Superposition of scatter levels (adding) is valid to obtain scatter of multiple (two-pane) window arrays. The window edges should perhaps be polished. Painting of the window edge also reduces the light-scatter levels.

References

[1] Munis, R. H. and Finkel, M. W., "Goniometric Measurements of Infrared Transmitting Materials," *Applied Optics*, Vol. 7, 1968, p. 2001.

[2] Tousey, R. and Koomen, M. J., "The Visibility of Stars and Planets During Twilight," *Journal of the Optical Society of America*, Vol. 43, No. 3, 1953, pp. 177-183.

[3] Ney, E. P. and Huch, W. F., "Optical Environment in Gemini Space Flights," *Science*, Vol. 153, 1966, pp. 297-299.

[4] Johnson, F. S., "The Solar Constant," *Journal of Meteorology*, Vol. II, No. 6, Dec. 1954, pp. 431-439.

[5] *Gemini Midprogram Conference, Including Experimental Results*, NASA SP-121, Feb. 23-25, 1966, pp. 283-297 and pp. 315-323.

[6] Hardy, A. C., "How Large is a Point Source?" *Journal of the Optical Society of America*, Vol. 57, No. 1, Jan. 1967, pp. 44-47.

[7] Blackwell, R. H., "Contrast Thresholds of the Human Eye," *Journal of the Optical Society of America*, Vol. 36, No. 11, Nov. 1946, p. 624.

AUGUST 1971 J. SPACECRAFT VOL. 8, NO. 8

Trajectory Requirements for Comet Rendezvous

ALAN L. FRIEDLANDER,* JOHN C. NIEHOFF,† AND JOHN I. WATERS‡
IIT Research Institute, Chicago, Ill.

This paper presents a new look at spacecraft mission opportunities to the short-period comets in the time period 1975–1995. The objective is to identify the most promising rendezvous opportunities and flight modes from the standpoint of trajectory requirements and launch vehicle/payload capabilities. A "broad-brush" treatment of wide scope underlies the analysis. Selection criteria leading to 16 comet apparitions for study are described. The candidate flight modes include; 3-impulse ballistic transfers, Jupiter-gravity-assist transfers, solar-electric and nuclear-electric low-thrust transfers. Results show that the best early opportunities are Comets Encke/80, d'Arrest/82, and Kopff/83. Although these missions can be performed ballistically, solar-electric propulsion offers greatly improved performance. Practical accomplishment of the very difficult Halley rendezvous depends upon the development and availability of nuclear-electric propulsion by 1983.

Introduction

SPACECRAFT missions to the comets can play an important role in the total space exploration program. An improved knowledge of cometary bodies should contribute to our understanding of the dynamics and origin of the solar system. In particular, "in situ" scientific measurements can provide information on the comet nucleus and the distribution of particles and fields in the coma and tail regions. This type of data is extremely difficult if not impossible to obtain from Earth-based observations.

A number of earlier studies[1–4] have reported on periodic comets and their scientific exploration by means of spacecraft intercept missions. These studies have presented the scientific objectives, a compendium of existing cometary data, trajectory and sighting analysis, and a survey of suitable missions including payload selection and questions of mission constraints. Comet intercept or flyby missions are characterized by relatively low launch velocity requirements and short flight times, but very high approach velocities at the comet leaving little time for science experiments. Clearly, it is more opportune that the spacecraft match orbits with the comet and thus have many months to monitor the variations in physical activity as the comet approaches and passes through perihelion. The present paper considers the rendezvous mission mode which affords this opportunity for increased science value return.

Several previous and enlightening investigations of comet rendezvous have been reported in the literature.[5–8] The present study[9] expands upon earlier work in this area in terms of the scope of mission opportunities available and the comparison of candidate modes of flight for performing these missions. Specifically, the objective is to identify the most promising rendezvous missions and flight modes in the time period 1975–1995 from the standpoint of trajectory requirements and launch vehicle/payload capabilities. Both the ballistic and low-thrust flight modes with two variations on each are considered. Ballistic flights include 1) direct transfers utilizing three velocity impulses and 2) gravity-assist transfers via the planet Jupiter thus eliminating the midcourse propulsive impulse. The low-thrust propulsion mode includes application of 1) solar-electric powerplants and 2) nuclear-electric powerplants. Use of nuclear-electric spacecraft will be emphasized only for the very difficult but exciting rendezvous mission to Halley's Comet. All trajectories are optimized to give effectively a maximum payload (net spacecraft mass delivered) for a given flight time and launch vehicle selection. Emphasis is placed on the programed Titan class launch vehicle and flight times consistent with delivering a payload of about 450 kg. An additional constraint generally applied is that the rendezvous point occur in the region 0–200 days before comet perihelion.

Comet Orbits and Ballistic Intercepts

Comets may be classified into two general groups; the short-period comets having orbital periods less than 1000 years but more typically on the order of 5–10 years, and the

Presented as Paper 70-1072 at the AAS/AIAA Astrodynamics Conference, Santa Barbara, Calif., August 19–21, 1970; submitted September 17, 1970; revision received April 1971. This work has been performed for the Office of Planetary Programs, NASA Headquarters under Contract NASW-2023.

* Senior Engineer, Astro Sciences. Member AIAA.
† Senior Engineer, Astro Sciences. Associate Member AIAA.
‡ Research Engineer, Astro Sciences. Member AIAA.

Table 1 Comparison of ballistic flyby modes[a]

Comet	Fast flyby	Slow flyby[b]
Encke/80		
Launch vehicle	Titan 3D/Centaur	Titan 3D/Centaur
Flight time	80 days	890 days
Approach velocity	23 km/sec	2 km/sec
Grigg-Skjellerup/82	Titan 3C	Titan 3D/Centaur
	120 days	990 days
	18 km/sec	4 km/sec
d'Arrest/82	Atlas/Centaur	Titan 3D/Centaur
	225 days	1280 days
	15 km/sec	3 km/sec
Kopff/83	Atlas/Centaur	Titan 3D/Centaur
	190 days	1020 days
	8 km/sec	2 km/sec
Giacobini-Zinner/85	Atlas/Centaur/BII	Titan 3D/Centaur
	170 days	1800 days[c]
	21 km/sec	4 km/sec
Halley/86	Atlas/Centaur	Titan 3F/Centaur/BII
	155 days	2800 days[c]
	55 km/sec	6 km/sec

[a] Payload delivered to comet. 360–680 kg
[b] Slow flyby is a rendezvous type trajectory with deletion of the final impulse.
[c] Jupiter gravity-assist.

very long-period comets including the so-called new parabolic or hyperbolic comets. Generally, the short-period comets are fainter, less active and not nearly as spectacular as the new comets. However, because of their relatively frequent passes, their orbits can be determined and their future returns can be predicted fairly accurately. The short-period comets, then, are the most suitable mission candidates in terms of spaceflight planning requirements. Opportunities for such missions occur at an average rate of about one per year but perhaps only one in four of these is particularly attractive.

