on mountain tops, or in the desert. Continuous contact between the satellites and a small number of ground stations may be achieved by storing the data in the Earth resource satellites, although this would limit sensor collection on a program and selective basis. A promising solution to these problems appears to lie in deployment of a data relay satellite system in geostationary orbits.

References

[1] Space Applications Woods Hole Summer Study Report, "Earth Observations and Resources," Jan. 1968, National Academy of Sciences, Washington, D.C.

[2] Noda, M., "Problems and Suggested Solutions for Earth Resources Satellites Data Communications Systems," AIAA Paper 70-325, Culver City, Calif., 1970.

[3] Noda, M., "Hardware Aspects of Electronics for Manned Planetary Missions," *AIAA Technology for Manned Planetary Mission Meeting*, AIAA, New York, 1968.

[4] Thomas, P. G., "Earth-Resource Survey From Space," *Space-Aeronautics*, July 1968.

[5] "Big Eye in the Sky; Sensors to Monitor Earth," *Electronic Design*, 1 April 1969.

[6] Jaffe, L. and Summers, R. A., "The Earth Resources Survey Program Jells," *Astronautics and Aeronautics*, Vol. 9, No. 4, April 1971, pp. 24–40.

[7] George, T. A., "ERTS A and B—Engineering System," *Astronautics and Aeronautics Journal*, Vol. 9, No. 4, April 1971, pp. 41–51.

[8] Noda, M., "Communications, Instrumentation, and Data Handling for Manned Planetary Missions," *Journal of Spacecraft and Rockets*, Vol. 6, No. 6, June 1969, pp. 673–678.

[9] Federal Aviation Agency and Department of Commerce, *Aviation Weather*, U.S. Government Printing Office, Washington, D.C., 1965.

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Utilization of Jupiter Swingby Trajectories for Comet Exploration

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Jupiter swingby trajectories are investigated for comet flyby and rendezvous missions. The swingby is shown to result in approach velocities between 0.5 and 6 km/sec for 29 of the 37 short period comets considered. A Titan IIID/Centaur/Burner II launch vehicle will provide a flyby payload of over 2000 lb for these flybys. Rendezvous missions are defined for four comets (Honda-Mrkos-Pajdusakova, Tuttle-Giacobini-Kresak, D'Arrest and Daniel). The aforementioned launch vehicle with a 310 sec I_{sp} upper stage will provide at least a 700 lb payload at each of these comets.

Introduction

EARLY studies of comet intercept missions resulted in the determination of generally large approach velocities.[1–3] This meant that rendezvous missions were nearly impossible due to the extremely large propulsion requirements at comet arrival. The arrival velocities were sufficiently high that there was even some question as to the scientific usefulness of flyby missions. Recently, as mission analysts have turned their attention from the planets to other bodies of the solar system, an awareness of the possibility of performing comet missions through use of other trajectory modes (broken plane transfers, gravity assist, or low thrust) has renewed interest in such missions.

Much of the recent analysis has been directed at particular comets of interest due to either unique features (Halley's) or near term opportunity (D'Arrest), as well as low-thrust missions.[4–6] This paper presents a general survey of the mission requirements for comet flyby and rendezvous missions where a Jupiter swingby trajectory is used. The paper first presents the comet apparitions selected for analysis, and then discusses the trajectory characteristics and resulting payloads available.

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Comet Selection

One of the outputs of this study is a listing of the comet opportunities which have the lowest energy requirements for both flyby and rendezvous missions. With these data, the mission planner can determine the tradeoffs which exist when sighting, flight time, or other constraints are applied to comet missions.

For this study all short-period comets which have perihelion passages between 1976 and 2000 and which have been or could be observed at three or more perihelion passages previous to launch are considered. The multiple observations are necessary to allow a reasonable degree of confidence in predicting future perihelion passages and the associated orbital elements. This approach retains for consideration 37 out of 94 short-period comets.[7,8] These comets, with perihelion passage dates in the time period of interest, are delineated in Table 1. Halley's comet was not considered, since missions during its next apparition have been thoroughly discussed by other authors.[4,6] The high-launch energy and arrival velocities they have shown for ballistic gravity assisted trajectories to Halley's comet make a high-thrust rendezvous mission impractical.

