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ABSTRACT

Alternative strategies for ballistic missions to Halley's comet in 1985-86 are described. It is shown that a large science return would be acquired from a ballistic Halley intercept in spite of the high flyby speeds of almost 60 km/sec that are associated with this mission mode. The possibility of retargeting the cometary spacecraft to additional comets after the Halley intercept also exists. In one scenario two cometary spacecraft of identical design would be used to carry out four separate cometary encounters over a three-year period. One spacecraft would intercept Halley before its perihelion passage in December 1985 and then go on to comet Borrelly with an encounter in January 1988. The other spacecraft would be targeted for a post-perihelion Halley intercept in March 1986 before proceeding towards an encounter with comet Tempel-2 in September 1988. The flyby speeds for the Borrelly and Tempel-2 intercepts are 21 and 13 km/sec, respectively.

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OPPORTUNITIES FOR BALLISTIC MISSIONS TO HALLEY'S COMET

I. INTRODUCTION

The return of Halley's comet in 1985-86 will attract worldwide attention from the general public as well as the astronomical community. Halley has been an unusually bright comet and it has seldom gone by unnoticed. Observations of Halley's comet in ancient Chinese records go back to 239 BC. It is important historically because some of Halley's previous appearances have coincided with famous events such as the siege of Jerusalem in AD 66, the defeat of Attila the Hun at Chalons in AD 451, and the Norman conquest of England in AD 1066 (see Figure 1). A brief summary of Halley's observational history and physical characteristics is given in Table 1.

Figure 1. Halley's Comet in 1066 as Depicted on the Bayeux Tapestry

Table 1
Comet Halley Summary

Observational History: Halley's comet has been seen at every apparition since at least 86 BC, making twenty-seven appearances in all. It is a spectacular object displaying physical characteristics of a typical long-period comet, and was observed extensively during its 1910 apparition. Its exceptional brightness is indicated by the fact that naked eye observations were recorded over a four-month interval at this apparition. Brightness estimates taken from the 1910 data imply that Halley's absolute luminosity is nearly two magnitudes brighter after perihelion.

Nuclear Region and Coma: Halley's very bright nuclear region has been estimated to be several thousand kilometers in diameter. The failure to observe a solid nucleus when Halley transitted the sun on May 18, 1910 gives an upper bound of 50 km to any solid nucleus for this comet. Diameters for the visible coma near 1 AU in the post-perihelion phase are $\sim 5 \times 10^4$ km for the inner coma and $\sim 3 \times 10^5$ km for the outer coma. The spectrum of the coma region is almost entirely CN and C_2 superimposed on a continuous background. Jets and streamers invariably showed CN spectra. A number of transient phenomena were observed in the inner coma region. Explosive activity was particularly well established in April, May, and June 1910. Temporary secondary nuclei were observed to coalesce with the primary nucleus after a few hours or days.

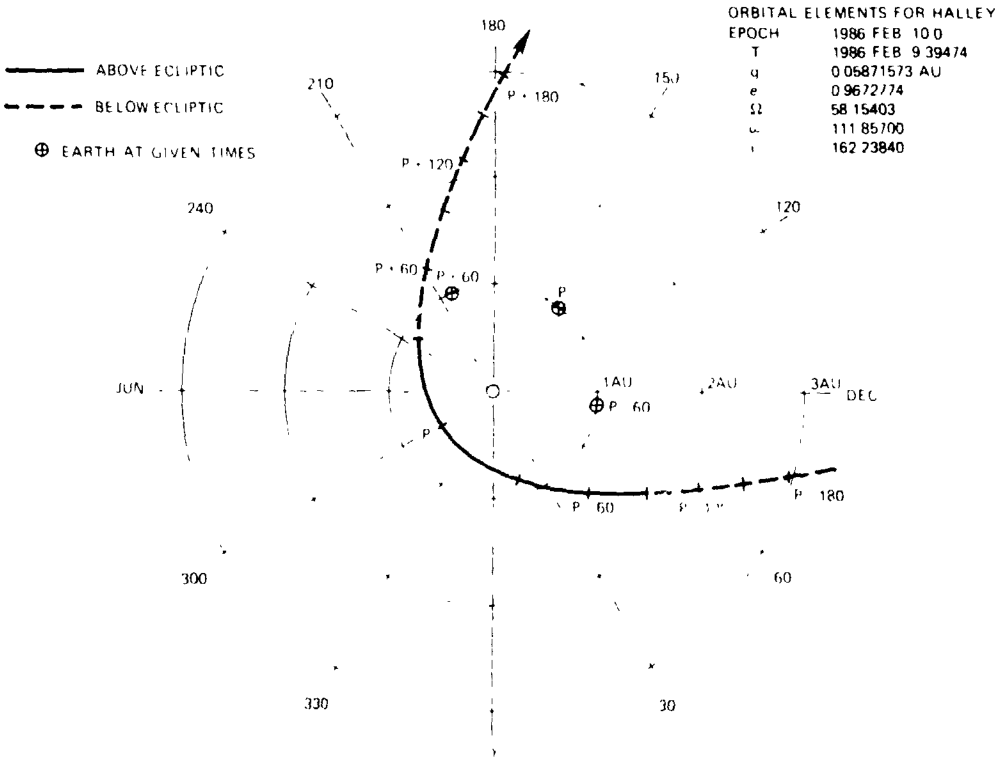
Tail: Two well-developed tails were seen in 1910. One was primarily gaseous (CO^+), and the other was mainly dust. Near its maximum, the observed tail length was ~ 0.35 AU. Several tail condensations ("knots") were also observed.

Dust: Halley is a very dusty comet. Dust densities are probably 1000 times greater than those found in dusty short-period comets.

Nongravitational Effects on Orbital Motion: A rigorous examination of Halley's nongravitational accelerations has not been completed as yet. However, it is known that the nongravitational effects amount to an average lengthening of Halley's period by 4.1 days at each apparition.

Observing prospects for Halley during its 1985-86 apparition can be evaluated by inspecting the orbital geometry shown in Figure 2. Although Halley will be lost in the sun's brightness near perihelion, it will be favorably situated for extensive telescopic observations before and after perihelion. The best period for naked eye observations should occur after Halley's perihelion passage from the end of March through April (Reference 1).

Because Halley is the only dramatically bright comet whose return can be accurately predicted, its 1985-86 apparition will present scientists with a unique opportunity for the definitive investigation of a large comet. Its scheduled appearance will permit systematic planning and adequate preparation for a wide variety of coordinated experiments. The value of early planning has been amply demonstrated by the wealth of data gathered from observations of comet Kohoutek in 1973-74 (Reference 2) and Halley's last appearance in 1910 (Reference 3). However, the most important aspect of the 1985-86 Halley opportunity is that, for the first time, it will be possible to obtain in-situ data from spacecraft flybys of the comet.



ORBITAL ELEMENTS FOR HALLEY

EPOCH	1986 FEB 10 0
T	1986 FEB 9 39474
q	0 05871573 AU
e	0 9672774
Ω	58 15403
ω	111 85700
i	162 73840

Figure 2. Orbit of Halley's Comet

Because of the highly uncertain environment of a comet, ballistic intercept missions have been strongly endorsed as the best way to initiate a program of cometary exploration (Reference 4). The ballistic mode is logical for a reconnaissance mission and is also reliable and inexpensive. As will be shown in the next section, the science return from a ballistic flyby will be quite adequate for the first cometary mission. Data from ballistic flybys will be invaluable for defining the scientific objectives of the more expensive and complicated rendezvous missions to comets.

This report will describe a variety of mission plans for ballistic flybys of Halley's comet. The advantages and disadvantages of the various options will be discussed and specific recommendations will be presented.

II. SCIENCE OBJECTIVES AND EXPERIMENTS

Flyby speeds for ballistic intercepts of Halley's comet are typically ~60 km/sec. Errors in Halley's ephemeris will limit the minimum flyby distance from the nucleus to about 2000 km.* Smaller values for these two important mission parameters would be desirable, but the primary science objectives of the initial cometary mission can be achieved with the present numbers.

Because of Halley's large dimensions and the exploratory nature of the first cometary mission, investigations of the large-scale cometary characteristics should be emphasized. With this guideline, the main science objectives of the Halley flyby are the following:

1. Imaging of the nuclear region at moderate resolution. Determine the nature of the multiple nuclear condensations that have been observed in Halley, and attempt to confirm the postulated existence of a halo of icy grains surrounding the nuclear region. Measure the sizes and shapes of the nuclear condensations.

2. Determine the abundance and spatial distribution of the neutral molecules and radicals in the coma.

3. Measure the density, spatial distribution, and energy distribution of the charged particles in the coma and tail regions.

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*In principle, Halley's ephemeris errors could be significantly reduced with spacecraft measurements (i.e., onboard navigation). Unfortunately, the probable presence of multiple nuclear condensations diminishes the reliability of this technique.

4. Investigate the properties of the cometary plasma and magnetic field.

5. Determine the nature of the solar-wind, comet interaction. Find the locations of the bow shock and the contact surface (if they exist).

6. Survey the characteristics of the dust grains, especially the size distribution, spatial distribution, and composition.

7. Investigate the time variation of the coma's structure including its hydrogen halo by making spectrophotometric measurements during the cometary approach and departure phases. (The principal advantages of a comet probe for spectrophotometric observations are higher intensities and better resolution than could be obtained from earth.)

To properly study the large-scale features of Halley's comet, correlative measurements in the coma and tail regions will be needed. This objective can be attained by using the dual-probe concept shown in Figure 3. One probe passes close to the nucleus on its sunward side, while the other traverses the tail region. The cross-sectional encounter geometry illustrated in Figure 3 is typical for ballistic intercepts of Halley in 1985-86.

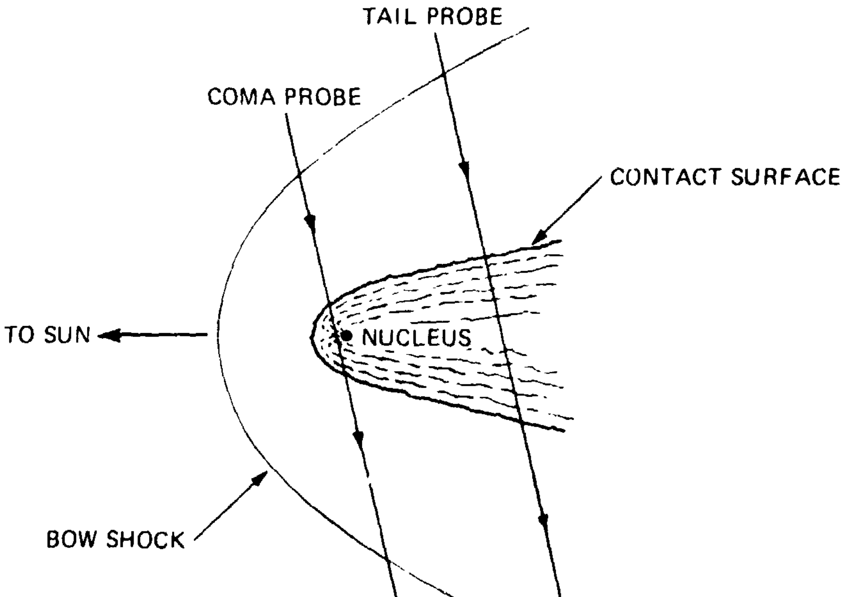

Figure 3. Dual-Probe Encounter Geometry

A representative science payload for a dual-probe Halley flyby is listed in Table 2. Although this list was intended to be a minimum payload, the experiment complement of Table 2 is sufficient for the accomplishment of all of the science objectives listed above. The high encounter velocity of the Halley flyby will preclude high-resolution imaging of the nuclear region, and spatial resolution will be degraded somewhat for all experiments. However, the high flyby speed is not expected to significantly affect the performance of any of the instruments listed in Table 2. With the exception of the neutral mass spectrometer, flight-proven instrumentation or slightly modified versions of current instrument designs would satisfy the requirements for a Halley flyby at 60 km/sec. Furthermore, the neutral mass spectrometers that are currently under development for cometary missions would give good performance for flyby speeds from zero to 100 km/sec. One version uses field ionization to generate singly-charged ions from ambient neutrals and applies a time-of-flight technique to determine the masses of the field ions (Reference 5). Laboratory tests have already demonstrated the feasibility of this concept, and there should be little difficulty in developing a satisfactory flight instrument in time for the Halley mission.