There are more than 50 periodic comets that have been observed and for which orbits have been determined. Halley's Comet has, of course, the greatest renown among both the public and scientific communities. Comet Encke, because of its short period (3.3 yr) and brightness, also has received large scientific interest. The median orbital elements of the periodic comet group are: inclination 15°, eccentricity 0.56, perihelion distance 1.3 a.u., aphelion distance 5.5 a.u., and orbital period 7 years. Halley's Comet is the notable exception here because of its unique retrograde motion (162° inclination), close perihelion (0.6 a.u.) and long period (75 years). Its next predicted return is in 1985–1986. Although the relatively large inclination and eccentricity of comets do not present serious problems in the case of ballistic flybys, these kinematic characteristics do result in high trajectory energy requirements for rendezvous missions.

Table 1 shows the performance characteristics of ballistic flyby missions for several comet opportunities. These opportunities are identified by the comet name and year of perihelion passage. The designation "fast flyby" refers to the usual ballistic intercept. As mentioned earlier, this flight mode is characterized by short flight times but very high approach velocities. A possible alternative to the rendezvous mission mode is the so-called "slow flyby." This would make use of the basic rendezvous trajectory (to be described), however, the final orbit matching impulse is not executed. The midcourse impulse (propulsive or gravity assist) is still made. The slow flyby would increase the experiment time to several days but at the expense of a very long flight time and a larger launch vehicle requirement. Except, possibly, for Halley's Comet, this mission mode appears to be of questionable utility as a compromise between the intercept and rendezvous modes. Hence, only the full rendezvous mission will be considered in the remainder of this paper.

Selection of Comet Opportunities

Comet mission opportunities for study have been selected initially on the basis of Earth-based telescopic sighting criteria. This method of selection is used to cull out a limited set of opportunities from the large number of short-period comets. The basic criteria are listed below: 1) At least two recent apparitions observed. 2) Year-of-passage recovery (first sighting) occurring 120 days or more before perihelion and extending over a period of at least 2 weeks. 3) Observation will be possible at total magnitude less than 12 for a period of 30 days near the comet's perihelion. A comet is considered to be observable if it is brighter than 20th magnitude and located 25° above the local horizon in a dark sky (sun 18° below the horizon). One hour of visibility is needed to expose a photographic plate.

The first criterion offers some assurance that the comet will return at its future apparitions as predicted. It would be most desirable that the two apparitions immediately preceding the rendezvous passage be observed so that an accurate orbit determination can be made. The second and third criteria are somewhat arbitrary but are intended to assure

Table 2 Comet opportunities having good Earth-based sighting conditions

Comet/Yr	Minimum Earth distance, a.u.	Accumulated hours of daily observation		Maximum brightness, total magnitude	Observable period when total mag. <12	
		$T_p - 120^d$	Total[b]		From	To
Encke/80	0.264	60	738	4.5	−60	−20
d'Arrest/82	0.732	246	914	10.6	−80	50
Grigg-Skjellerup/82	0.265	521	1718	10.6	−20	40
Kopff/83	0.784	439	1118	9.8	−130	80
Encke/84	0.647	542	1020	3.7	−40	−20
Giacobini-Zinner/85	0.479	114	1298	8.6	−70	70
Halley/86	0.450	637	924	1.5	−140 (60)	−30 (120)
Borrelly/87	0.442	20	1520	9.2	−80	40
Temple-2/88	0.721	490	1125	11.8	−60	10
Faye/91	0.605	94	1809	11.0	−60	40
Forbes/93	0.629	262	897	10.8	−90	40
Schaumasse/93	0.553	401	1865	9.0	−100	80
Tuttle/94	0.380	97	703	7.5	−70	0
Perrine-Mrkos/95	0.322	20	1614	11.3	−20	30
Kopff/96	0.593	210	1247	8.8	−110	100
Giacobini-Zinner/98	0.315	338	1210	7.8	−70	70

[a] For a 35° north latitude observatory site.
[b] For the period from $t_p - 300^d$ to $t_p + 300^d$.

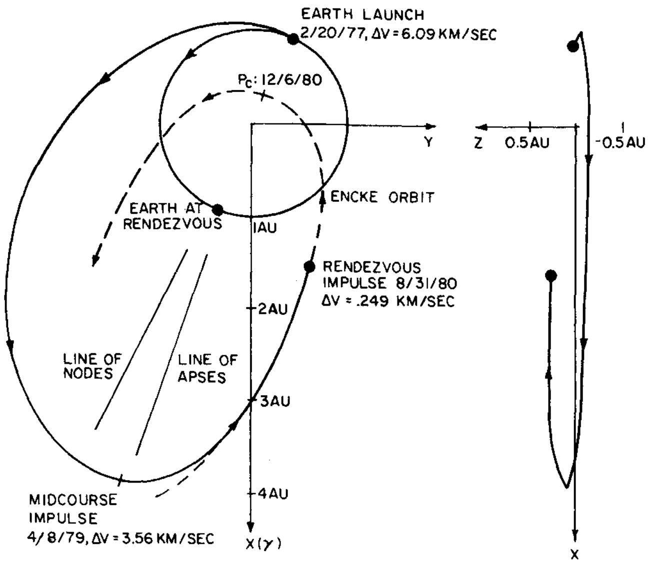

Fig. 1 The 3.5 year, 3-impulse rendezvous trajectory to Encke/80.

favorable observation conditions during both the rendezvous maneuvers and the subsequent science measurement period. An early recovery provides an accurate update of the comet's position in orbit, thereby easing the spacecraft guidance problem. The third criterion is required to obtain adequate Earth-based spectroscopic measurements which are thought to be useful in correlating the spacecraft measurements. The previous sighting criteria should not be considered as hard constraints dictating mission success, but they are thought to be of importance in mission design. Fortunately, many mission opportunities do satisfy these criteria.

A sighting analysis program was developed and applied to 38 comet apparitions comprising 21 different comets. The data obtained were used to categorize the various opportunities in terms of how well the sighting criteria were satisfied. Table 2 is a partial summary of the sighting analysis.[9] Note that comets are listed in chronological order and not by performance rating. Table 2 shows the minimum geocentric distance, the accumulated hours of daily observation, the maximum brightness, and the observable period near perihelion when the comet is brighter than 12th magnitude. Since there are a total of 16 comet apparitions between 1980 and 1999 having good Earth-based sighting conditions, it seemed reasonable to limit the trajectory analysis to these opportunities. A few exceptions were made for certain comets which have poor sighting conditions but which are Jupiter swingby opportunities; these will be discussed later. It should be noted also that the d'Arrest/76 opportunity, currently under consideration for a flyby mission, has excellent sighting conditions but may not be a primary candidate for rendezvous because of the early date.

3-Impulse Ballistic Trajectories

The characteristics of comet rendezvous trajectories may be described by referring to the illustration of Fig. 1. This figure shows an optimum 3-impulse transfer to Comet Encke having a flight time of 1288 days and arriving 97 days before the 1980 perihelion passage. Orbital geometry relationships between Earth launch position and the comet's lines of apsides and nodes are key determinants of trajectory optimization; the illustration shown is representative of most periodic comets.

