transfer trajectories. Consequently, the hyperbolic solar escape velocities, $V_\infty = \sqrt{2E}$, will be significantly higher. This will enable the spacecraft to reach and explore interstellar regions far beyond that which could be reached by direct transfer trajectories within the same time period.

If NASA chooses to allocate a very large and expensive Titan IV/Centaur launch vehicle to send a small 100-kg spacecraft to Pluto on a fast, high-energy, direct transfer trajectory via brute force rocket power to explore that planet, it would be much more cost-effective to replace the kick stage with 64 additional spacecraft, and send them to Venus on a low-energy trajectory. The spacecraft could then be gravitationally propelled individually to 65 separate targets throughout the entire solar system to explore not only Pluto, but every other planet, many satellites, asteroids, comets, the Sun, regions far above and below the ecliptic plane, and deep interstellar space, simultaneously in a single mission.[35] Although the trip time to Pluto would require about 12–16 yr, the scientific return from all of the spacecraft could be greater than the combined results of all previous interplanetary missions for exploring the solar system. By taking advantage of the economics of mass producing a prototype spacecraft, the total cost of the mission could be significantly below the proposed plan to send two 100-kg spacecraft to Pluto using two separate Titan IV/Centaur launch vehicles.

In conclusion, it is interesting to note that from the inception of gravity-propelled space travel through 1990, essentially all mission analysis studies concluded that the exploration of the outer planets, especially Pluto, should be carried out by gravity-propelled trajectories.[9,10,36–41] Fast, direct transfer trajectories required so much launch energy that they were never seriously considered. The Jupiter radiation belts could be penetrated by well-known methods of radiation hardening. The fact that advances in spacecraft miniaturization make it technically feasible to send a spacecraft directly to Pluto using very large and expensive launch vehicles does not alter the basic physics of chemical rocket propulsion. Most of the mass accelerated to Pluto by such vehicles will be burned-out rocket stages and empty propellant tanks, not scientific instruments. Because the dominant cost factor of space travel is determined by the launch vehicle and not by the spacecraft, it is difficult to see any economic advantage in the proposed Pluto fast flyby missions. There is no scientific advantage.

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