Trajectory Analysis

Several trajectory modes exist which can be utilized for ballistic missions to the comets. Although only the Jupiter swingby trajectory mode was considered in this study as a means of achieving low-energy comet missions, the other

Table 1 Future perihelions of short-period comets[a] in order of present period

Encke	*8/77*,[b]	12/80,	3/84,	*7/87*,	11/90,	2/94,	6/97
Grigg-Skjellerup	*4/77*,	5/82,	6/87,	*7/92*,	8/97		
Honda-Mrkos-Pajdusakova	4/80,	*5/85*,	9/90,	*1/96*			
Tempel 2	2/78,	*5/83*,	9/88,	*3/94*,	9/99		
Tuttle-Giacobini-Kresak	*1/79*,	8/84,	*2/90*,	8/95			
Pons-Winnecke	11/76,	*4/83*,	8/89,	*12/95*			
Kopff	3/77,	*8/83*,	1/90,	*7/96*			
Giacobini-Zinner	2/79,	*9/85*,	4/92,	*12/98*			
Forbes	*9/80*,	1/87,	*2/93*,	3/99			
Wolf-Harrington	3/78,	*9/84*,	4/91,	*10/97*			
Schwassmann-Wachmann 2	3/81,	*8/87*,	1/94				
Wirtanen	5/80,	*3/86*,	9/91,	*3/97*			
d'Arrest	8/76,	*9/82*,	2/89,	*7/95*			
Perrine-Mrkos	5/82,	3/89,	*12/95*				
Reinmuth 2	*1/81*,	10/87,	*7/94*				
Brooks 2	*11/80*,	10/87,	*9/94*				
Arend-Rigaux	*1/78*,	11/84,	9/91,	*7/98*			
Harrington	*12/80*,	10/87,	*9/94*				
Johnson	*11/83*,	*11/90*,	10/97				
Finlay	6/81,	6/88,	*6/95*				
Borrelly	2/81,	*12/87*,	*10/94*				
Daniel	7/78,	*8/85*,	8/92,	*9/99*			
Harrington-Abell	4/76,	4/83,	*4/90*,	3/97			
Faye	2/77,	*7/84*,	11/91,	3/99			
Whipple	3/78,	*6/86*,	*1/95*				
Ashbrook-Jackson	8/78,	*1/86*,	*6/93*				
Reinmuth 1	10/80,	*5/88*,	11/95				
Arend	*5/83*,	5/91,	*6/99*				
Schaumasse	9/76,	*12/84*,	3/93				
Wolf	*5/84*,	8/92					
Comas Sola	9/78,	*8/87*,	7/96				
Vaisala 1	8/82,	5/93					
Neujmin 3	*12/82*,	*11/93*					
Tuttle	1/81,	7/94					
Schwassmann-Wachmann 1	*8/89*						
Neujmin 1	*10/84*						
Crommelin	*9/84*						

[a] Given as month/year.
[b] Italicized dates are those for which Jupiter is in approximately the proper location for swingby missions to occur.

modes will be discussed briefly. Direct intercept comet missions have previously been considered.[1–3] Although they may require Earth departure velocities lower than those for Jupiter missions, characteristically the comet approach velocities are measured in the 10's of km/sec. The lowest approach velocity published exceeds 8 km/sec. Such velocity requirements render rendezvous missions impractical for realistic launch vehicles and produce only brief periods of time within which scientific experiments could be performed near comet intercept.

Another possible trajectory mode is the broken-plane multiple-impulse transfer. In this mode, a velocity impulse is applied to the spacecraft near the nodal line of the comet to place the spacecraft in the cometary plane. This maneuver is also used to adjust the spacecraft perihelion to allow intercept of the comet near its perihelion.[9,10] Although this mode can produce very low-comet approach velocities, the plane change maneuver can be large due to the inclination of the comet orbit (typically 10°–30°). Thus, the payload for a flyby mission suffers significant penalties. However, launches become possible for every cometary perihelion.

The use of the Jupiter swingby trajectory substitutes the mass of Jupiter for the onboard propulsion system in achieving the desired plane change into the comets' orbital plane. However, Jupiter obviously must be in the correct location in its orbit to allow such a maneuver; the proper location is approximately the longitude of the node nearer the aphelion of the comet. The other parameter of importance is the date at which Jupiter is near this longitude. Making the preliminary assumption that intercept occurs at the comets' perihelion, and that the comets' line of apses and line of nodes are coincident, use was made of a study by Deerwester to estimate the approximate flight time from Jupiter to the comet.[11] If this screening approach placed Jupiter within about 60° of the ideal location, then a complete matrix of Earth-Jupiter-comet trajectories was computed. The apparitions for which this was done are italicized in Table 1. The comet elements were principally taken from data published by the Illinois Institute of Technology Research Institute.[2,3]

One variation of the Jupiter swingby mode which was not considered here but is reported to show promise is a powered maneuver near Jupiter.[12,13] In this case, the departure conditions at Jupiter are modified by use of a ΔV applied in an optimal manner. Such a maneuver would tend to relax somewhat the constraint on Jupiter's location at the time of swingby and would allow for additional tailoring of the Jupiter-comet trajectory.