Considerable savings in the required velocity increment (ΔV) of ballistic rendezvous trajectories can be obtained by executing a midcourse plane change maneuver near the nodal line of the comet orbit. This policy is particularly effective for comets having fairly high inclinations. As flight time increases the plane change occurs at a greater distance from the sun and, hence, at a lower velocity and ΔV cost. Missions for which the total flight time is close to the orbital period of the destination comet often results in minimum total ΔV. This occurs because many of the short-period comets have their line of nodes nearly coincident with their line of apsides (projected into the ecliptic). Under these circumstances, the optimum 3-impulse trajectory begins with an impulse applied when the Earth is near the comet's major axis on the perihelion side. At a point close to the trajectory aphelion, which should occur near the comet's line of nodes, a midcourse plane change is made so that the second arc of the trajectory is very nearly in the orbital plane of the comet and the motion approximates the comet's motion. The final rendezvous impulse is made to exactly match the comet's velocity. Bielliptic, nodal transfers of this description generally require the greatest velocity increment at Earth departure and more modest increments at the midcourse and terminal points.

Mission initialization is assumed to be a 100 naut mile circular orbit about the Earth. The first impulse is required to depart the circular orbit onto the appropriate hyperbolic escape trajectory. Two body conic motion approximations are assumed for all trajectory phases. It is also assumed that the ballistic trajectories are not strongly dependent upon the vehicle configuration so that a minimum ΔV trajectory is an adequate approximation to a maximum delivered payload trajectory. Of course, in calculating the payload, the

Table 3 Three-impulse ballistic rendezvous trajectories

Comet/Yr	Launch date	Flight time, yr	Arrival, days before Perihelion	Velocity requirement, km/sec ΔV_1[a]	ΔV_2	ΔV_3	ΔV_{total}	Payload[b], kg Titan 3D/Centaur/BII
Encke/80	3/14/78	2.50	86	5.41	4.67	2.06	12.14	25
	2/20/77	3.53	97	6.09	3.56	0.25	9.90	370
	2/20/76	4.57	81	6.11	3.07	1.59	10.77	235
	2/14/75	5.63	67	6.43	2.97	1.74	11.14	190
d'Arrest/82	8/16/79	2.96	47	6.07	2.41	2.55	11.03	200
	8/17/78	3.85	86	6.33	2.32	1.52	10.17	325
	8/12/77	4.83	98	6.57	2.21	0.61	9.39	455
	8/18/76	5.80	105	7.11	1.93	0.01	9.05	465
	8/14/75	6.81	104	7.24	1.74	0.62	9.60	360
Kopff/83	8/6/81	1.93	39	4.34	2.23	4.66	11.23	70
	7/25/80	2.90	62	5.28	1.86	2.61	9.75	400
	7/16/79	3.86	85	5.84	1.70	1.41	8.95	540
	7/14/78	4.78	115	6.22	1.50	0.79	8.51	665
	7/1/77	5.84	106	6.44	1.62	0.79	8.85	570
	7/7/76	6.81	110	6.78	1.34	0.86	8.98	510

[a] Departure from 100 naut mile Earth orbit, characteristic launch velocity = 7.79 + ΔV_1 (km/sec).
[b] $\Delta V_2 + \Delta V_3$ + 0.2 km/sec (guidance) imparted by single stage, I_{sp} = 400 sec.

Table 4 Summary of three-impulse comet rendezvous opportunities

Comet/Yr	Launch date	Flight time, yr	Arrival, days before Perihelion	Payload, kg Titan 3D/Centaur/BII	Payload, kg Titan 3F/Centaur
Encke/80	2/20/77	3.53	97	370	515
d'Arrest/82	8/12/77	4.83	98	450	600
Grigg-Skjellerup/82	4/11/77	4.81	100	435	580
Kopff/83	7/16/79	3.86	85	540[b]	790
Encke/84	2/26/80	3.82	97	350	485
Giacobini-Zinner/85	9/29/79	5.64	107	245	330
Borrelly/87	12/6/81	5.74	103	295	400
Temple-2/88	8/1/84	3.86	96	505	675
Faye/91[a]	10/28/85	5.77	102	490	665
Forbes/93	7/31/89	3.32	138	485[b]	700
Schaumasse/93[a]	2/2/87	5.78	113	400	545
Tuttle/94	Excessive ΔV Requirements				
Perrine-Mrkos/95	11/19/90	4.72	99	420	560
Kopff/96	7/21/92	3.50	75	530[b]	765
Giacobini-Zinner/98	10/9/92	5.45	109	255	340

[a] 5-impulse transfer.
[b] Burner II stage not required.

individual impulses are employed in accordance with the various vehicle stage specifications.

Table 3 presents the trajectory data and velocity requirement for ballistic missions to Comets Encke, d'Arrest and Kopff. The example payload calculation is for the Titan 3D/Centaur/Burner II launch vehicle.[10] A single upper stage employing space storable propellants (I_{sp} = 400 sec) is assumed for imparting the second and third ΔV impulses plus a 200 m/sec allowance for guidance.[10] The different trajectories for each comet represent local optimum solutions which differ by approximately one year in flight time. Note that the trajectories may be classified by the year of launch since the optimum Earth launch position is essentially fixed by the comet's orbital geometry. Missions which require a post-injection velocity increment ($\Delta V_2 + \Delta V_3$) in excess of 5 km/sec are not practical because of insufficient payload. A moderate payload increase could be obtained by considering use of an additional stage and splitting the post-injection maneuver requirements. However, this was found to be warranted only for the Halley rendezvous mission to be described in the next section. In general, the total ΔV should be less than 11 km/sec for a practical trajectory selection utilizing Titan/Centaur class vehicles. A result of interest not indicated by Table 3 is that the optimum total ΔV characteristic is rather insensitive to the arrival date except very near perihelion. This fact can be important in mission tradeoff analysis when one factors in realistic arrival time constraints.

Since space does not permit listing detailed data for all the comets under consideration, Table 4 is provided as a trajectory/payload summary of the ballistic flight mode. The trajectories selected for this summary represent either optimum flight times (maximum payload) or shorter flight times if the payload capability is at least 450 kg. The Titan 3F refers to the proposed 7-segment solid version of the Titan launch vehicle. Payload capability is better than 450 kg for eleven mission opportunities. Six of these opportunities have flight times in the range 3–4 years. On a comparative basis, ballistic missions to Kopff, Temple-2 and Forbes have the best payload/flight time characteristics and can utilize the programmed Titan 3D/Centaur/BII launch vehicle. Earlier missions such as Encke/80 or d'Arrest/82 would require either the larger launch vehicle or a longer flight time.