Table 2
Typical Experiment Complement for Cometary Flyby Mission

Instrument	Coma Probe	Tail Probe	Comments
Imaging System Lyman-Alpha Photometer	X X		Performance optimized for moderate resolution.
Neutral Mass Spectrometer Ion Mass Spectrometer	X X	 X	Instrumentation is expected to give good performance at flyby speeds under 100 Km/sec.
Magnetometer Plasma Wave Detector Electron Analyzer Plasma Analyzer	X X X X	X X 	Performance of these instruments will be relatively insensitive to flyby speed.
Dust Analyzer	X		Flyby speed should be greater than 10 Km/sec.

An important bonus of the ballistic Halley mission is the possibility of retargeting the spacecraft to another comet after the Halley flyby. The additional cometary intercept is achieved by modifying the spacecraft trajectory with earth-swingby maneuvers and will be described in the next section. The dimensions of the secondary targets are much smaller than Halley, and their physical characteristics are quite different (see Appendix A). In general, the additional cometary encounters will have lower flyby speeds (13 → 21 km/sec) and smaller miss distances (< 1000 km). Obviously, the science value of the Halley mission will be enhanced considerably by including additional cometary encounters in the flight plan. Because cometary behavior will never be fully understood until in-situ measurements are obtained from several different types of comets, intercepts with at least two classes of comets should be a major goal of the first cometary mission.

Remote observations of Halley's comet from ground-based observatories and earth-orbiting telescopes will contribute in an important way to the success of the Halley intercept mission. Spacecraft data will be complemented and better understood if remote measurements of Halley's physical activity are recorded throughout the 1985-86 apparition. Spectral coverage in the ultraviolet and infrared is especially desirable. Photographs of the coma and tail regions, with a time resolution that is fast enough to track the motions of tail condensations, should also be obtained.

III. MISSION ALTERNATIVES

In this section a number of attractive mission profiles for ballistic intercepts of Halley's comet are described. When comparing the relative merits of the alternative plans given below, some attention should be given to the following:

1. Encounter location. Spacecraft miss distances will be somewhat smaller in the pre-perihelion phase. For instance, estimated miss distances during the pre-perihelion period range from 3000 km on December 10, 1985, to 2000 km on December 20, 1985. After perihelion, miss distances have been estimated at 10,000 km on March 20, 1986, and 7000 km on March 30, 1986. However, post-perihelion encounters have the advantage that Halley will probably be more active at this time.

2. Encounter geometry. For early detection of solid nuclei, a small phase angle* is preferred. On the other hand, cross-sectional mapping of the

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*The phase angle is defined as the angle between the relative velocity vector at encounter and the sun-comet line. A phase angle of zero degrees corresponds to an approach from the sunlit side of the nucleus.

cometary atmosphere is also desirable. Therefore, phase angles between 40° and 70° are probably optimal.

3. Favorable geometry for earth-based observations. Encounters that take place close to the earth and at large solar elongations are preferred.

4. Inclusion of additional targets in the mission profile. If additional cometary intercepts can be carried out without major spacecraft modifications (e.g., excessive onboard propulsion capability), the mission will be very cost effective.

5. Mission cost and complexity. Smaller launch-energy requirements usually imply less expensive launch-vehicle costs. Spacecraft thermal and power subsystems can be simplified if the heliocentric distances throughout the mission can be kept approximately between 0.80 AU and 1.40 AU (i.e., 1.5 → 0.5 solar constants).

Because all the missions discussed in this report require launches in 1985, a launch using the Space Shuttle has been assumed. The payload capability of the Shuttle with various upper-stage combinations is given in Figure 4. Two lightweight spin-stabilized upper stages with their respective payloads can easily be carried on the same shuttle flight. However, the heavier Interim Upper Stage (IUS) combinations will probably be limited to one flight unit per shuttle launch. It is also worth noting that the cost for a spin-stabilized upper stage will be approximately 20% of the price for the basic two-stage IUS.

A. Dual Launch Opportunities

It is possible to accommodate two independently-targeted interplanetary spacecraft with a single Shuttle launch. This can be done by placing both spacecraft into an earth parking orbit that contains the two required launch asymptotes. Each spacecraft is then injected into its specified interplanetary trajectory with a spin-stabilized upper stage. Of course, the launch windows for the two missions must overlap, and the required launch energies should be less than 24 km^2/sec^2 for spacecraft weights of about 500 kg (see Figure 4). It is also beneficial, but not absolutely necessary, for the declinations of both launch asymptotes to be less than 55°.

Two rather interesting dual launch possibilities have been identified in connection with the 1985-86 Halley opportunity. One involves both pre- and post-perihelion encounters with Halley, while the other combines a multiple encounter mission to comets Giacobini-Zinner and Borrelly with a pre-perihelion intercept of Halley.

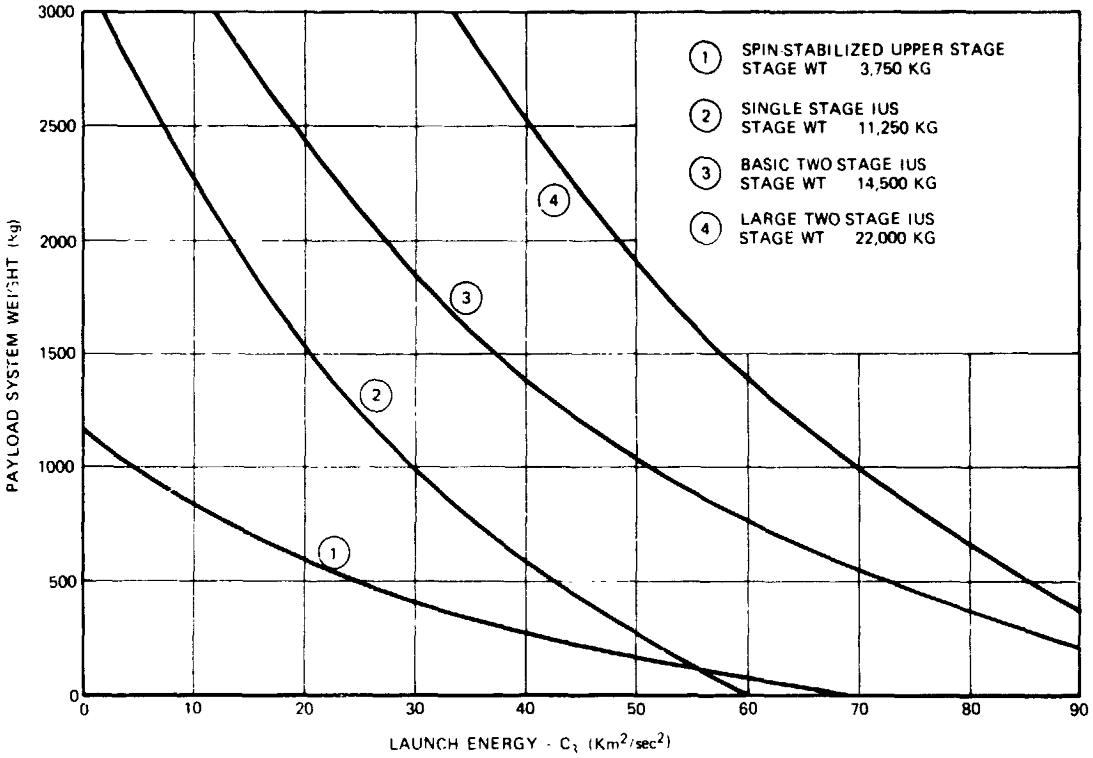


Figure 4. Payload Capability of Shuttle with Solid Upper Stage

1. Halley Pre and Post-Perihelion Encounters. The first part of July 1985 is the best time for a dual launch to Halley. In this interval, the launch energies for both trajectories are less than 15 km^2/sec^2. The basic plan for the dual launch to Halley is depicted in Figure 5, and the nominal mission parameters are summarized in Table 3. Notice that the earth will be in good position for supporting observations at both encounters. Because the intercepts will take place about 100 days apart, preliminary results from the pre-perihelion encounter could be used to optimize the targeting strategy for the post-perihelion encounter.

The encounter geometries for both cases are shown in Figure 6. Cross-sectional traverses occur in each instance, but the pre-perihelion encounter has a better phase angle. The geometry illustrated in Figure 6 is quite similar to the other pre- and post-perihelion Halley intercepts that are discussed below.

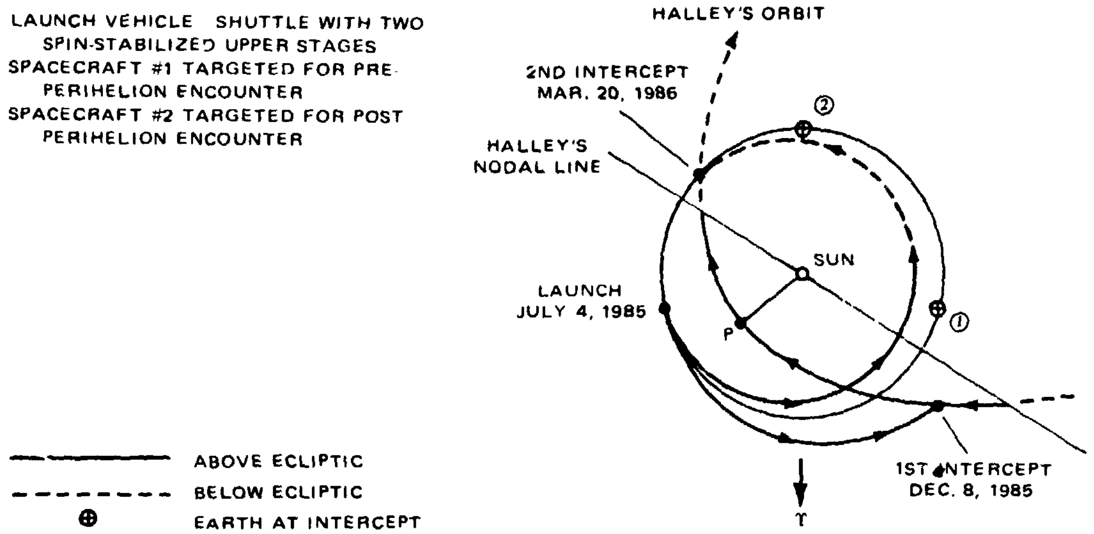


Figure 5. Dual Launch to Halley's Comet

Table 3
Nominal Parameters for Dual Launch to Halley*

	Pre-Perihelion Intercept (P -63 Days)	Post-Perihelion Intercept (P +39 Days)
Encounter Parameters		
Intercept Date	Dec. 8, 1985	Mar. 20, 1986
Sun Distance (AU)	1.37	1.00
Earth Distance (AU)	0.71	0.80
Phase Angle (Degrees)	57.7	112.2
Flyby Speed (km/sec)	55.3	64.5
Launch Parameters		
Launch Energy-C_3 (km^2/sec^2)	14.5	9.1
Declination of Launch Asymptote (Degrees)	33.5	54.3
Spacecraft Transfer Orbit		
Perihelion (AU)	1.01	0.81
Aphelion (AU)	1.44	1.03
Inclination (Degrees)	4.6	4.7
Period (Years)	1.40	0.88

*These parameters are fairly constant within a 10-day launch window. For example, throughout this period, the launch energy is <15.1 km^2/sec^2 for the pre-perihelion intercept and <9.4 km^2/sec^2 for the post-perihelion intercept.