The present analysis resulted in the finding of many low-approach velocity trajectories (compared to the earlier intercept studies). These minimal approach velocity solutions are delineated in Table 2. The launch opportunities coincide with those for Jupiter missions and are listed by year. Next, the Earth departure characteristic velocity (departure ΔV plus circular velocity for a 185 km/100 naut. miles orbit), total trip time and comet approach velocity are specified. Finally, the Jupiter related parameters of trip time to Jupiter, passage radius and Jovocentric inclination are presented. The comet arrival is specified in days before (−) or after (+) perihelion.

Trip times are long, relative to those with which we are presently familiar, but not as long as those for the Grand Tour missions. The Jupiter passage is seen to generally occur at a large radius (10-250 Jupiter radii). In general, the Jupiter swingby is used primarily as a means of achieving the desired heliocentric inclination and not as a means of changing the energy of the spacecraft transfer orbit (as for the Grand Tour missions, for instance). Because of the large mass of Jupiter, close passages are not required. These data served

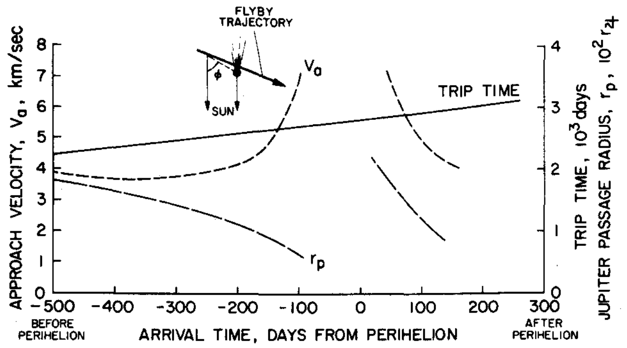

Fig. 1 Flyby mission characteristics: Pons-Winnecke (launch: 6/26/75—perihelion: 4/2/83).

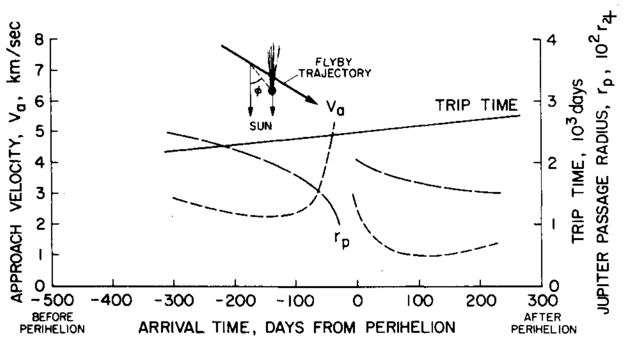

Fig. 2 Flyby mission characteristics: Tempel 2 (launch: 7/30/76—perihelion: 5/30/83).

only to indicate the low-approach velocities achievable and the general characteristics of this trajectory mode. A more detailed discussion of these data and the resulting payloads available for flyby missions and rendezvous missions to selected comets are presented in the next two sections.

Flyby Mission Analysis

In general, the first mission to a planetary target is a flyby mission. This procedure allows better definition of onboard measurements and engineering systems for employment with the more complex orbiter or rendezvous missions to follow. Such would also be expected for comet exploration. Because of the relatively long trip times associated with the Jupiter swingby trajectory mode, these flyby missions should occur as early as possible to assure feedback to later rendezvous missions. Thus, launch in the latter 1970's or very early 1980's would be desirable. Table 2 lists 15 opportunities with launches between 1975 and 1982. Five of these have been selected for further discussion. The choice of Pons-Winnecke, Tempel 2, Honda-Mrkos-Pajdusakova, Whipple and Borrelly provides a variation from 1–5 km/sec in the relative comet approach velocity. Those selected also encompass both bright and diffuse comae and tails. Observations of these comets have been sufficiently often and detailed that prediction of their elements can be done with reasonable confidence. Characteristics of each comet will be briefly reviewed and the trajectory parameters defined in the following sections.