Jupiter-Assisted Ballistic Trajectories

The use of a Jupiter swingby to assist in reducing the total ΔV requirements of comet rendezvous has been discussed by Michielsen[6] and Kruse[7] with regard to Halley's Comet, and by Manning[8] for a number of short-period comets. Their results will be summarized along with new data obtained in the present study. Mission parameters for nine comet apparitions are presented in Table 5. Flight times range from 3.12 yr to 7.7 yr. It is noted that the Jupiter swingby distance is quite large in most cases. Hence, the science return from Jupiter would probably not be a significant factor for these missions. The rendezvous payload is greater than 450 kg for five mission opportunities, four of which could utilize the Titan 3D/Centaur/BII launch vehicle. Rendezvous with Halley's Comet is, of course, a special case and would require the Saturn V/Centaur, a two-stage retro maneuver, and a very long flight

Table 5 Jupiter-assisted comet rendezvous opportunities

Comet/Yr	Launch date	Flight time, yr	Arrival, days before Perihelion	Jupiter periapse R_J	Rendezvous impulse, km/sec	Launch vehicle	Rendezvous[a] payload, kg
d'Arrest/82	9/13/77	4.68	123	72.8	2.16	Titan 3D/Cent/BII	500
H-M-P/85	12/16/80	4.16	100	54.8	0.63	Titan 3D/Cent/BII	820
	12/31/81	3.12	100	7.5	3.20	Titan 3D/Cent/BII	345
Giacobini-Zinner/85	11/2/79	5.27	200	53.1	4.43	Titan 3F/Cent	210
Halley/86[b]	9/13/77	7.7	258	7.9	5.83	Saturn V/Cent	635[c]
	10/16/78	6.9	152	5.0	6.42	Saturn V/Cent	410[c]
Whipple/86	1/1/82	4.18	100	15.8	3.80	Titan 3F/Cent	430
Borrelly/87	12/31/81	5.53	150	71.5	4.90	Titan 3F/Cent	200
T-G-K/90	5/14/85	4.50	150	200.0	2.63	Titan 3F/Cent	385
Temple-2/94[d]	7/27/88	4.9	200	167.0	1.30	Titan 3D/Cent/BII	735
Daniel/99[d]	12/13/92	6.0	300	145.6	0.50	Titan 3D/Cent/BII	1040

[a] Rendezvous impulse + 0.2 km/sec (guidance) imparted by single stage, I_{sp} = 400 sec.
[b] Trajectory data from Michielsen.[6]
[c] Rendezvous impulse + 0.6 km/sec (guidance) imparted by two-stages, I_{sp} = 400 sec.
[d] Trajectory data from Manning.[8]

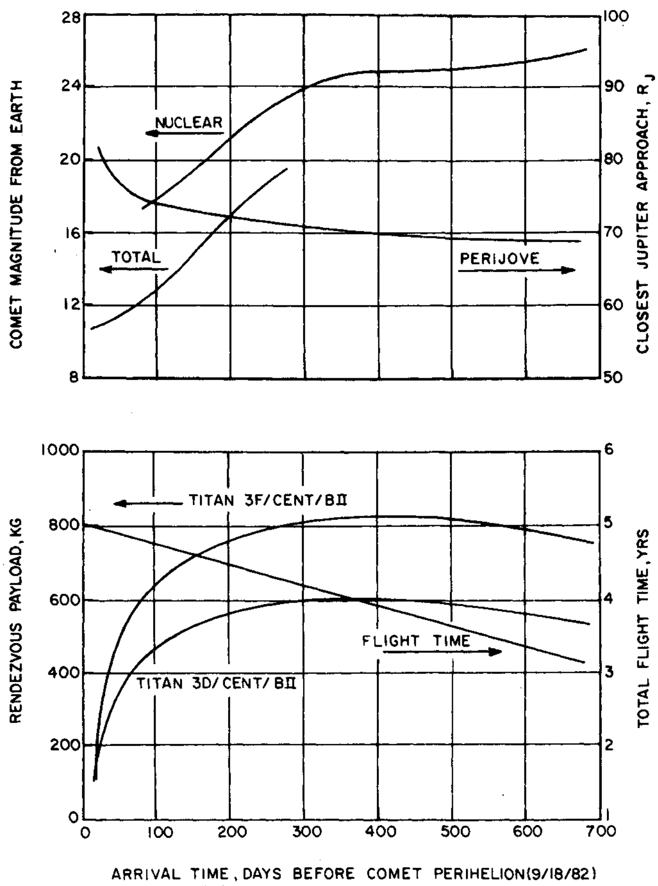

Fig. 2 Jupiter-assisted d'Arrest/82 rendezvous mission parameters.

time. Of the two earliest opportunities (d'Arrest and H-M-P), the H-M-P mission launched in 1980 has very low-velocity requirements. However, this mission suffers from extremely poor sighting conditions for Earth-based observations. Since d'Arrest satisfies both the sighting and payload criterion, it is considered to be the best choice for early application of the swingby flight mode.

Mission characteristics of the d'Arrest rendezvous are shown in Figs. 2 and 3. Payload is found to be rather insensitive to the arrival time over the broad extent 200–700 days before perihelion. The distance of closest Jupiter approach is very large, varying between 68 radii for the 3 year flight and 90 radii for the 5 year flight. A minimum comet approach velocity of 1.65 km/sec occurs at a rendezvous point of about 500 days before perihelion. Brightness and observability of the comet from Earth have been mentioned as possible constraints on the trajectory selection. The example trajectory selection arrives 123 days before perihelion which should allow sufficient time for Earth-based recovery operations. This point occurs just before the rapid falloff in payload as the perihelion is approached. The resultant payload (500 kg) is about 17% below the maximum value. The trajectory profile shown in Fig. 3 indicates that d'Arrest passes near Jupiter before spacecraft rendezvous. Hence, it was necessary to compute the postassist trajectory based on the perturbed comet orbital elements because of this near encounter. The launch characteristic velocity is 14.7 km/sec, the flight time to Jupiter is 2.26 yr, and the hyperbolic velocity at Jupiter swingby is 6.04 km/sec.

It is interesting to compare the postlaunch ΔV requirements of the Jupiter swingby and the multi-impulse flight modes. With reference to Table 4, the common missions are d'Arrest/82, Giacobini-Zinner/85, and Borrelly/87. The sum of the midcourse and rendezvous impulses for each of these 3-impulse missions are 2.83, 4.06, and 3.64 km/sec, respectively. The single rendezvous impulses in the swingby mode are 2.16, 4.43, and 4.90 km/sec, respectively. Hence, while Jupiter provides a ΔV reduction of 0.67 km/sec for the d'Arrest mission, the swingby mode is not even competitive with the multi-impulse mode for the Giacobini-Zinner and Borrelly missions. This result is not atypical and points out the fact that good Jupiter-assisted opportunities are relatively rare.

Solar-Electric Low-Thrust Trajectories

Trajectory analysis of the solar-electric flight mode was limited to only a few comet opportunities as determined by the preceding ballistic mode results. Basically, these opportunities are Encke/80, d'Arrest/82, and Kopff/83. The purpose here is to compare the performance with good ballistic missions thus allowing a reasonable basis for tradeoff. Halley's Comet was also considered to determine whether or not solar-electric propulsion is at all practical for this mission. Low-thrust propulsion is initiated outside of the Earth's sphere of influence after a high-thrust launch and injection to a specified hyperbolic excess velocity VHL. This velocity along with the initial power level P_0 and constant specific impulse I_{sp} may be chosen so as to maximize payload. Thrust direction and coast periods are also optimized.