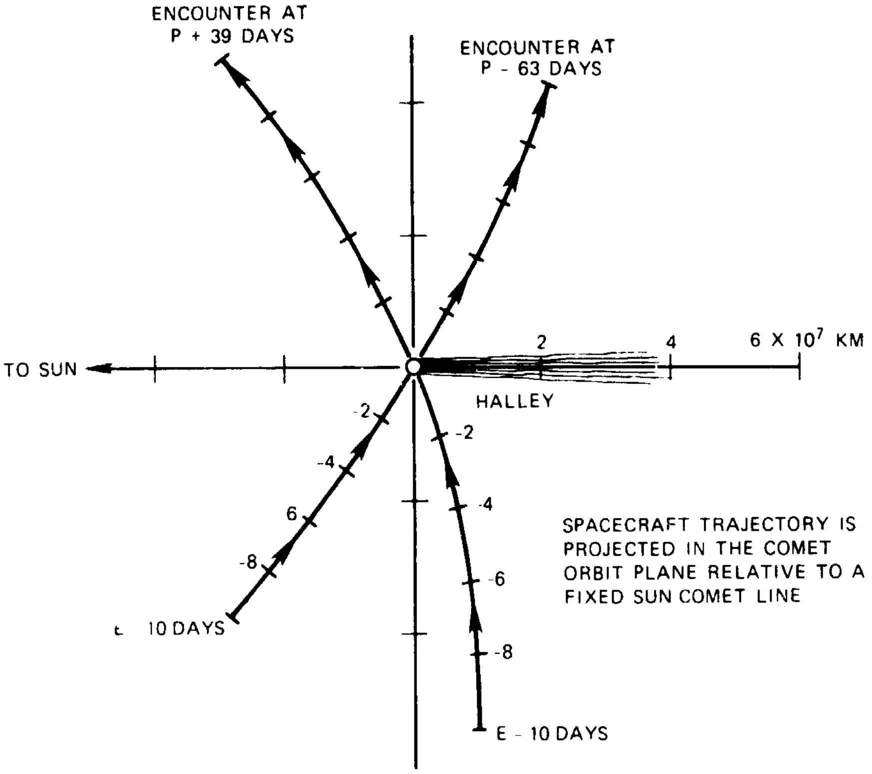


Figure 6. Halley Encounter Geometry

2. Halley and Multi-Comet Mission. Another dual launch opportunity occurs in March 1985. The nominal mission plan for this launch date is outlined in Table 4. In this plan one spacecraft is targeted for a pre-perihelion encounter with Halley on December 13, 1985. The second spacecraft is placed into a trajectory that intercepts comet Giacobini-Zinner on September 11, 1985, and then returns to the earth's vicinity on March 10, 1986. The earth-return trajectory is shown in Figure 7. Two earth-swingby maneuvers are then used to retarget the spacecraft towards an encounter with comet Borrelly on December 25, 1987. Details of these maneuvers are shown in Figure 8. This mission was reviewed by the NASA-sponsored Comet Working Group in May 1975 and received their endorsement as one of the two best missions for initiating the study of comets. A more complete description of this mission is given in Reference 6.

Recently, two alternative mission profiles for the multi-comet mission have been found. The alternative profiles utilize different earth-swingby maneuvers to retarget the spacecraft to either comet Grigg-Skjellerup or comet Tempel-2 instead of comet Borrelly. Details of these profiles are presented in Table 5. Variations in the mission parameters for all of these options over a ten-day launch window are given in Appendix B.

Table 4
Dual Launch Multi-Comet Mission

Launch Date: March 10, 1985

Launch Vehicle: Shuttle with two spin-stabilized Upper Stages

Spacecraft #1: Intercept Comet Halley @ P-58 Days
  Launch Energy-C_3: 22.2 Km^2/sec^2
  Declination of Launch Asymptote: -51.5°

Spacecraft #2: Intercept Comets Giacobini-Zinner and Borrelly
  Launch Energy-C_3: 12.3 Km^2/sec^2
  Declination of Launch Asymptote: -4.1°

Encounter Date	Sun Distance (AU)	Earth Distance (AU)	Flyby Speed (Km/sec)
Halley December 13, 1985	1.29	0.80	54.7
Giacobini-Zinner September 11, 1985	1.03	0.46	20.6
Borrelly December 25, 1987	1.36	0.53	17.3

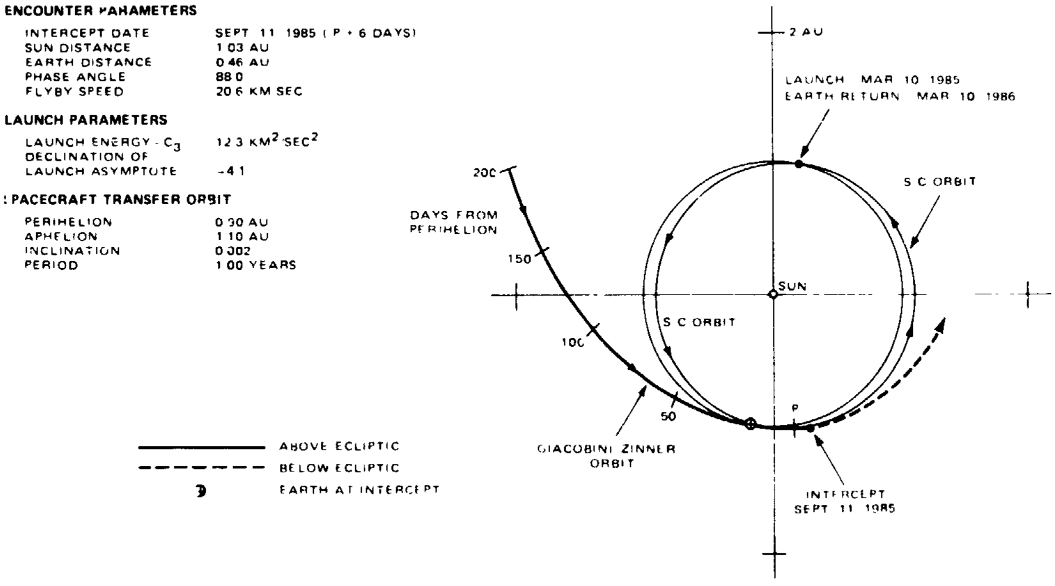


Figure 7. Giacobini-Zinner Intercept with Earth Return

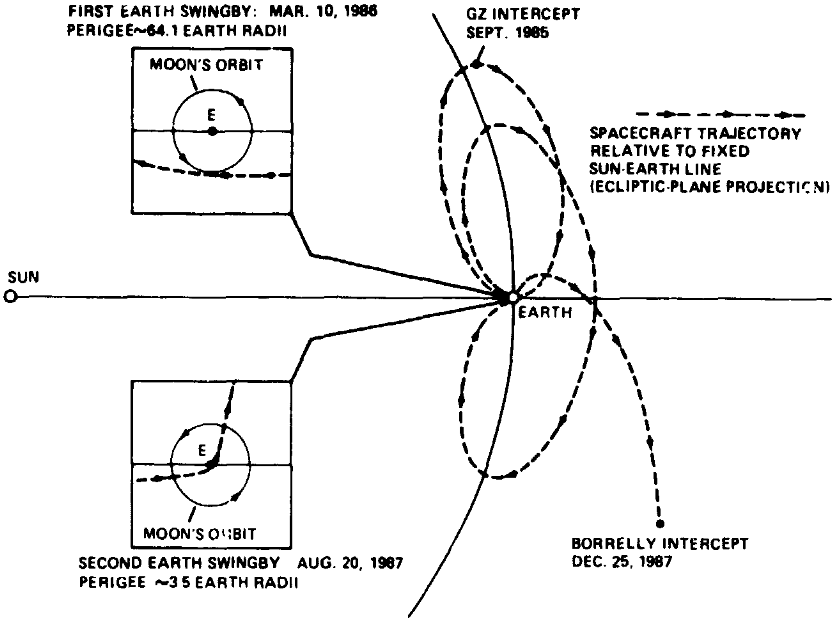
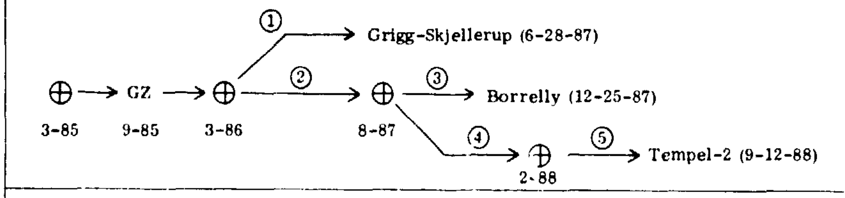


Figure 8. Spacecraft Trajectory for Multiple Encounter Mission to Giacobini-Zinner and Borrelly

Table 5
Alternate Mission Profiles Following the Giacobini-Zinner Intercept



Earth Swingbys

Swingby Date	Perigee (Earth Radii)	Bend Angle (Degrees)	Heliocentric Inclination After Swingby (Degrees)
① March 10, 1986	4.18	66.5	5.4
② March 10, 1986	64.05	8.4	0.0
③ August 20, 1987	3.54	72.2	0.7
④ August 20, 1987	2.08	90.4	6.8
⑤ February 15, 1988	9.26	40.1	5.1

Cometary Encounters

Encounter Date	Sun Distance (AU)	Earth Distance (AU)	Phase Angle (Degrees)	Flyby Speed (Km/sec)
(GS) June 28, 1987	1.00	0.89	98.0	12.8
Ⓑ December 25, 1987	1.36	0.53	74.7	17.3
(T2) September 12, 1988	1.38	0.95	83.4	11.7

B. Halley Intercept with Earth Return

Earth-return trajectories that include a Halley intercept are also possible. In Table 6 launch dates for earth-return trajectories are listed for both pre-perihelion and post-perihelion Halley intercepts. By varying the intercept date at Halley, a fairly long launch window was obtained for these trajectories. All of the trajectories listed in Table 6 return to earth approximately one year after launch.