Table 2 Missions with minimal relative velocities

Launch year	Comet	Perihelion date	Arrival time, days	Total trip time, yr	V_c, km/sec	Relative velocity, km/sec	Trip time to Jupiter days	Jupiter passage radius, $r_{♃}$	Jupiter passage incl., deg
'73	Encke	8/16/77	−110	4.1	14.7	4.6	533	31.5	170.0
	T-G-K	1/13/79	−240	5.1	14.3	1.1	757	228.5	68.5
'74	Grigg-Sk	4/11/77	+415	4.0	14.8	5.1	523	8.7	168.5
'75	Pons-Win	4/2/83	−350	6.8	14.7	3.7	551	153.5	111.2
'76	Tempel 2	1/15/83	−140	6.4	14.2	2.3	730	201.4	71.0
	Johnson	11/26/83	−65	7.1	14.3	4.4	864	72.6	77.0
	d'Arrest	9/17/82	−355	5.0	14.6	1.2	951	153.2	70.6
'78	Neujmin 3	12/8/82	−110	3.9	14.5	4.2	771	13.0	175.1
	Neujmin 1	10/9/84	−260	5.3	14.5	3.9	749	230.9	124.1
'79	Wolf	6/6/84	−110	4.3	14.6	4.0	696	6.7	140.9
	Faye	7/9/84	+310	5.5	14.5	3.1	867	56.5	166.7
	Gia-Zin	9/1/85	−310	5.0	14.9	4.0	612	51.5	150.1
'80	H-M-P	5/22/85	−160	4.0	14.3	0.7	780	54.7	179.3
	Daniel	8/2/85	+220	5.3	14.3	4.7	825	53.0	151.5
'81–'82	Wirtanen	3/26/86	−150	3.8	14.1	4.4	791	17.2	165.3
	Crommelin	9/1/84	+300	3.5	15.4	5.5	493	2.0	171.8
	Whipple	6/25/86	−60	4.3	14.0	3.8	918	16.0	177.2
	Borrelly	12/16/87	−300	5.2	14.5	4.2	734	65.1	132.5
'83	Comas Sola	8/22/87	−150	4.1	14.2	5.5	865	25.6	171.0
	S-W 2	8/26/87	+370	5.5	14.3	3.7	937	63.7	166.1
	S-W 1	8/30/89	+630	8.3	14.1	5.6	764	67.2	24.1
'84	Reinmuth 1	5/13/88	−195	3.6	14.2	3.3	720	1.6	14.3
'85	T-G-K[a]	2/6/90	−180	4.3	14.8	2.8	917	144.1	151.1
'86	Grigg-Sk	7/21/92	−250	5.5	14.8	4.8	527	70.4	146.9
'87	Pons-Win	12/27/95	−330	7.6	14.9	4.6	518	124.4	121.6
'88	Tempel 2[a]	3/16/94	−300	4.8	14.8	4.1	1072	200.0	138.6
	d'Arrest	7/7/95	−250	6.2	14.5	2.6	688	152.0	86.5
'89	Neujmin 3	11/19/93	−50	4.1	14.5	3.3	683	5.6	173.0
	Reinmuth 2	7/17/94	+300	5.7	14.7	4.0	893	62.1	169.7
	Harrington	9/4/94	+300	5.8	14.7	3.3	907	113.7	165.7
'91	Finlay	6/6/95	−125	3.2	14.7	3.6	643	3.2	173.0
	Arend	6/6/99	−400	6.5	14.5	3.2	763	167.5	65.0
'92	Perrine-Mrkos	12/18/95	+330	4.0	14.8	5.5	598	3.9	169.8
	Wolf-Harr	10/18/97	+310	5.7	14.3	3.6	821	70.2	142.0
	Daniel	9/24/99	−300	6.0	14.3	0.5	820	145.6	69.8
'95	Arend-Rig	7/28/98	−125	3.1	14.4	4.6	611	2.9	162.7

[a] T-G-K has a close passage to Jupiter in 1988 and Tempel 2 in 1990 which were not accounted for in the original paper. The new elements for these opportunities were obtained from B. Marsden and are reported in Ref. 14.

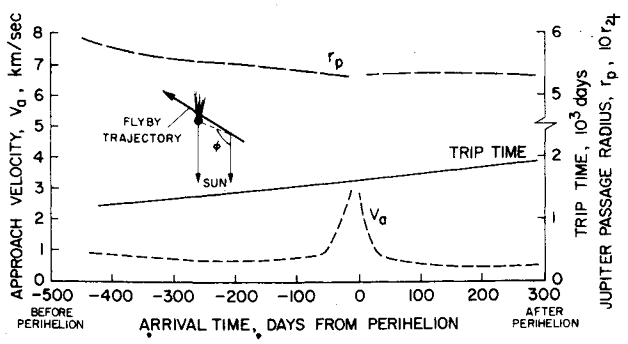

Fig. 3 Flyby mission characteristics: Honda-Mrkos-Pajdusakova (launch: 12/6/80—perihelion: 5/22/85).