Figure 4 shows the region of optimum arrival dates in the vicinity of perihelion for constant flight time trajectories to Comet d'Arrest/82. Trajectory requirements are given in

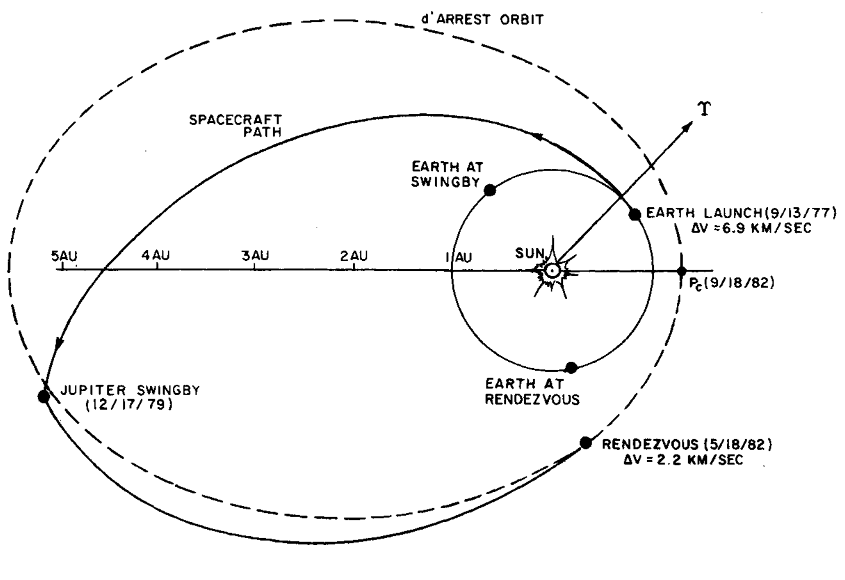

Fig. 3 The 4.7 year, Jupiter-assisted rendezvous trajectory to d'Arrest/82.

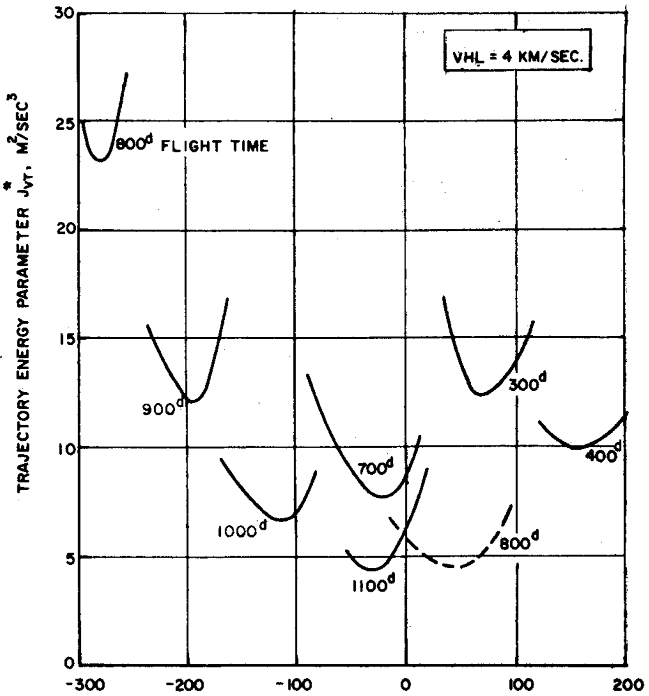

Fig. 4 **Effect of arrival time on solar-electric trajectory requirements for d'Arrest/82 rendezvous.**

terms of the so-called "energy parameter" J_{VT} defined by

$$J_{VT} = \int_0^{t_f} a^2(t) \frac{P_0}{P(t)} dt, (\mathrm{m^2/sec^3})$$

where $a(t)$ is the thrust acceleration, $P(t)$ is the instantaneous power and t_f is the flight time. Different values of the launch velocity VHL cause a shifting of the curves up or down but have little effect on the optimum arrival date. For a propulsion system specific mass of 30 kg/kw, values of J_{VT} greater than about 15 m²/sec³ result in vanishing payload and, hence, are not of practical interest. Beginning with the high-energy 800 day flight, note the nearly equal shifting of optimum arrival time with flight time. This reflects the fact that the optimum Earth launch position is essentially fixed by the comet's orbital geometry. Also, for a given flight time such as 800 days, there are more than one local minimum points separated by nearly one year. Relatively fast rendezvous flights of 300 or 400 days are possible but require a postperihelion arrival. The generation of basic data maps such as Fig. 4 can be a useful first step in the selection of comet rendezvous trajectories for a later, more detailed analysis of parameter optimization.

Figure 5 illustrates the ecliptic and out-of-plane trajectory profiles of the 700 day flight to d'Arrest arriving 20 days before the 1982 perihelion. In this case, the launch hyperbolic velocity of 3 km/sec is near optimum for the Titan 3C launch vehicle. The spacecraft traverses almost a full revolution about the sun, reaches a maximum solar distance of about 2.4 a.u. and a maximum out-of-plane distance of about 0.6 a.u.

Solar-electric propulsion might be expected to have marginal utility for the Halley rendezvous mission because the change from posigrade to retrograde motion is most efficiently made at large solar distances where the propulsion power available is greatly reduced. Figure 6 shows an example trajectory to Halley launched in 1978 and arriving 60 days before the 1986 perihelion. The spacecraft is 0.8 a.u. below the ecliptic plane at an aphelion distance of 7.4 a.u. when the momentum reversal begins. Although the

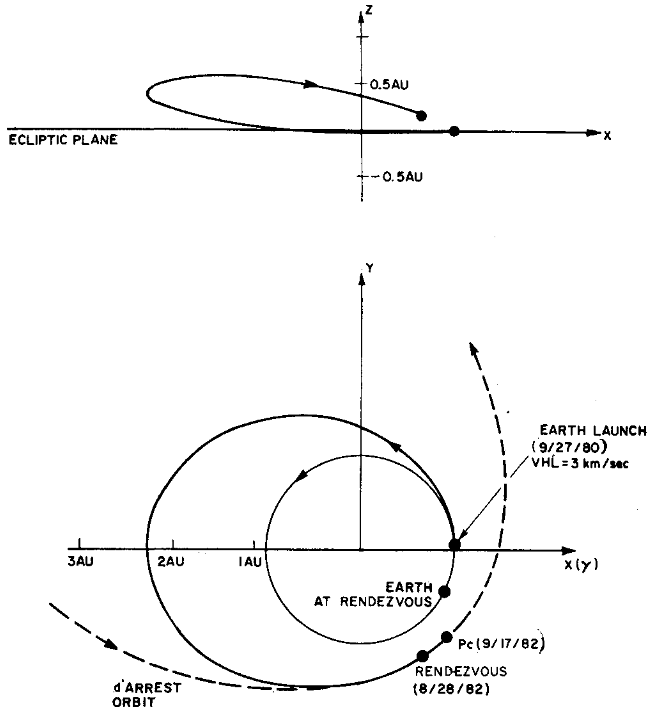

Fig. 5 **The 700 day, solar-electric rendezvous trajectory to d'Arrest/82.**

power available at this point is only $\frac{1}{25}$th of the initial power, a small value of thrust acceleration is effective in changing the trajectory because of the slow motion at this distance. The major drawback of this flight mode is that the propulsion time required is a large fraction of the very long 7.4 yr flight time.