To minimize the launch-energy requirement, nominal launch dates of July 21, 1985, for the pre-perihelion intercept and August 25, 1985, for the post-perihelion intercept were selected. Using the earth-swingby technique, it is possible to retarget both of these trajectories to either comet Borrelly in January 1988 or comet Tempel-2 in September 1988. The total mission duration with these encounters would be about three years which is quite reasonable.

1. Pre-Perihelion Encounter. The trajectory for the pre-perihelion Halley intercept with earth return is shown in Figure 9, and alternative mission profiles to Borrelly and Tempel-2 are summarized in Table 7. Launch-window

Table 6
Launch Dates for Halley Intercept with Earth Return

Launch Parameters			Halley Encounter Parameters				
Launch Date	Launch Energy (Km^2/sec^2)	Declination of Launch Asymptote (Degrees)	Intercept Date	Sun Distance (AU)	Earth Distance (AU)	Phase Angle (Degrees)	Flyby Speed (Km/sec)
Pre-Perihelion Encounter							
7-6-85	71.9	0.9	12-22-85	1.16	0.96	67.6	56.4
7-21-85	69.4	-1.5	12-19-85	1.20	0.90	65.4	55.0
8-5-85	74.0	-2.0	12-16-85	1.25	0.85	63.2	53.9
Post-Perihelion Encounter							
6-26-85	70.5	53.2	4-1-86	1.23	0.47	119.9	56.6
7-16-85	48.0	50.4	4-2-86	1.20	0.50	117.5	56.9
8-5-85	38.7	45.4	3-31-86	1.17	0.54	115.6	57.5
8-25-85	36.3	38.9	3-28-86	1.13	0.59	113.8	58.4
9-14-85	39.4	32.1	3-26-86	1.09	0.66	111.9	59.6
10-4-85	49.8	25.6	3-22-86	1.04	0.74	109.8	61.4
10-24-85	71.8	18.4	3-18-86	0.96	0.86	107.0	64.3

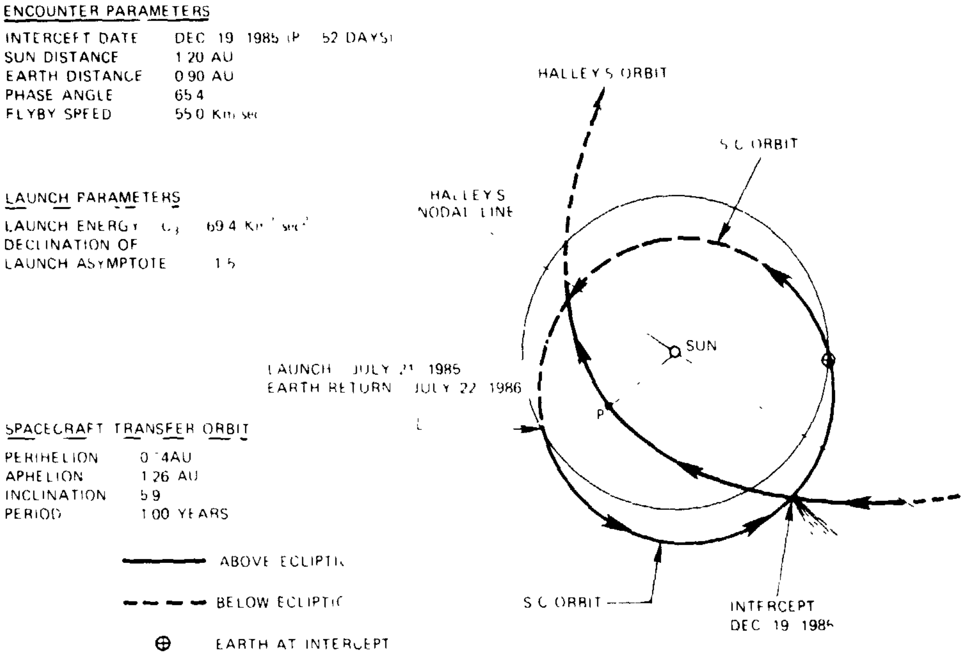
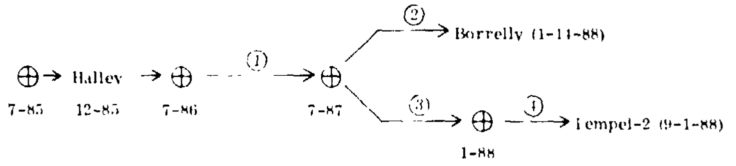


Figure 9. Halley Pre-Perihelion Intercept with Earth Return

Table 7
Alternative Mission Profiles Following the Pre-Perihelion Halley Intercept



Earth Swingbys

Swingby Date	Perigee (Earth Radii)	Bend Angle (Degrees)	Heliocentric Inclination After Swingby (Degrees)
① July 22, 1986	1.56	42.9	11.8
② July 22, 1987	1.57	12.7	14.2
③ July 22, 1987	3.17	25.6	16.3
④ January 19, 1988	4.72	17.5	15.1

Cometary Encounters

Encounter Date	Sun Distance (AU)	Earth Distance (AU)	Phase Angle (Degrees)	Flyby Speed (Km/sec)
Ⓑ January 11, 1988	1.39	0.68	91.1	21.1
(T2) September 1, 1988	1.39	0.91	78.3	15.5

variations are given in Appendix B. Complete trajectories for both options are depicted in Figure 10. Note the similarity of the encounter locations with respect to the sun-earth line.

A pre-perihelion intercept trajectory with an earth return two years after launch is also possible. Details of this trajectory, which includes retargeting options to comets Borrelly and Reinmuth-1, are given in Appendix C. This mission profile was not considered to be as attractive as the one-year earth-return case mainly because the aphelion distance for the two-year earth-return trajectory is 2.2 AU, which is rather large.

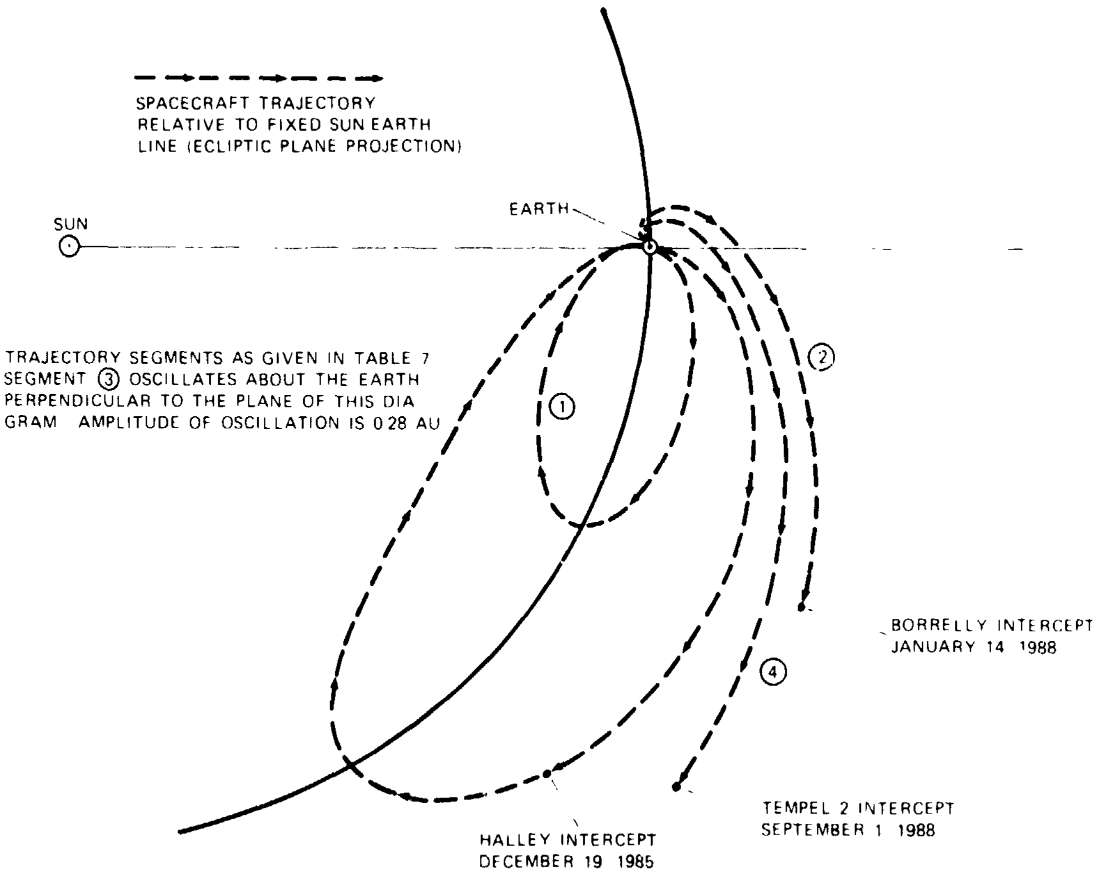


Figure 10. Alternative Spacecraft Trajectories following the Pre-Perihelion Halley Intercept

2. Post-Perihelion Encounter. The earth-return trajectory for the post-perihelion Halley intercept is shown in Figure 11. Summaries of the alternative mission profiles to Borrelly and Tempel-2 are given in Table 8. Comparison of Tables 7 and 8 shows that the flyby speeds for the Borrelly and Tempel-2 encounters are somewhat lower for the trajectories associated with the post-perihelion Halley intercept. The trajectory options listed in Table 8 are illustrated in Figure 12. Variations of the key mission parameters for a ten-day launch window are given in Appendix B.

Two additional mission alternatives are possible with the post-perihelion Halley intercept. These possibilities, which feature intercepts of comet Encke in September 1987 and comet Pons-Winnecke in August 1989, are discussed in Appendix C. The Encke and Pons-Winnecke alternatives are distinctly inferior to the Borrelly and Tempel-2 mission options.

IV. POSSIBLE SCENARIOS

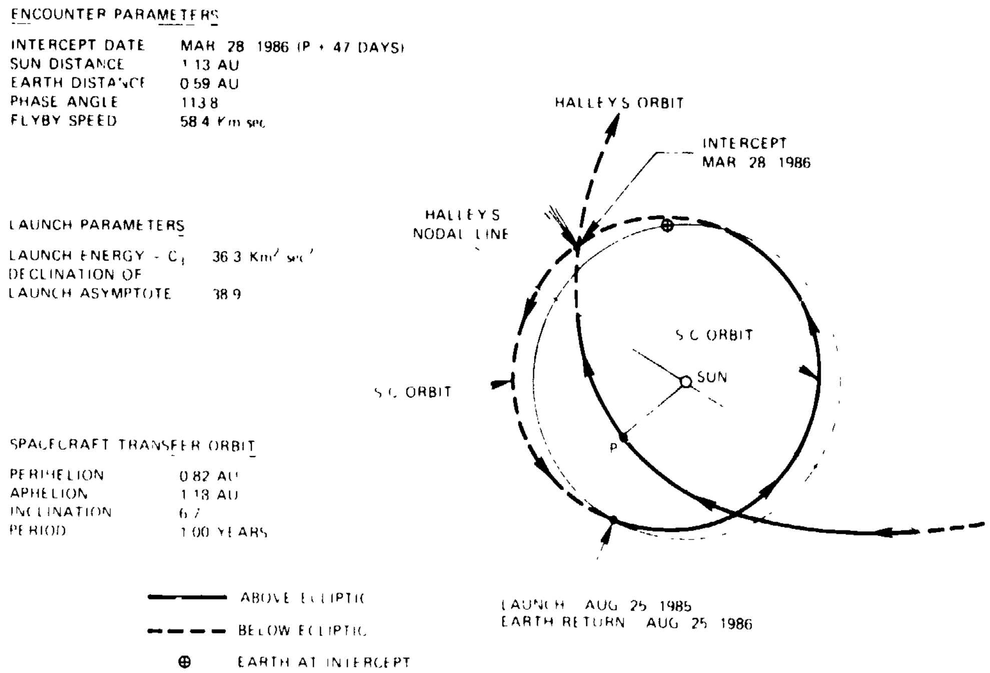
Numerous mission strategies could be formulated with the trajectory alternatives described in the last section. Four particularly interesting possibilities are listed here. Briefly, the four plans are:

1. A dual launch in July 1985 with pre- and post-perihelion Halley intercepts. This plan is outlined in Figure 5 and Table 3. Launch requirements can be satisfied by a single Shuttle with two spin-stabilized upper stages.