The characteristic velocity V_c shown in Table 2 for the minimal comet approach velocity missions is obviously a primary determiner of the launch vehicle capability. The specific value shown is typical of the range of arrival dates of interest, with the exception of near perihelion arrivals for a few comets. Therefore, the V_c variation with arrival date will not be shown on the following figures to reduce the number of curves. A 20-day launch window was assumed and a velocity increment of 100 m/sec was allowed for midcourse guidance and navigation corrections. (For a detailed analysis of guidance and navigation requirements, the reader is referred to Refs. 14 and 15.)

Pons-Winnecke

This comet has a short tail and a nucleus of about 2 km diam which appears to be in several pieces. The coma is fairly bright and has been observed up to 230 days before perihelion. Figure 1 shows the comet approach velocity, trip time and the Jupiter passage radius as a function of the arrival time as measured from the comet's perihelion passage date. The launch energy does not vary significantly for arrival before perihelion and the Titan IIID/Centaur/Burner II launch vehicle provides a payload of about 2000 lb with a 20-day launch window. The inset displays the relative approach geometry for an arrival 200 days before perihelion, the angle ϕ being the sun-spacecraft-comet angle. The spacecraft approach is seen to be from outside and ahead of the comet.

Tempel 2

Coma develops about 150 days before perihelion and is generally diffuse with a consensed nucleus near perihelion. A tail usually develops near perihelion and lasts about 150 days. The comet has been observed up to 400 days before perihelion. The mission trajectory characteristics are shown in Fig. 2 as described previously. The launch energy is nearly constant again having a major increase only for arrivals about 40 days before perihelion. The Titan IIID/Centaur/Burner II can provide a payload of 2600 lb for a 20-day launch window.

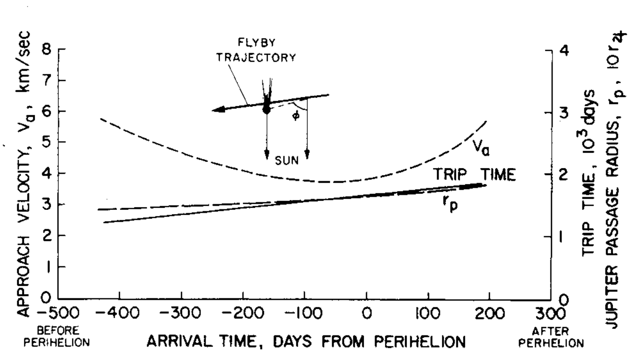

Fig. 4 Flyby mission characteristics: Whipple (launch: 12/31/81—perihelion: 6/25/86).

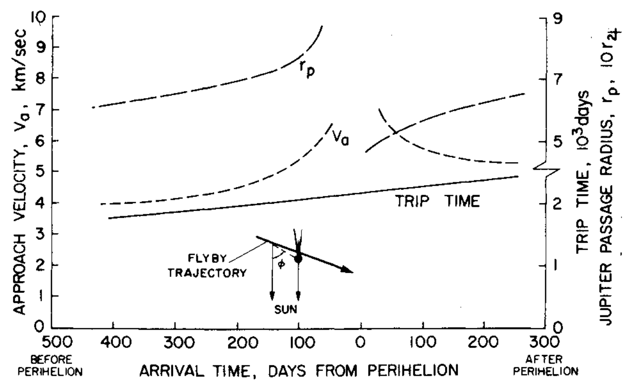

Fig. 5 Flyby mission characteristics: Borrelly (launch: 12/31/81—perihelion: 12/16/87).

Honda-Mrkos-Pajdusakova

The nucleus is weak and diffuse as is the coma which also is fairly large ($\simeq 4 \times 10^4$ km diam). A faint tail has also been observed. This comet is included due to the low-approach velocity in spite of its poor observational record. The trajectory characteristics shown in Fig. 3 reveal a relative approach velocity of 0.7 km/sec, one of the two lowest values found. The launch-energy requirement indicated in Table 2 is consistent for the range of arrival dates considered; however, the approach velocity peaks at about 3 km/sec for arrival 8 days before perihelion. A Titan IIID/Centaur/Burner II can provide a payload of 2600 lb.

Whipple

Whipple exhibits a large well-defined coma through perihelion with a fairly well condensed nucleus. A definite tail is usually displayed near perihelion. There is some indication that the brightness of the comet is decaying about one magnitude per decade. Figure 4 shows the trajectory characteristics. For this comet there is a slight jump in launch requirements for arrivals near perihelion. A Titan IIID/Centaur launch vehicle can provide a payload of 3500 lb with about a 20-day launch window for this mission.

Borrelly

This gaseous comet has a well-condensed nucleus and a diffuse small coma. A definite tail is associated with Borrelly. It was observed in 1960 from about 90 days before perihelion until 80 days after perihelion. The trajectory characteristics shown in Fig. 5 reveal a large increase in the approach velocity for perihelion arrivals. A Titan IIID/Centaur/Burner II launch vehicle can provide a payload of at least 2200 lb for arrivals less than 250 days before perihelion. Arrivals of 100 days before perihelion have an approach velocity of 5.4 km/sec.