Table 6 provides a summary of the SEP flight mode results obtained for the four comet missions investigated. Values listed for launch velocity, power and specific impulse are

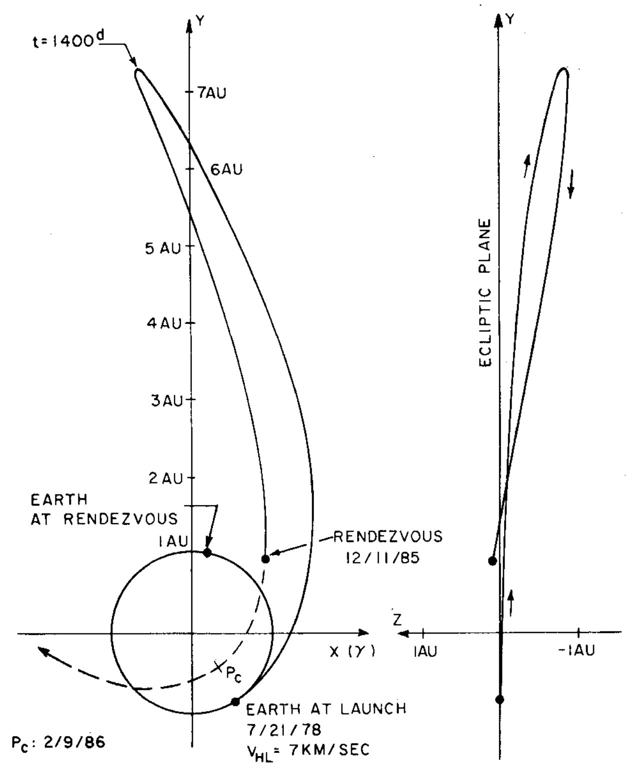

Fig. 6 **The 2700 day, solar-electric rendezvous trajectory to Halley/86.**

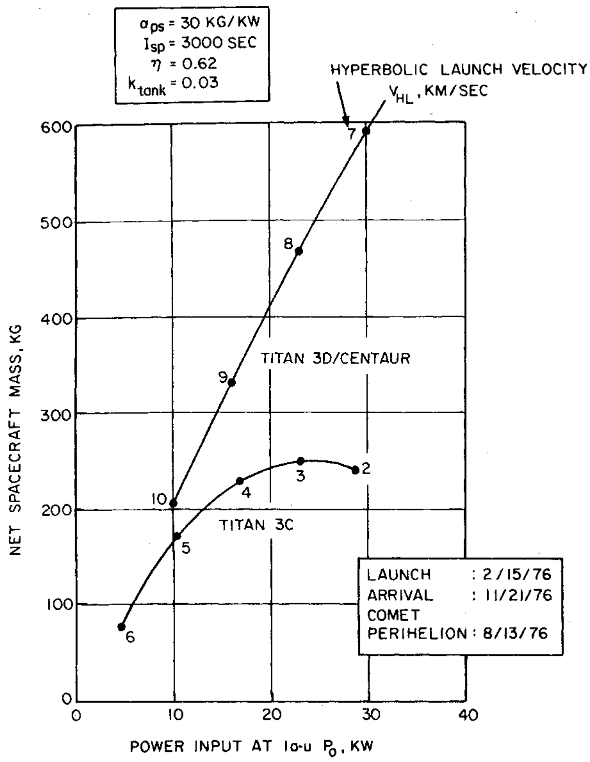

Fig. 7 Solar electric payload capability for 280 day rendezvous mission to d'Arrest/76.

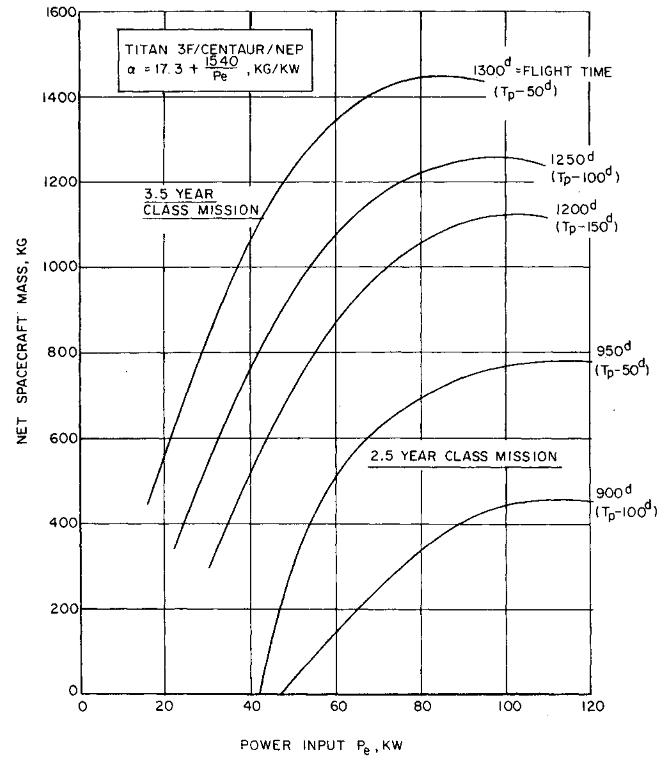

Fig. 8 Nuclear-electric payload capability for Halley rendezvous missions.

near-optimum for the launch vehicle selections. Net spacecraft mass is defined as the payload delivered to rendezvous after subtracting the propulsion system and propellant tankage mass. Missions to Encke, d'Arrest, and Kopff are similar in that the flight times are under 2.5 yr, the payload is about 450 kg, and the SEP spacecraft could be launched by the Titan 3C. Optimum propulsion power is 20–25 kw at a specific impulse of 3500 sec. If desirable, smaller powerplants (15 kw) could be utilized at some expense in payload or by employing the Titan 3D/Centaur launch vehicle. Because of similar orbital characteristics of many short-period comets, one may predict that the results of these three missions apply generally to an entire class of comet mission opportunities. The Halley mission is a special case and does not appear to be as attractive for SEP application. The Titan 3F/Centaur provides a marginal payload of only 235 kg, the power rating is high, and the flight time is over 7 yr.