2. A dual launch in March 1985 with a pre-perihelion Halley intercept and a multiple encounter mission to comets Giacobini-Zinner and Borrelly. This mission is summarized in Table 4. A single Shuttle with two spin-stabilized upper stages will satisfy launch requirements.

3. A single launch in July 1985 with a pre-perihelion Halley intercept followed by an encounter with comet Borrelly (see Table 7). The July mission would be augmented by another solo launch in August 1985 that would include a post-perihelion Halley intercept followed by an encounter with comet Tempel-2 (see Table 8). This plan would require two Shuttle launches with appropriate IUS stages.

4. A dual launch in August 1985 with both spacecraft targeted for post-perihelion encounters with Halley. One spacecraft would pass close to the nucleus and the other would enter the tail region as shown in Figure 3. Both spacecraft would then return to earth. One would be retargeted to comet Borrelly and the other would be sent to comet Tempel-2 (see Table 8). A simple Shuttle launch with one IUS stage would be sufficient.



ENCOUNTER PARAMETERS

INTERCEPT DATE	MAR 28 1986 (P + 47 DAYS)
SUN DISTANCE	1.13 AU
EARTH DISTANCE	0.59 AU
PHASE ANGLE	113.8
FLYBY SPEED	58.4 Km/sec

LAUNCH PARAMETERS

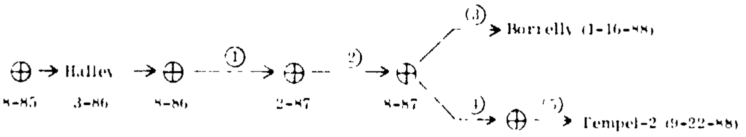
LAUNCH ENERGY - C_3	36.3 Km^2/sec^2
DECLINATION OF LAUNCH ASYMPTOTE	38.9

SPACECRAFT TRANSFER ORBIT

PERIHELION	0.82 AU
APHELION	1.18 AU
INCLINATION	6.7
PERIOD	1.00 YEARS

Figure 11. Halley Post-Perihelion Intercept with Earth Return

Table 8
Alternative Mission Profiles Following the Post-Perihelion Halley Intercept



Earth Swingbys

	Swingby Date	Perigee (Earth Radii)	Bend Angle (Degrees)	Heliocentric Inclination After Swingby (Degrees)
①	August 25, 1986	1.99	55.2	11.7
②	February 21, 1987	–	–	Standoff Encounter*
③	August 25, 1987	3.95	35.3	9.2
④	August 25, 1987	–	–	Standoff Encounter*
⑤	February 21, 1988	6.81	22.5	10.5

Cometary Encounters

	Encounter Date	Sun Distance (AU)	Earth Distance (AU)	Phase Angle (Degrees)	Flyby Speed (Km/sec)
(B)	January 16, 1988	1.40	0.70	90.0	17.7
(T2)	September 22, 1988	1.39	0.99	91.6	13.2

*Trajectory change is not required. Swingby is targeted to permit return to earth at next scheduled date.

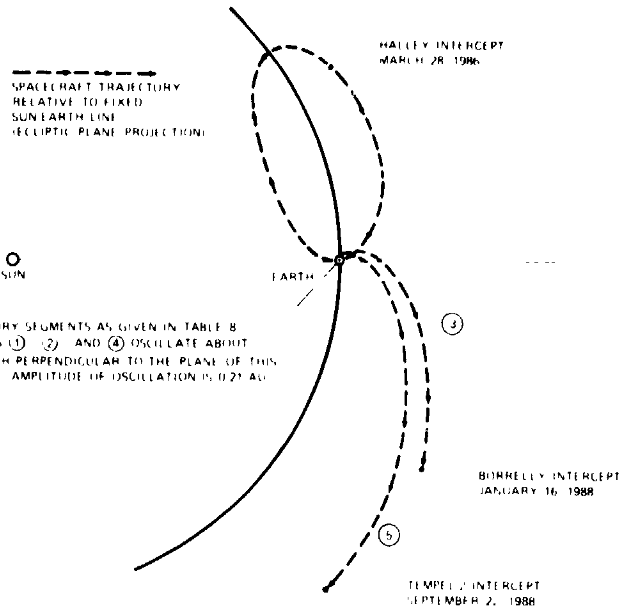


Figure 12. Alternative Spacecraft Trajectories following the Post-Perihelion Halley Intercept

All of the scenarios outlined above would require two cometary spacecraft. However, a simple spin-stabilized spacecraft that could function at heliocentric distances between 0.8 AU and 1.4 AU should easily satisfy the mission requirements. Additional cost savings could be realized by using a common spacecraft design. The inclusion of separate tail probes would be optional.

Plan #3 would be somewhat more expensive than the other mission strategies because two Shuttle launches would be required instead of only one. However, the science return would be maximized with this plan, and a high degree of redundancy and mission flexibility would also be attained. Four independent cometary intercepts including pre- and post-perihelion encounters with Halley would be achieved.

V. RELATIONSHIP TO PROPOSED RENDEZVOUS AND SLOW-FLYBY MISSIONS

Recently, two rather unorthodox schemes for a rendezvous with Halley's comet have been proposed. Both plans require advanced propulsion capability that seems to be feasible, but which has had little development thus far. Launches of spacecraft with these advanced propulsion systems would have to take place in early 1982 to achieve a rendezvous with Halley in 1985-86. One

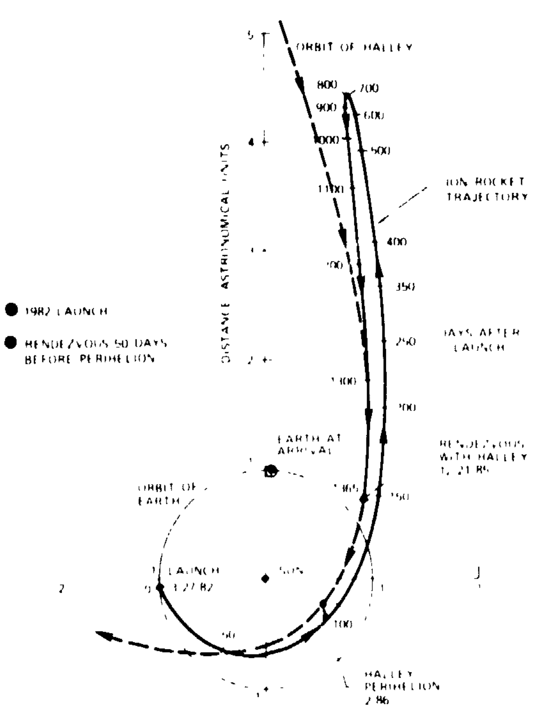


Figure 13. Halley Rendezvous Trajectory Using Ion Drive (from Reference 7)

concept uses an "Ion drive" system (advanced solar-electric propulsion) to produce a rendezvous with Halley about 50 days before perihelion (Reference 7). The mission profile for this plan is illustrated in Figure 13. The other concept calls for a "solar sail" measuring 800 meters on a side to provide the propulsion that is needed to match Halley's retrograde orbit (Reference 8). Unfortunately, the solar-sail technique would not accomplish the rendezvous until about 50 days after Halley's perihelion passage.

Assuming that a Halley rendezvous mission using one of the propulsion systems mentioned above will be attempted in 1982 as planned, would there be any reason to schedule additional missions to Halley? It appears that this question can be answered in the affirmative, and that a supplementary ballistic mission to Halley should be considered for the following reasons:

1. Complementary Science. A rendezvous mission would conduct an intensive study of Halley's nuclear and inner coma regions. Correlative data from a ballistic flyby through Halley's tail would contribute significantly to the interpretation of the rendezvous measurements. The same would be true for imaging and photometric data that would be obtained by the ballistic spacecraft while the rendezvous spacecraft is located in the vicinity of the nucleus. The experiments carried on the ballistic spacecraft would also

be quite different, and would emphasize plasma properties, solar-wind interaction, and dust composition. Finally, the ballistic spacecraft will intercept additional comets after its encounter with Halley

2. International Participation. The ballistic mission mode would be relatively inexpensive and advanced technology would not be required. Therefore, it would be easier for other nations to participate in this component of a Halley program. Conceivably, the ballistic spacecraft could be built by some other nation with the United States providing the Shuttle launch capability.

3. Fail-Safe Strategy. Because of the many risks and uncertainties associated with the advanced propulsion systems that would be used in the rendezvous mission, a backup ballistic mission would increase the chances of at least a partially successful Halley mission. Another Halley opportunity will not occur again until 2062, and it would be wise to provide some redundancy for the 1985-86 apparition.

If, for some reason, the development of the advanced propulsion technology takes somewhat longer than expected, it has been suggested that the rendezvous mission should be replaced by a "slow" flyby of Halley at about 15 km/sec (References 8 and 9). This slow-flyby mission, which would be launched in 1983, would still need the full propulsion capability required by the 1982 rendezvous mission. In the opinion of the present authors, this proposal just does not make sense. First of all, the advantage of a slower flyby speed at Halley does not appear to justify the greatly increased complexity and risk of the slow-flyby mission when compared to a simple and reliable ballistic flyby. As discussed in Section II, the science return from a Halley flyby mission would not be degraded substantially by higher flyby speeds. Secondly, the ballistic missions would be able to intercept additional comets (at flyby speeds from 13 → 21 km/sec). Therefore, it could be argued that the total science return would be greater for the ballistic mission mode. Finally, it should be stressed that the cost for a ballistic Halley mission involving two spacecraft (e.g., plan #3 of Section IV) would still be considerably less expensive than the slow-flyby proposal.

VI. CONCLUDING REMARKS

It has been shown that a high-velocity ballistic intercept of Halley's comet would yield a large amount of fundamental and valuable scientific data on the nature of cometary phenomena. Several outstanding mission alternatives have been identified, and possible implementation schemes have been discussed. One particularly attractive plan would require only two spacecraft (probably of identical design) to carry out pre- and post-perihelion encounters with Halley as well as intercepts of two additional comets.