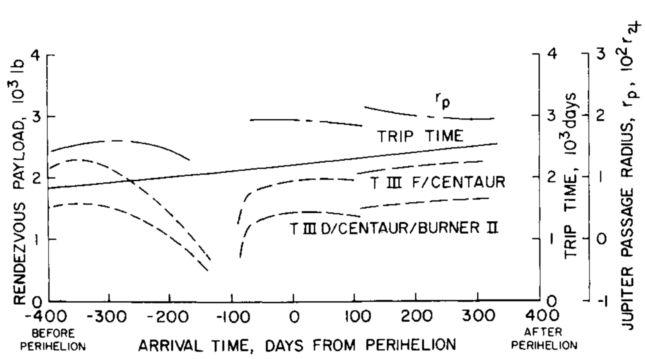

Fig. 6 Rendezvous mission characteristics: D'Arrest (launch: 7/30/76—perihelion: 9/17/82) upper stage I_{sp} = 310 sec.

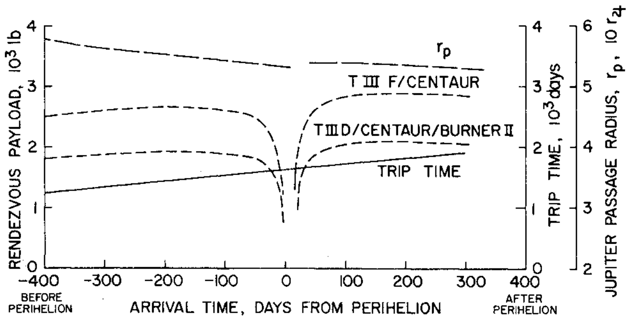

Fig. 7 Rendezvous mission characteristics: Honda-Mrkos-Pajdusakova (launch: 12/6/80—perihelion: 5/22/85) upper stage I_{sp} = 310 sec.

Rendezvous Mission Analysis

For the ballistic type comet mission considered in this paper, one of the major concerns in the selection of a particular comet rendezvous mission is the velocity increment (ΔV) required at the comet for the spacecraft to match the cometary orbit. With typical upper stage propellants which can be stored for the associated trip times, an I_{sp} of about 310 to 385 sec can be expected. Thus velocity increments much greater than 3 km/sec force one toward the consideration of Saturn V class launch vehicles. Their use for these missions does not seem reasonable; thus, the desire is to achieve the lowest possible rendezvous ΔV. Four missions were selected with ΔV's of less than 3 km/sec; D'Arrest, Honda-Mrkos-Pajdusakova, Tuttle-Giacobini-Kresak, and Daniel.

The selection of the nominal arrival date for rendezvous missions involves a somewhat different philosophy than that for flyby missions. For flyby missions, the desire is to obtain the maximum information from one pass. Thus, a fully formed coma and tail could be desired. This results in arrival times near or even after the perihelion of the comet.

In the case of a rendezvous mission, the spacecraft will accompany the comet along its orbit: thus, the desire is to observe the formation of the coma and tail. Since the coma is generally formed at about 2 a.u. or greater, arrivals hundreds of days before perihelion are desirable. If the rendezvous occurs after perihelion passage, the spacecraft must orbit with the comet for many years before such data can be obtained. The coma formation is used as an arrival time selection criterion since tail formation generally follows the coma formation or may never occur.

Payload contours as a function of the arrival time, measured from perihelion, are presented for two launch vehicles, the Titan IIID/Centaur/Burner II and the Titan IIIF (7 segment)/Centaur. The rendezvous stage was assumed to provide an I_{sp} of 310 sec with inerts of 10%. A launch window of about 20 days was selected and the midcourse ΔV requirements were assumed to be 100 m/sec.

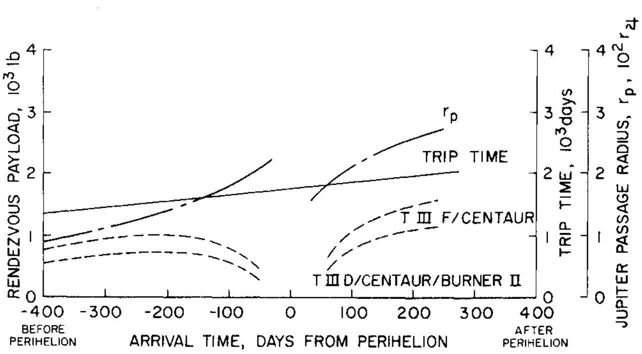

Fig. 8 Rendezvous mission characteristics: Tuttle-Giacobini-Kresak (launch: 5/4/85—perihelion: 2/6/90) upper stage I_{sp} = 310 sec.