In the previous discussion of Fig. 4, it was mentioned that a short flight time rendezvous with d'Arrest is possible if a postperihelion arrival is acceptable. This result motivated us to examine the d'Arrest 1976 opportunity which is currently under consideration as a ballistic intercept mission (feasible with an Atlas/Centaur launch and a flight time of about 100 days). As a possible but more expensive alternative, a 280 day SEP rendezvous mission is considered. This mission would be launched in early 1976 near the comet's line of ascending node and arrive 100 days after the d'Arrest perihelion of August 13, 1976. During the first half of the flight, the spacecraft remains near 1 a.u. while traversing a path out of the ecliptic plane to match the comet's inclination of 17°. At a point 10 days after perihelion (90 days before actual rendezvous), the spacecraft is about 14×10^6 km from d'Arrest and closing with a relative velocity of 3.6 km/sec. Figure 7 shows the payload capability of two Titan class launch vehicles as a function of power rating. For example, the Titan 3D/Centaur launch with a SEP spacecraft operating at a considerably off-optimum power of 15 kw could provide a payload of about 300 kg.

Nuclear-Electric Halley Rendezvous

The first indication of the performance gain offered by nuclear-electric propulsion for the Halley mission was given by Kruse.[7] Employing his results as a takeoff point, the present study has investigated this mission application in considerable depth with regard to a range of flight times, propulsion system parameters and payload capability of several launch vehicle candidates.

Propulsion system specific mass is assumed to vary inversely with the power rating P_e according to the equation

$$\alpha_{ps} = 17.3 + (1540/P_e), \text{ (kg/kw)}$$

The coefficients of the previous equation were obtained by fitting the assumed relationship to recently estimated specific mass data at power design points of 100 kw and 300 kw.[11]

Table 6 Solar-electric comet rendezvous opportunities

Comet/Yr	Launch date	Flight time, days	Arrival, days before Perihelion	Power input, kw	Launch vehicle	Rendezvous[a] payload, kg
Encke/80	3/7/78	900	100	20	Titan 3C	470
d'Arrest/82	9/27/80	700	20	20	Titan 3C	425
Kopff/83	6/29/81	700	50	25	Titan 3C	500
Halley/86	7/21/78	2700	60	48	Titan 3F/Centaur	235

[a] Propulsion system specific mass, specific impulse, efficiency and tankage α_{ps} = 30 kg/kw, I_{sp} = 3500 sec, η = 0.66, kt = 0.03.

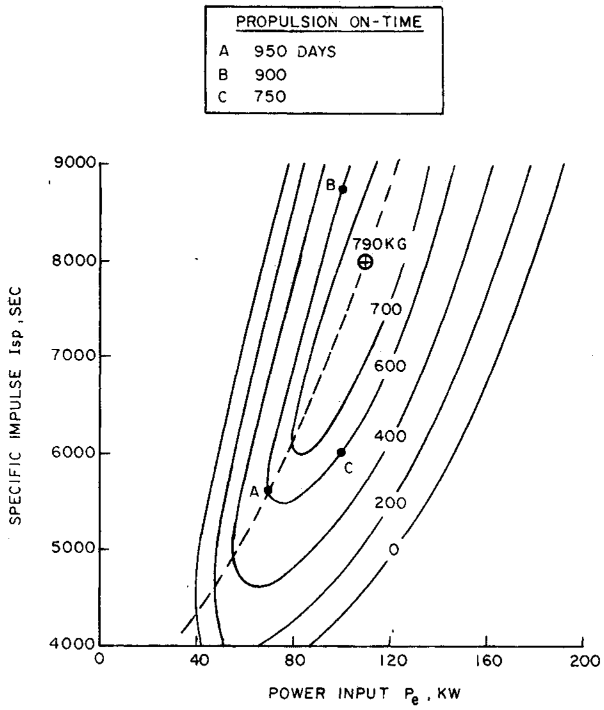

Fig. 9 Net mass (payload) contours for 950 day, nuclear-electric rendezvous mission to Halley/86.

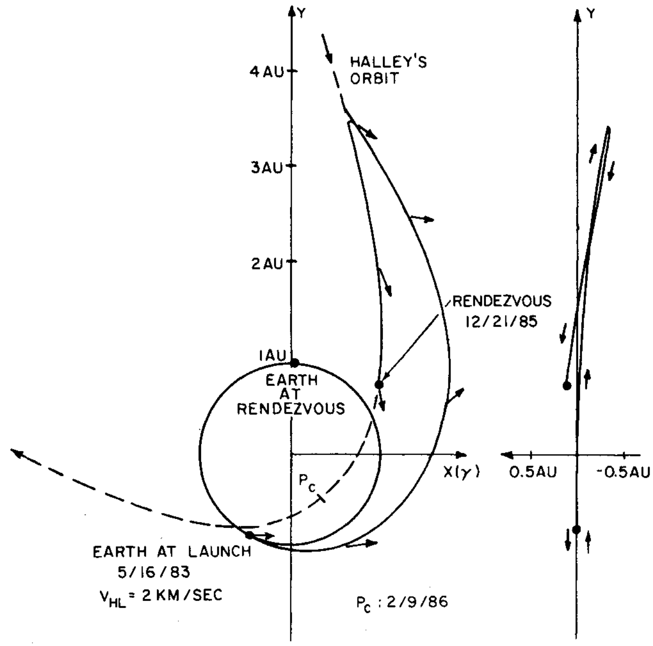

Fig. 10 The 950 day, nuclear-electric rendezvous trajectory to Halley/86.

Propulsion system efficiency assumed in the analysis is slightly more optimistic than is currently available; 74% at I_{sp} = 4000 sec.

Figure 8 shows the payload capability of the Titan 3F/Centaur launch vehicle for several flight times between 900 and 1300 days. The near-optimum arrival point (days before perihelion) is given for each flight time. Hyperbolic launch velocity and specific impulse are optimized at all points along the curves of maximum net mass vs power input. Optimum power lies in the range 80–120 kw, but the excess payload availability could allow a lower than optimum power design point. Advantages of lower power operation include a smaller vehicle configuration and lower powerplant cost. Figure 8 also illustrates the payload advantage of arriving closer to perihelion. For example, taking the 1983 launch/2.5 year class mission, the maximum net mass is increased from 460 kg to 790 kg by delaying the arrival point from 100 days to 50 days before perihelion.

Figure 9 provides additional design information on the 950 day flight. The data are shown as payload contours plotted in a parameter grid of specific impulse and power input. Again, hyperbolic launch velocity is optimized along these contours and lies in the range 1–6 km/sec. The maximum payload of 790 kg is associated with the parameters; VHL = 2 km/sec, I_{sp} = 8000 sec and P_e = 110 kw. The broken line curve represents the locus of maximum payload (for fixed power) shown previously in Fig. 8. Propulsion on time is very nearly equal to the 950 day flight time along this curve. To illustrate how propulsion on time can be reduced, consider the 600-kg payload contour which has the minimum power coordinates of (70 kw, 5600 sec). Taking a vertical cut at P_e = 100 kw yields the two I_{sp} points of 6000 sec and 8750 sec. The lower I_{sp} design point provides a 200 day reduction in propulsion on time.