The high potential for international participation in the Halley mission should also be mentioned. Excellent observing conditions for the Halley encounters will allow the international community of astronomers to play an active and important role in this mission. Cooperative projects such as Spacelab and the Space Telescope would also contribute. For instance, a dedicated Spacelab flight with an ultraviolet-optical-infrared astronomy payload could be scheduled during the post-perihelion encounter when Halley is very bright. In addition, other nations could provide instrumentation for some of the in-situ experiments and could even furnish cometary spacecraft and/or tail probes.

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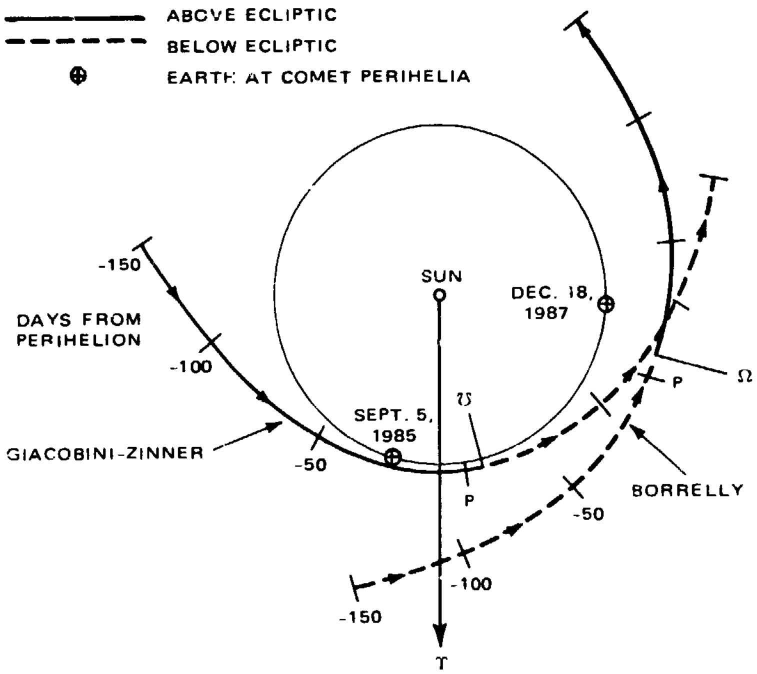
APPENDIX A

Orbital and Physical Characteristics of Secondary Comet Targets

Orbital parameters of four comets that are cited in Section III as candidate mission targets are given in Figures A-1 and A-2. Physical characteristics of these comets are summarized in Tables A-1 to A-4.



ORBITAL ELEMENTS FOR GIACOBINI-ZINNER AND BORRELLY (EQUINOX 1950.0)

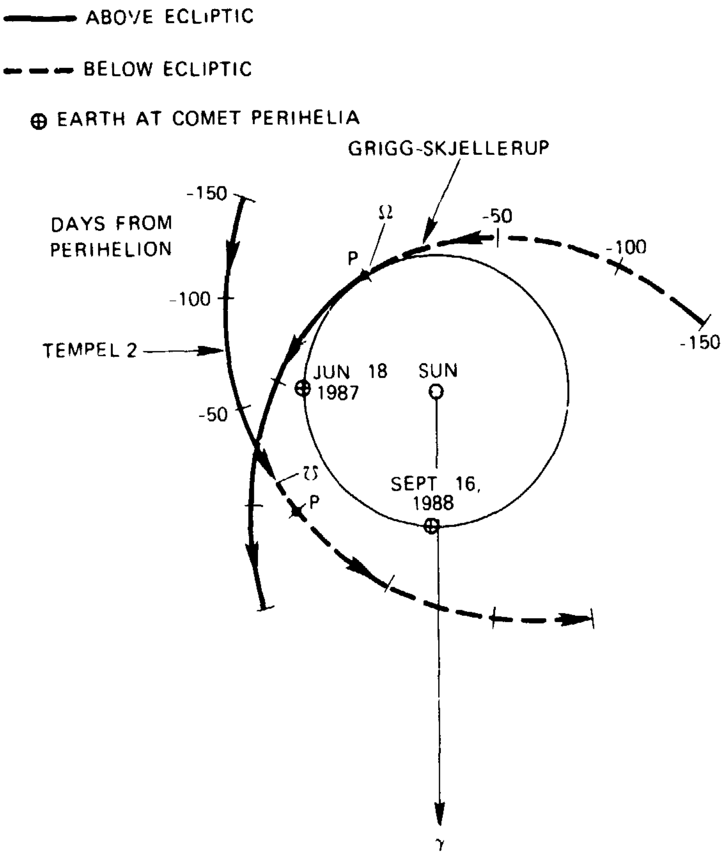
GIACOBINI-ZINNER

EPOCH	1985 SEPT. 12.0
T	1985 SEPT. 5.69583
q	1.0282459 AU
e	0.7075535
Ω	194.70649°
ω	172.48534°
i	31.87811°

BORRELLY

EPOCH	1987 DEC. 11.0
T	1987 DEC. 18.26830
q	1.3567347 AU
e	0.6242364
Ω	74.74641°
ω	353.32292°
i	30.32392°

Figure A-1. Orbits of Comets Giacobini-Zinner and Borrelly



ORBITAL ELEMENTS FOR GRIGG-SKJELLERUP AND TEMPEL-2 (EQUINOX 1950 0)

GRIGG-SKJELLERUP

EPOCH	1987 MAY 25 0
T	1987 JUN. 18.04286
q	0.9933182 AU
e	0.6647083
Ω	212 62759
ω	359 31778
i	21 10630

TEMPEL-2

EPOCH	1988 OCT 6 0
T	1988 SEPT 16.75124
q	1 3834317
e	0.5444299
Ω	119 11838
ω	191 04133
i	12 43174

Figure A-2. Orbits of Comets Grigg-Skjellerup and Tempel-2

Table A-1
Comet Giacobini-Zinner Summary

Observational History: Giacobini-Zinner has been observed at nine apparitions since its discovery in 1900. Because of unfavorable orbital geometry it was poorly observed at two apparitions (1940, 1966) and missed completely in 1907, 1920, and 1953. However, numerous observations of its behavior near perihelion were obtained in 1946, 1959, and 1972 when it passed relatively close to the earth. Giacobini-Zinner is one of the brightest periodic comets when it is near perihelion. It is noteworthy that the absolute luminosity of this comet appears to be constant or even increasing with time. Irregular brightness variations over periods of a few days have been reported.

Nuclear Region and Coma: A well-defined nuclear condensation develops near perihelion. Observations in 1972 suggest that Giacobini-Zinner possesses an inner and outer coma. The observable diameter of the outer coma is $\sim 5 \times 10^4$ km, while the diameter of the inner coma is about 2×10^4 km. The spectrum of Giacobini-Zinner shows a strong continuum which indicates a large dust component. The abundances of CN and C_2 radicals have been compared with Encke, and it was found that while the abundance of CN was approximately equal in both comets, the abundance of C_2 was greater for Encke.

Tail: A narrow straight tail begins to develop about three months prior to perihelion. Near perihelion, the observed tail length is $\sim 5 \times 10^5$ km. A dust tail has also been reported.

Dust: Giacobini-Zinner is quite dusty for a short-period comet. Its dust density is estimated to be about 50 times greater than Encke's but is probably 1000 times smaller than Halley's. The Giacobinid (or Draconid) meteor showers that are associated with Giacobini-Zinner have probably been the most spectacular meteor displays of the present century. These showers were particularly strong in 1933 and 1946. Studies of the 1946 shower indicate that the Giacobinid meteors are abnormally fragile as compared with meteors from other showers.

Nongravitational Effects on Orbital Motion: A rigorous investigation by Yeomans (Reference 10) has shown that Giacobini-Zinner's nongravitational forces have increased with time over the 1900-1965 interval. (This unusual characteristic is shared with Biela's comet which disappeared in 1852). The orbital motion of Giacobini-Zinner is somewhat erratic as indicated by the 1972 observations which imply that the nongravitational forces have decreased or stopped altogether. An apparent discontinuity in the comet's motion between 1959 and 1965 should also be noted.

Table A-2
Comet Borrelly Summary

Observational History: Borrelly has been observed at nine apparitions since its discovery in 1904. Excellent orbital geometry during its first four apparitions (1905, 1911, 1918, 1925) produced a large number of observations. However, a perturbation by Jupiter in 1936 changed Borrelly's period, and the geometric conditions for near-perihelion observations have been poor ever since that time. Borrelly was not observed at all in 1939 and 1946. Fortunately, another perturbation by Jupiter in 1972 has again changed Borrelly's period so that favorable orbital geometry will be available in 1981 and 1987. From the numerous early observations, it has been well-established that Borrelly is quite active for a comet with a perihelion distance of about 1.4 AU.

Nuclear Region and Coma: A bright nuclear condensation has always been observed when favorable geometric conditions have existed. The observable coma diameter is $\sim 5 \times 10^4$ km. No spectroscopic observations have been reported.

Tail: A narrow bright tail has been observed during six of the apparitions, and generally persists for several months. Observed tail lengths are $\sim 5 \times 10^5$ km.

Dust: No data available.

Nongravitational Effects on Orbital Motion: The nongravitational forces affecting the motion of Borrelly have been investigated by Yeomans (Reference 10). It was found that although Borrelly is affected by substantial nongravitational forces, the transverse component of the nongravitational acceleration has remained constant over the entire 70-year observational interval.

Table A-3
Comet Grigg-Skjellerup Summary

Observational History: Grigg-Skjellerup was first observed in 1902. However, because of a close approach to Jupiter in 1905 and a poor determination of its initial orbit, it was not seen again until 1922. It has been observed at every return since then, making a total of 12 appearances from 1902 to 1972. Grigg-Skjellerup is an extremely faint comet, and the total number of recorded observations is rather small. Its earliest pre-perihelion recovery occurred at a heliocentric distance of only 1.23 AU. However, after perihelion in 1972 it was observed to a distance of 2.18 AU. Favorable orbital geometry for the 1977 return should provide the best opportunity for viewing this comet since 1942.

Nuclear Region and Coma: Near perihelion in 1972 Grigg-Skjellerup exhibited a fairly sharp nucleus that was located at the antisolar apex of a weak, fan-shaped coma. This feature is rather typical and is similar to comet Encke's appearance near 1 AU. To date, spectroscopic observations are nonexistent.

Tail: A tail has not been observed.

Dust: In 1967 and 1972 Grigg-Skjellerup passed within 0.004 AU of the earth's orbit at the comet's ascending node. Although the earth followed the comet to this area shortly afterward (97 and 51 days, respectively), anticipated meteor showers did not occur. These negative results are not conclusive, but do support an assumption that Grigg-Skjellerup's dust content is relatively low.

Nongravitational Effects on Orbital Motion: The nongravitational forces for Grigg-Skjellerup are extremely small. Their effect on the comet's orbit is well-understood as indicated by the fact that the predicted time of perihelion passage in 1972 was in error by less than 0.01 days.

Table A-4
Comet Tempel-2 Summary

Observational History: Tempel-2 has been observed at 15 apparitions since its discovery in 1873. Because of unfavorable orbital geometry, it was poorly observed at three apparitions (1904, 1915, and 1956) and missed completely in 1883, 1889, 1910, 1935, and 1941. Exceptionally good returns have occurred in 1899, 1925, and 1967 when the comet was near opposition at the time of its perihelion passage. Its relatively high intrinsic brightness in 1967 indicates that it is still very active. For its last five apparitions, Tempel-2 has been recovered at distances of more than two AU from both the earth and the sun.