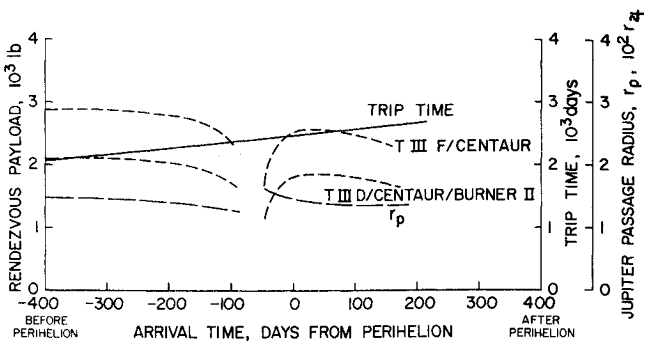

Fig. 9 Rendezvous mission characteristics: Daniel (launch: 12/13/92—perihelion: 9/24/99) upper stage I_{sp} = 310 sec.

D'Arrest

This is a diffuse comet which brightens with a well defined nucleus shortly after perihelion. A faint broad tail has also been observed. The 1976 passage promises to be a time of good observation which has greatly increased interest in a later rendezvous mission. Figure 6 presents a summary of the characteristics for a 1982 rendezvous with a 1976 launch. Others have studied the 1977 launch opportunity which is almost as good in payload and a year shorter in trip time. However, that launch opportunity coincides with the Jupiter-Saturn-Pluto grand tour launch period. Thus, I selected the 1976 launch opportunity even though full use of the 1976 observations could not be made.

A maximum payload of over 1600 lb exists for arrivals 350 days before perihelion. At this time, however, the comet would be extremely faint. A gap in the payload curves occurs at about 100 days before perihelion due to the Earth-Jupiter leg crossing the 180° transfer angle ridge. Arrivals around perihelion can have payloads of 1400 lb. Then another break occurs where the Jupiter-comet leg crosses the 180° transfer angle ridge and the available payload increases. Since most of the coma activity occurs shortly after perihelion, an arrival about one month before perihelion would appear desirable.

Honda-Mrkos-Pajdusakova

This comet was described in the flyby analysis section. The payload, associated trip time and Jupiter passage radius are shown in Fig. 7. A maximum payload of 1900 or 2600 lb, depending upon the launch vehicle, exists for arrivals prior to the comet's perihelion passage. Postperihelion arrivals allow slightly larger payloads. In general, however, preperihelion arrivals are desirable to allow observation of the coma and tail formation. Thus, a nominal arrival time of at least 200 days before perihelion would appear desirable. The reduction in payload for arrivals near perihelion results from the 180° transfer angle ridge being crossed on the Jupiter-comet trajectory leg.

Table 3 Rendezvous opportunities where gravity-assist missions compare favorably with multi-impulse missions

			Gravity assist		Multi-impulse	
Launch year	Comet	Perihelion date	Trip time	ΣV	Trip time	ΣV
'73	T-G-K	1/13/79	5.1	15.4	...	...
'76	D'Arrest	9/17/82	5.0	16.8	5.8	16.9
'79	Wolf	6/6/84	4.3	18.6	7.2	18.7
'80	H-M-P	5/22/85	4.0	15.0	4.3	17.0
'81	Whipple	6/25/86	4.3	17.8	6.5	>17.3
'85	T-G-K	2/6/90	4.3	17.6	...	...
'88	D'Arrest	7/7/95	6.2	17.1	5.8	16.9
'91	Arend	6/6/99	6.5	17.7	7.2	18.7
'92	Daniel	9/24/99	6.0	14.8	6.7	17.2

Tuttle-Giacobini-Kresak

A strongly condensed nucleus and large coma have been observed for this comet. The coma appears to peak in size about 50 days after perihelion. No tail of any significance has been observed. Orbital elements of this comet are known with reasonable accuracy. Payload data are shown in Fig. 8. The minimum approach velocity of about 2.8 km/sec results in a maximum payload of approximately 1000 lb for arrival prior to the comet's perihelion. Use of a rendezvous stage I_{sp} of 385 sec with the Titan IIIF/Centaur would raise the payload to 1300 lb.

Daniel

Daniel is a diffuse comet with little central condensation but a large coma. A broad well-established tail has been observed. Approach velocities for this comet were the lowest found. As a result, payloads approaching 3000 lb were obtained with the Titan IIIF/Centaur launch vehicle for arrivals 300 days before perihelion (see Fig. 9). By the time of launch (1992) more advanced upper stages would allow even greater payloads for detailed and extended examination of this comet.