Figure 10 illustrates the ecliptic and out-of-plane trajectory profiles of the 950 day Halley mission launched in May 1983. Thrust direction, indicated by the arrows at several points along the trajectory, rotates clockwise with respect to the sun line at a slow rate—under 1°/day during most of the flight. Retrograde motion begins near the trajectory aphelion (3.6 a.u.) which occurs about 600 days after launch. Halley is 1.82 a.u. from the spacecraft at this time and catching up.

Flight Mode Comparisons

Ballistic and low-thrust flight modes are compared in Table 7 in terms of launch vehicle requirements and flight time for four selected comet missions. Payload capability is approximately 450 kg in each case except where noted otherwise. Gravity-assist opportunities are not available for the Encke/80 and Kopff/83 missions, and the 3-impulse

Table 7 Flight mode comparisons[a]

	Ballistic mode		Low-thrust mode	
Comet/Yr	3-impulse	Gravity assist	Solar-electric	Nuclear-electric
Encke/80				
Launch vehicle	Titan 3F/Centaur		Titan 3C	Titan 3F/Centaur[b]
Flight time	3.5 yr		2.5 yr	1.4 yr
d'Arrest/82	Titan 3D/Centaur/BII	Titan 3D/Centaur/BII	Titan 3C	
	4.8 yr	4.7 yr	1.9 yr	
Kopff/83	Titan 3D/Centaur		Titan 3C	
	3.9 yr		1.9 yr	
Halley/86		Saturn V/Centaur	Titan 3F/Centaur	Titan 3F/Centaur
		7.7 yr	7.4 yr (235 kg)	2.6 yr

[a] Approximately 450 kg net spacecraft delivered to rendezvous.
[b] 1990 apparition.

mode is not appropriate for the Halley mission because of the excessive velocity requirements. Nuclear-electric results were not generated for rendezvous opportunities before the mid-1980's.

Of the 3-impulse ballistic missions studied, Comets Encke and Kopff are the best opportunities in that the flight times are not excessively long (less than 4 yr). The Titan 3F/Centaur is required to perform the Encke mission, but the Kopff mission could be accomplished with the smaller Titan 3D/Centaur. A ballistic rendezvous with d'Arrest is somewhat better accomplished by utilizing a Jupiter gravity-assist rather than the direct 3-impulse mode. The Jupiter assist mode offers no advantage in flight time or launch vehicle, but it does add about 45 kg to the delivered spacecraft mass. Solar-electric propulsion offers the best performance potential for each of the missions to Encke/80, d'Arrest/82, and Kopff/83. Employing the Titan 3C launch vehicle, SEP flights reduce the flight time requirement to only 2–2.5 yr. Constant power, nuclear-electric flights allow still greater reductions in flight time for comet rendezvous. For example, the Encke mission (1990 perihelion) requires a flight time of only 1.4 yr. The Halley mission is ideally suited to nuclear-electric propulsion, this being the only way of obtaining a relatively short flight time. To accomplish the Halley rendezvous ballistically would require a launch vehicle commitment of the Saturn V plus upper stages and a flight duration of almost 8 yr.

Conclusions

Comet rendezvous missions in the time period 1975–95 are both attractive and feasible from a trajectory/payload standpoint. Several mission opportunities utilizing near state-of-the-art ballistic flight systems have been identified. However, as a general class of missions, comet rendezvous has a high ΔV requirement which tends to restrict practical ballistic flights to only a few opportunities. Indirect ballistic flights via a Jupiter swingby are sometimes effective in reducing the total ΔV requirement but, here again, the number of opportunities are limited. Low-thrust flight systems, particularly solar-electric propulsion for opportunities through the mid-1980's, offer the best potential for rendezvous missions. Performance advantages include shorter flight times, smaller launch vehicles and/or larger payloads, power availability, and efficient terminal maneuverability. The superior performance potential of future nuclear-electric spacecraft has been demonstrated in particular for the very difficult Halley mission. Practical accomplishment of the mission to Halley's Comet would seem to depend upon the development and availability of nuclear-electric propulsion by 1983.

Three comet opportunities are recommended for a follow-on mission study at the pre-Phase A level of effort. The first mission selection would be Comet Encke with a 1977(78) launch. This choice is made because: 1) the Encke mission offers a reasonable basis for tradeoff between the ballistic and solar-electric flight modes, 2) there exists a good "back-up" opportunity 3 years later, 3) the scientific interest in Encke, and 4) the evidence that Encke is rapidly decreasing in level of activity and may soon become extinct and of asteroidal nature. The second selection is Comet Kopff with a 1979(81) launch; this is easier than the Encke mission from a trajectory standpoint. The third selection is Halley's Comet, and is made largely because of the public and scientific interest in this comet.

References

[1] Roberts, D. L., "The Scientific Objectives of Deep Space Investigations-Comets," Astro Sciences Rept. P-3, 1964, IIT Research Institute, Chicago, Ill.

[2] Roberts, D. L., "A Compendium of Data of Some Periodic Comets," Astro Sciences Rept. P-9, 1964, IIT Research Institute, Chicago, Ill.

[3] Narin, F. and Pierce, P. M., "Perturbation, Sighting and Trajectory Analysis for Periodic Comets: 1965–75," Astro Sciences Rept. T-5, 1964, IIT Research Institute, Chicago, Ill.

[4] Friedlander, A. L., "On the Problem of Comet Orbit Determination for Spacecraft Intercept Missions," Astro Sciences Rept. T-19, 1967, IIT Research Institute, Chicago, Ill.

[5] Park, R. A. et al., "Solar-Electric Propulsion Missions to the Comets," Paper presented at the AAS Meeting, Boston, Mass., May 26, 1967.

[6] Michielsen, H. F., "A Rendezvous With Halley's Comet in 1985–86," *Journal of Spacecraft and Rockets*, Vol. 5, No. 3, March 1968, pp. 328–334.

[7] Kruse, D. H. and Fox, M. K., "Trajectory Analysis of Low Thrust and Ballistic Rendezvous Missions to Halley's Comet," Rept. ERR-FW-794, 1968, General Dynamics, Fort Worth, Tex.; also AIAA Paper 69-933, Princeton, N.J., 1969.

[8] Manning, L. R., "Comet Rendezvous Missions," AIAA Paper 70-1074, Santa Barbara, Calif., 1970.

[9] Friedlander, A. L., Niehoff, J. C., and Waters, J. I., "Trajectory and Propulsion Characteristics of Comet Rendezvous Opportunities," Astro Sciences Rept. T-25, 1970, IIT Research Institute, Chicago, Ill.

[10] "Launch Vehicle Estimating Factors Handbook," Jan. 1970, NASA.

[11] Davis, J. P., "Review of Status of Thermionic Reactor Systems," Preprint (69-WA/Ener-5), presented at the ASME Winter Annual Meeting, Nov. 16–20, 1969, Los Angeles, Calif.