Nuclear Region and Coma: Multiple nuclei were observed in 1873. However, only one nuclear condensation was present at the other apparitions. At various times, the nuclear condensation has been eccentrically located in the coma. Near perihelion, the observable diameter of the coma is 5×10^4 km. In 1925 Tempel-2 showed a weak continuous spectrum with high-intensity bands at 3883 (CN), 4033, and 4722 Angstroms. The continuous spectrum grew stronger near perihelion.

Tail: A broad, fan-shaped tail has been observed at eight apparitions. A dark rift in the tail was seen during the 1899 apparition. Near perihelion, the observed tail length is approximately 1.5×10^5 km. The tail persists for about three months around the time of perihelion passage.

Dust: Spectroscopic data indicate that a moderate dust content is present near perihelion.

Nongravitational Effects on Orbital Motion: The nongravitational forces for Tempel-2 are very small and have been well-behaved over the entire observational interval.

APPENDIX B

Launch-Window Variations for Multi-Comet Options

The multi-comet missions described in this report utilize earth-swingby maneuvers for trajectory modification. To employ an earth-swingby maneuver, the initial trajectory must return to earth after the first cometary encounter. If the time for the cometary intercept is fixed, there is only one launch date for a free earth-return trajectory. Other launch dates will require a moderate ΔV maneuver to return to earth. However, if the cometary intercept time can be varied, a range of launch dates for trajectories with free earth returns can be obtained.

To minimize the launch-energy requirement for the Giacobini-Zinner intercept, an encounter at the comet's nodal crossing point has been prescribed for all launch dates. Therefore, ΔV maneuvers will be needed to obtain a launch window. These maneuvers can be minimized by executing them about 60 days before the Giacobini-Zinner intercept. Maneuver requirements and other mission parameters connected with the Giacobini-Zinner mission profiles are listed in Table B-1.

The launch-energy requirement for Halley intercept trajectories with free earth returns is not very sensitive to small variations in the Halley encounter time. Therefore, the launch window for the Halley mission was obtained by simply varying the time of the Halley encounter. Parameter variations for a ten-day launch window are listed in Tables B-2 and B-3.

Table B-1
Ten-Day Launch Window for Giacobini-Zinner Intercept

	N - 5 Days	Nominal	N + 5 Days
Launch Date	3-5-85	3-10-85	3-15-85
Launch Energy -C_3 (Km^2/sec^2)	10.8	12.3	14.1
Decl. of Launch Asymp. (Degrees)	-5.8	-4.1	-2.5
Giacobini-Zinner Intercept Date	9-11-85	9-11-85	9-11-85
Sun Distance (AU)	1.03	1.03	1.03
Earth Distance (AU)	0.46	0.46	0.46
Phase Angle (Degrees)	88.1	87.9	87.8
Flyby Speed (Km/sec)	20.6	20.6	20.6
Earth-Return ΔV (m/sec)	113.3	-	126.0
Grigg-Skjellerup Option			
Earth Swingby Date	3-12-86	3-10-86	3-8-86
Perigee (Earth Radii)	4.37	4.18	4.00
Bend Angle (Degrees)	66.3	66.5	66.6
Grigg-Skjellerup Intercept Date	6-27-87	6-28-87	6-28-87
Sun Distance (AU)	1.00	1.00	1.00
Earth Distance (AU)	0.89	0.89	0.88
Phase Angle (Degrees)	97.7	98.0	98.4
Flyby Speed (Km/sec)	12.8	12.8	12.9
Borrelly Option			
First Earth Swingby Date	3-12-86	3-10-86	3-8-86
Perigee (Earth Radii)	70.24	64.05	58.59
Bend Angle (Degrees)	8.0	8.4	8.8
Second Earth Swingby Date*	8-21-87	8-20-87	8-18-87
Perigee (Earth Radii)	3.90	3.54	3.16
Bend Angle (Degrees)	69.9	72.2	74.8
Borrelly Intercept Date	12-28-87	12-25-87	12-23-87
Sun Distance (AU)	1.36	1.36	1.36
Earth Distance (AU)	0.55	0.53	0.52
Phase Angle (Degrees)	77.0	74.7	73.5
Flyby Speed (Km/sec)	17.3	17.3	17.4
Tempel-2 Option			
First Earth Swingby Date	3-12-86	3-10-86	3-8-86
Perigee (Earth Radii)	70.24	64.05	58.59
Bend Angle (Degrees)	8.0	8.4	8.8

Table B-1 (Continued)

	N - 5 Days	Nominal	N + 5 Days
Second Earth Swingby Date	8-21-87	8-20-87	8-18-87
Perigee (Earth Radii)	2.16	2.08	2.00
Bend Angle (Degrees)	90.4	90.4	90.4
Third Earth Swingby Date	2-17-88	2-15-88	2-14-88
Perigee (Earth Radii)	9.17	9.26	9.31
Bend Angle (Degrees)	41.5	40.1	38.9
Tempel-2 Intercept Date	9-12-88	9-12-88	9-12-88
Sun Distance (AU)	1.38	1.38	1.38
Earth Distance (AU)	0.95	0.95	0.95
Phase Angle (Degrees)	83.5	83.4	83.2
Flyby Speed (Km/sec)	11.6	11.7	11.7

*Powered swingby (ΔV = 16.0 m/sec) required for launch at N − 5 days.

Table B-2
Ten-Day Launch Window for Pre-Perihelion Halley Intercept

	N - 5 Days	Nominal	N + 5 Days
Launch Date	7-16-85	7-21-85	7-26-85
Launch Energy - C_3 (Km^2/sec^2)	69.4	69.4	70.1
Decl. of Launch Asymp. (Degrees)	-0.9	-1.5	-1.9
Halley Intercept Date	12-20-85	12-19-85	12-18-85
Sun Distance (AU)	1.19	1.20	1.22
Earth Distance (AU)	0.92	0.90	0.88
Phase Angle (Degrees)	66.2	65.4	64.7
Flyby Speed (Km/sec)	55.4	55.0	54.6
First Earth Swingby Date	7-17-86	7-22-86	7-27-86
Perigee (Earth Radii)	1.54	1.56	1.58
Bend Angle (Degrees)	43.4	42.9	42.3
Borrelly Option			
Second Earth Swingby Date	7-17-87	7-22-87	7-27-87
Perigee (Earth Radii)	1.57	1.57	1.57
Bend Angle (Degrees)	42.8	42.7	42.5
Borrelly Intercept Date	1-12-88	1-14-88	1-16-88
Sun Distance (AU)	1.39	1.39	1.40
Earth Distance (AU)	0.66	0.68	0.70
Phase Angle (Degrees)	90.4	91.1	91.7
Flyby Speed (Km/sec)	21.4	21.1	20.8
Tempel-2 Option			
Second Earth Swingby Date	7-17 [illegible]	7-22-87	7-27-87
Perigee (Earth Radii)	3.44	3.17	2.89
Bend Angle (Degrees)	24.0	25.6	27.3
Third Earth Swingby Date	1-15-88	1-19-88	1-24-88
Perigee (Earth Radii)	4.40	4.72	4.98
Bend Angle (Degrees)	18.5	17.5	16.6
Tempel-2 Intercept Date	8-29-88	9-1-88	9-5-88
Sun Distance (AU)	1.40	1.39	1.39
Earth Distance (AU)	0.90	0.91	0.92
Phase Angle (Degrees)	75.9	78.3	80.7
Flyby Speed (Km/sec)	15.6	15.5	15.5

Table B-3
Ten-Day Launch Window for Post-Perihelion Halley Intercept

	N - 5 Days	Nominal	N + 5 Days
Launch Date	8-20-85	8-25-85	8-30-85
Launch Energy -C_3 (Km^2/sec^2)	36.4	36.3	36.5
Decl. of Launch Asymp. (Degrees)	40.6	38.9	37.2
Halley Intercept Date	3-29-86	3-28-86	3-28-86
Sun Distance (AU)	1.14	1.13	1.12
Earth Distance (AU)	0.58	0.59	0.61
Phase Angle (Degrees)	114.2	113.8	113.3
Flyby Speed (Km/sec)	58.1	58.4	58.7
First Earth Swingby Date	8-20-86	8-25-86	8-30-86
Perigee (Earth-Radii)	1.98	1.99	2.00
Bend Angle (Degrees)	55.3	55.2	54.9
Second Earth Swingby Date*	2-16-87	2-21-87	2-26-87
Borrelly Option			
Third Earth Swingby Date	8-20-87	8-25-87	8-30-87
Perigee (Earth Radii)	4.17	3.95	3.65
Bend Angle (Degrees)	33.9	35.3	37.2
Borrelly Intercept Date	1-16-88	1-16-88	1-17-88
Sun Distance (AU)	1.40	1.40	1.40
Earth Distance (AU)	0.69	0.70	0.70
Phase Angle (Degrees)	90.0	90.0	90.0
Flyby Speed (Km/sec)	18.0	17.7	17.3
Tempel-2 Option			
Third Earth Swingby Date*	8-20-87	8-25-87	8-30-87
Fourth Earth Swingby Date	2-16-88	2-21-88	2-26-88
Perigee (Earth Radii)	6.99	6.81	6.53
Bend Angle (Degrees)	21.9	22.5	23.2
Tempel-2 Intercept Date	9-19-88	9-22-88	9-25-88
Sun Distance (AU)	1.38	1.39	1.39
Earth Distance (AU)	0.98	0.99	1.00
Phase Angle (Degrees)	89.5	91.6	93.7
Flyby Speed (Km/sec)	13.4	13.2	13.1

*Standoff Encounter

APPENDIX C

Additional Mission Alternatives

The nominal trajectory for a pre-perihelion Halley intercept with an earth return two years after launch is shown in Figure C-1. Retargeting options to other comets and launch-window variations for this trajectory are given in Table C-1. Orbital parameters for comets Borrelly and Reinmuth-1 are furnished in Figures A-1 and C-2, respectively.

The post-perihelion Halley intercept with an earth return one year after launch can be retargeted to either comet Encke or comet Pons-Winnecke. The orbits for these comets are illustrated in Figures C-2 and C-3. Mission parameters for the retargeting options are listed in Tables C-2 and C-3. The Pons-Winnecke option has the same nominal launch date that was used for the mission profiles of Table 8. However, a different nominal launch date was chosen for the Encke option because ΔV maneuvers are required for earlier launch dates. It should also be noted that the launch window for the Encke option is further restricted by small perigee distances at later launch dates.