Comparison with Other Ballistic Modes

The final test of any method is how it compares to other possible means of solution. For comet rendezvous missions the primary alternate methods are multi-impulse and low thrust. At this time, low-thrust data is available for only a few comet missions.[6] Thus, no general comparison can be made; however, general results are available for multi-impulse solutions.[6,9,10] The missions where the gravity assist rendezvous compares favorably with the multi-impulse rendezvous are delineated in Table 3. Also shown are two cases where no multi-impulse solutions are published but which exhibit low-energy and/or short trip times. For all other missions in Table 2, the multi-impulse solutions are potentially better. It should also be noted that additional solutions can be found for the multi-impulse method since there is no restriction due to Jupiter's location.

For "slow flyby" missions, the gravity assist trajectories of Table 2 are superior to the multi-impulse in terms of payload. This results from the plane change being made by Jupiter's mass and not by an onboard propulsive maneuver.

Conclusions

This study has shown the usefulness of the Jupiter swingby mode for comet flyby and rendezvous missions. Flyby missions that have comet approach velocities significantly lower than those associated with direct trajectories have been found for 29 of the 37 comets investigated. The penalties for obtaining these low velocities are flight times on the order of 4–6 yr. Payloads of 2000–3000 lb can be obtained from launch vehicles of the Titan/Centaur class.

Rendezvous missions to 4 comets have been defined with payloads on the order of 1000–3000 lb for the Titan/Centaur class of launch vehicle with a 310 sec I_{sp} rendezvous stage. These missions are to the following comets: 1) D'Arrest, 2) Honda-Mrkos-Pajdusakova, 3) Tuttle-Giacobini-Kresak, and 4) Daniel. The trip times are from 4–6 yr. Arrival at these comets occurs sufficiently before perihelion so that observation of the coma and tail formation is possible.

References

[1] Comet Intercept Study, Rept. 8668-6002-RU-000, March 1963, Space Technology Lab., Redondo Beach, Calif.

[2] Narin, F. and Pearce, P. M., "Perturbation, Sighting, and Trajectory Analysis for Periodic Comets: 1965–1975," Rept. T-7, Oct. 1964, IIT Research Inst., Chicago, Ill.

[3] Narin, F. and Rejzer, B., "Sighting and Trajectory Analysis for Periodic Comets: 1975–1986," Rept. T-11, March 1965, IIT, Research Inst., Chicago, Ill.

[4] Michielsen, H. F., "A Rendezvous with Halley's Comet in 1985–1986," *Journal of Spacecraft and Rockets*, Vol. 5, No. 3, March 1968, pp. 328–334.

[5] Roberts, Phillip H., Jr., "Mission Analysis of the D'Arrest '76 Opportunity," AIAA Paper 70-1073, Santa Barbara, Calif., 1970.

[6] Friedlander, A. L. et al., "Trajectory and Propulsion Characteristics of Comet Rendezvous Opportunities," TR T-25, Aug. 1970, IIT Research Inst., Chicago, Ill.

[7] Porter, J. G., "Catalogue of Cometary Orbits—1960," Memoirs, British Astronomical Association, Vol. 39, No. 3, June 1961.

[8] Roberts, D. L., "A Compendium of Data on Some Periodic Comets," Rept. P-9, July 1964, IIT Research Inst., Chicago, Ill.

[9] Michielsen, H. F., private communication, 1969, Lockheed Missiles & Space Co., Sunnyvale, Calif.

[10] Waters, John I., "Application of an Impulsive Trajectory Optimization Method to the Comet Rendezvous Problem," AIAA Paper 71-93, New York, 1971.

[11] Deerwester, J. M., "Jupiter Swingby Missions to Non-Specific Locations in Interplanetary Space," TN D-5271, June 1969, NASA.

[12] Robey, D. H., private communication, 1969, North American Rockwell Corp., Downey, Calif.

[13] Dazzo, E. J., "Outer Planet Exploration Missions, Final Report," SD 70-32-3, Jan. 1970, Space Div., North American Rockwell Corp., Downey, Calif.

[14] Fraser, D. C., "Guidance and Navigational Requirements for Flyby and Swingby Missions to the Outer Planets, Final Report, Vol. IV: Additional Missions," R-678, Oct. 1971, MIT Charles Stark Draper Lab., Cambridge, Mass.

[15] Fraser, D. C., et al., "Guidance and Navigation for Comet Rendezvous Missions," AAS Preprint 71-116, 17th Annual Meeting, June 28–30, 1971, Seattle, Wash.