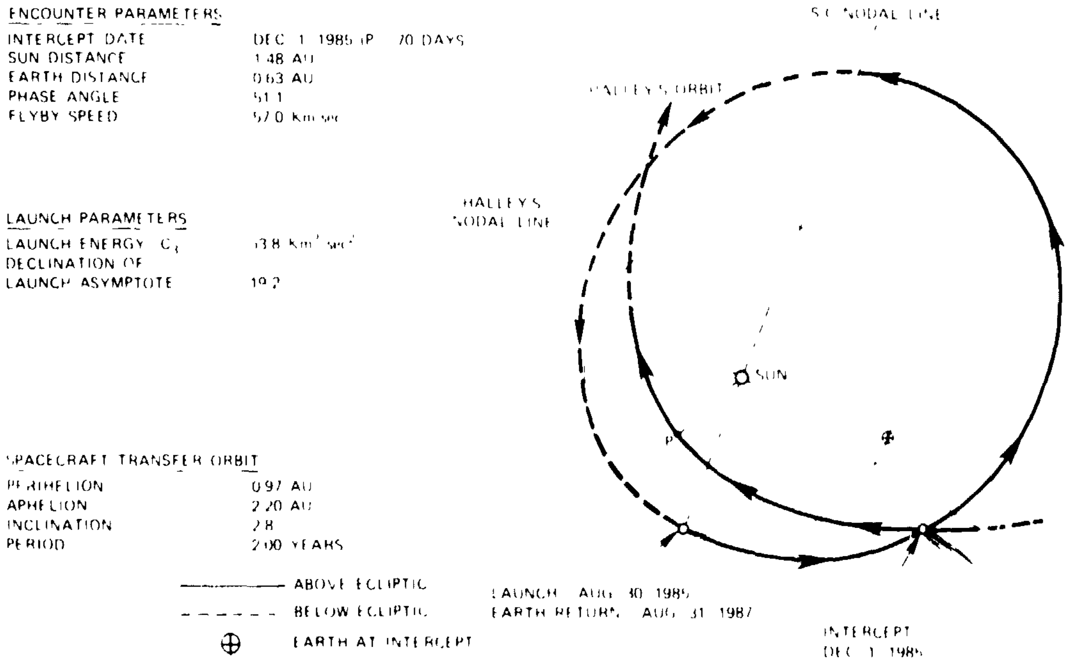
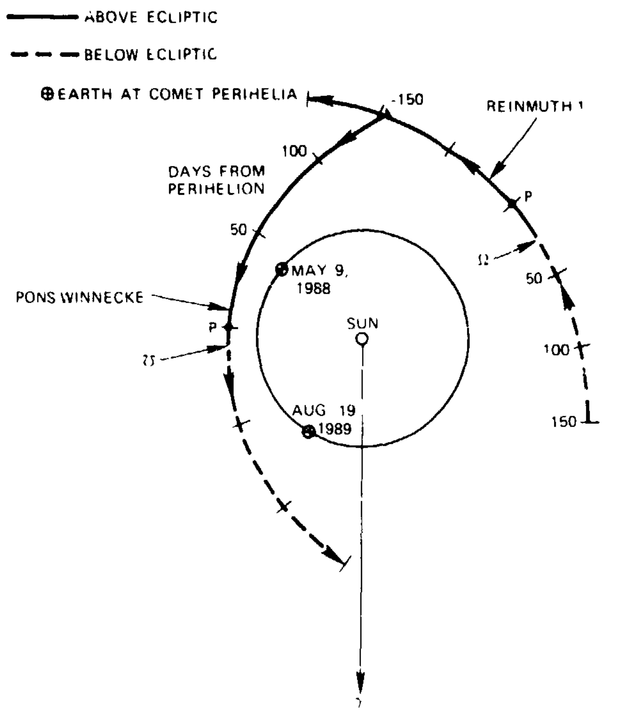


Figure C-1. Halley Pre-Perihelion Intercept with Two-Year Earth Return

Table C-1
Pre-Perihelion Halley Intercept with Two-Year Earth Return

	N - 5 Days	Nominal	N + 5 Days
Launch Date	8-25-85	8-30-85	9-4-85
Launch Energy -C_3 (Km^2/sec^2)	45.2	53.8	65.1
Decl. of Launch Asymp. (Degrees)	20.9	19.2	17.8
Halley Intercept Date	12-1-85	12-1-85	12-1-85
Sun Distance (AU)	1.48	1.48	1.48
Earth Distance (AU)	0.63	0.63	0.63
Phase Angle (Degrees)	51.4	51.1	50.8
Flyby Speed (Km/sec)	57.0	57.0	57.1
Earth-Return ΔV (m/sec)	–	–	60.1
Borrelly Option			
Earth Swingby Date	8-26-87	8-31-87	9-3-87
Perigee (Earth Radii)	1.70	1.34	1.12
Bend Angle (Degrees)	53.2	55.2	56.6
Borrelly Intercept Date	1-20-88	1-23-88	1-26-88
Sun Distance (AU)	1.41	1.42	1.43
Earth Distance (AU)	0.73	0.76	0.79
Phase Angle (Degrees)	91.7	93.2	94.5
Flyby Speed (Km/sec)	17.8	17.6	17.4
Reinmuth-1 Option			
Earth Swingby Date	8-26-87	8-31-87	9-3-87
Perigee (Earth Radii)	1.82	1.37	1.11
Bend Angle (Degrees)	51.1	54.6	56.8
Reinmuth-1 Intercept Date	5-19-88	5-28-88	6-3-88
Sun Distance (AU)	1.87	1.88	1.88
Earth Distance (AU)	2.31	2.37	2.42
Phase Angle (Degrees)	80.8	85.9	89.5
Flyby Speed (Km/sec)	10.7	10.8	11.0



ORBITAL ELEMENTS FOR
PONS WINNECKE AND
REINMUTH 1 (EQUINOX 1950 0

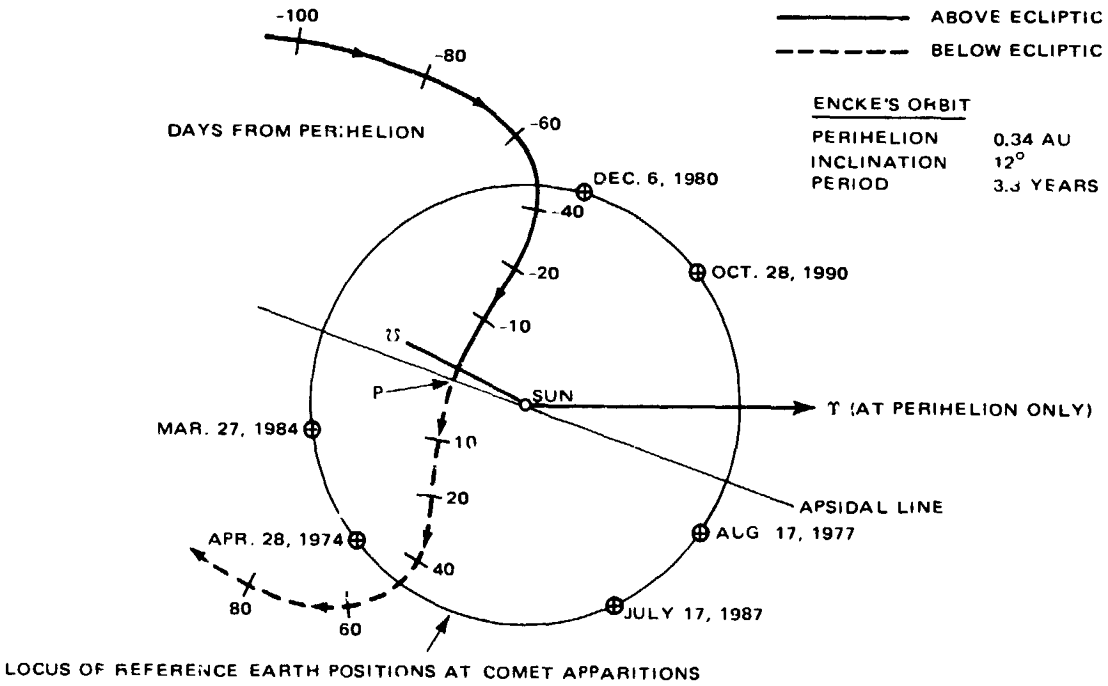
PONS-WINNECKE

EPOCH	1989 AUG 22 0
T	1989 AUG 19 8577
q	1 260979 AU
e	0 633506
Ω	92 7477
ω	172 3237
i	22 2731

REINMUTH 1

EPOCH	1988 APR 29 0
T	1988 MAY 9 09058
q	1 8697385 AU
e	0 5029966
Ω	119 18154
ω	13 00104
i	8 14016

Figure C-2. Orbits of Comets Reinmuth-1 and Pons-Winnecke



ENCKE'S ORBIT

PERIHELION	0.34 AU
INCLINATION	12°
PERIOD	3.3 YEARS

Figure C-3. Orbit of Comet Encke in Bipolar Coordinates

Table C-2
Post-Perihelion Halley Intercept with Pons-Winnecke Option

	N - 5 Days	Nominal	N + 5 Days
Launch Date	8-20-85	8-25-85	8-30-85
Launch Energy -C_3 (Km^2/sec^2)	36.4	36.3	36.5
Decl. of Launch Asymp. (Degrees)	40.6	38.9	37.2
Halley Intercept Date	3-29-86	3-28-86	3-28-86
Sun Distance (AU)	1.14	1.13	1.12
Earth Distance (AU)	0.58	0.59	0.61
Phase Angle (Degrees)	114.2	113.8	113.3
Flyby Speed (Km/sec)	58.1	58.4	58.7
First Earth Swingby Date	8-20-86	8-25-86	8-30-86
Perigee (Earth Radii)	1.98	1.99	2.00
Bend Angle (Degrees)	55.3	55.2	54.9
Second Earth Swingby Date*	2-16-87	2-21-87	2-26-87
Third Earth Swingby Date	8-20-87	8-25-87	8-30-87
Perigee (Earth Radii)	3.21	5.09	13.63
Bend Angle (Degrees)	40.7	29.3	12.8
Fourth Earth Swingby Date	8-20-88	8-25-88	8-30-88
Perigee (Earth Radii)	1.88	1.79	1.38
Bend Angle (Degrees)	57.0	58.7	67.3
Pons-Winnecke Intercept Date	8-25-89	8-30-89	9-3-89
Sun Distance (AU)	1.26	1.27	1.27
Earth Distance (AU)	1.19	1.21	1.22
Phase Angle (Degrees)	113.3	116.0	117.8
Flyby Speed (Km/sec)	15.6	16.3	16.7

*Stand off Encounter

Table C-3
Post-Perihelion Haley Intercept with Encke Option

	N - 5 Days	Nominal	N + 5 Days
Launch Date	8-30-85	9-4-85	9-9-85
Launch Energy -C_3 (Km^2/sec^2)	36.5	37.1	38.1
Decl. of Launch Asymp. (Degrees)	37.2	35.5	33.8
Halley Intercept Date	3-28-86	3-27-85	3-26-85
Sun Distance (AU)	1.12	1.11	1.10
Earth Distance (AU)	0.61	0.62	0.64
Phase Angle (Degrees)	113.3	112.9	112.4
Flyby Speed (Km/sec)	58.7	58.9	59.3
Earth Swingby Date*	8-30-86	9-4-86	9-9-86
Perigee (Earth Radii)	1.81	1.38	1.03
Bend Angle (Degrees)	57.1	66.6	75.8
Encke Intercept Date	9-1-87	8-30-87	8-29-87
Sun Distance (AU)	1.06	1.03	1.01
Earth Distance (AU)	1.02	1.00	0.98
Phase Angle (Degrees)	166.5	166.1	165.8
Flyby Speed (Km/sec)	31.2	31.1	31.1

*Powered Swingby (ΔV = 130.6 m/sec) required for launch at N – 5 Days.