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OPPORTUNITIES FOR BALLISTIC MISSIONS TO HALLEY'S COMET

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16 Abstract

This document describes alternative strategies for ballistic missions to Halley's comet in 1985-86 and shows that a large scientific return would be acquired from a ballistic Halley intercept in spite of the high flyby speeds of almost 60 km/s 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 3-year period. One spacecraft would intercept Halley's comet 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 postperihelion Halley intercept in March 1986 before proceeding toward an encounter with comet Tempel-2 in September 1988. The flyby speeds for the Borrelly and Tempel-2 intercepts are 21 and 13 km/s, respectively.

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OPPORTUNITIES FOR BALLISTIC MISSIONS TO HALLEY'S COMET

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INTRODUCTION

The return of Halley's comet in 1985-86 will attract worldwide attention from both the general public and the astronomical community. Halley has been an unusually bright comet, and it has seldom gone unnoticed. Ancient Chinese records show observations of Halley's comet as early as 239 B.C. It is important historically because some of Halley's previous appearances have coincided with famous events, such as the siege of Jerusalem in 66 A.D., the defeat of Attila the Hun at Chalons in 451 A.D., and the Norman conquest of England in 1066 A.D. (figure 1). A brief summary of Halley's observational history and physical characteristics follows:

- Observational history. Halley's comet has been seen at every apparition since at least 86 B.C. (a total of 27 appearances), and was observed extensively during its 1910 apparition. It is a spectacular object displaying the physical characteristics of a typical long-period comet. Its exceptional brightness is indicated by the fact that

Figure 1. Halley's comet in 1066 as depicted on the Bayeux Tapestry.

naked-eye observations were recorded over a 4-month interval at its 1910 apparition. Brightness estimates 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 transited 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 postperihelion phase are $\sim 5 \times 10^4$ km for the inner coma and $\sim 3 \times 10^5$ 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.

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 the next section will show, the scientific return from a ballistic flyby

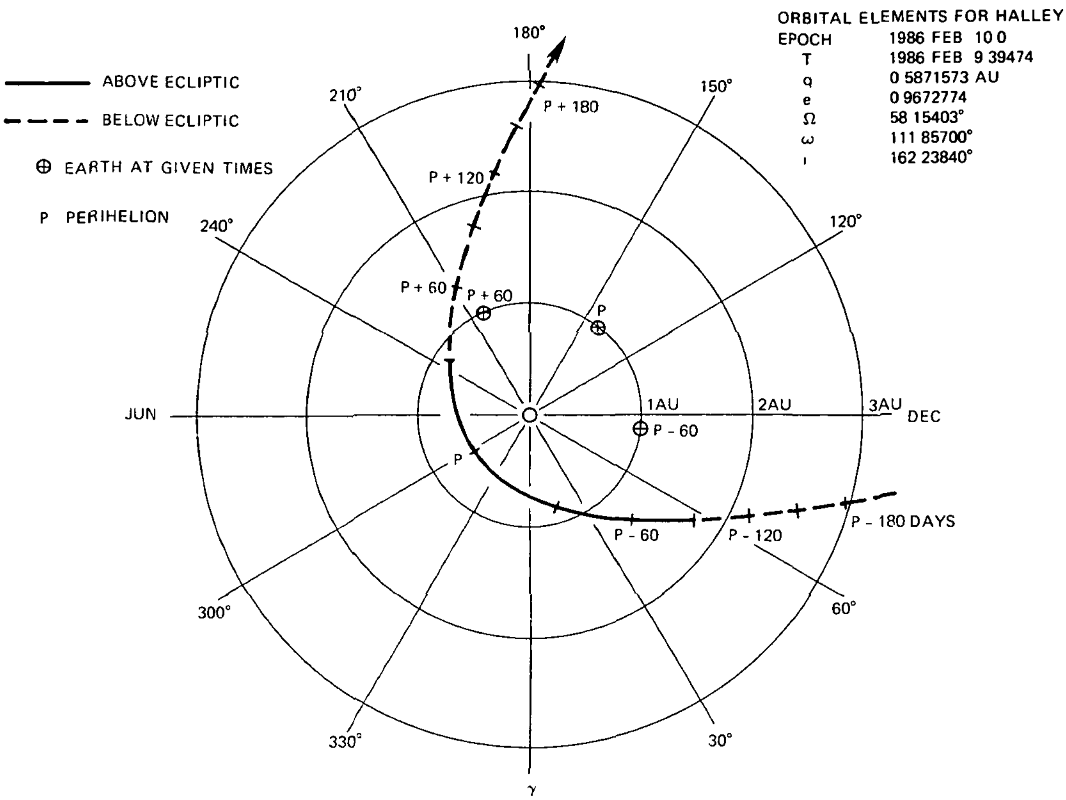


Figure 2. Orbit of Halley's comet.

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 document describes a variety of mission plans for ballistic flybys of Halley's comet, discusses the advantages and disadvantages of the various options, and presents specific recommendations.

SCIENCE OBJECTIVES AND EXPERIMENTS

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

*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.

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 scientific objectives of the Halley flyby are

- Imaging of the nuclear region at moderate resolution, determining the nature of the multiple nuclear condensations that have been observed in Halley's comet, attempting to confirm the postulated existence of a halo of icy grains surrounding the nuclear region, and measuring the sizes and shapes of the nuclear condensations
- Determining the abundance and spatial distribution of the neutral molecules and radicals in the coma
- Measuring the density, spatial distribution, and energy distribution of the charged particles in the coma and tail regions
- Investigating the properties of the cometary plasma and magnetic field
- Determining the nature of the solar-wind/comet interaction and finding the locations of the bow shock and the contact surface (if they exist)
- Surveying the characteristics of the dust grains, especially size distribution, spatial distribution, and composition
- Investigating 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 that higher intensities and better resolution are possible than those obtained from Earth.)

To properly study the large-scale features of Halley's comet, correlative measurements in the coma and tail regions are 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, 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.

Table 1 lists a representative scientific payload for a dual-probe Halley flyby. Although this list was intended to be a minimum payload, the experiment complement is sufficient for accomplishing all the scientific objectives listed previously. 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 1. 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/s. Furthermore, the neutral mass spectrometers now being developed for cometary missions would give good performance for flyby speeds from zero to 100 km/s. One version uses field ionization to generate singly-charged ions from ambient neutrals and

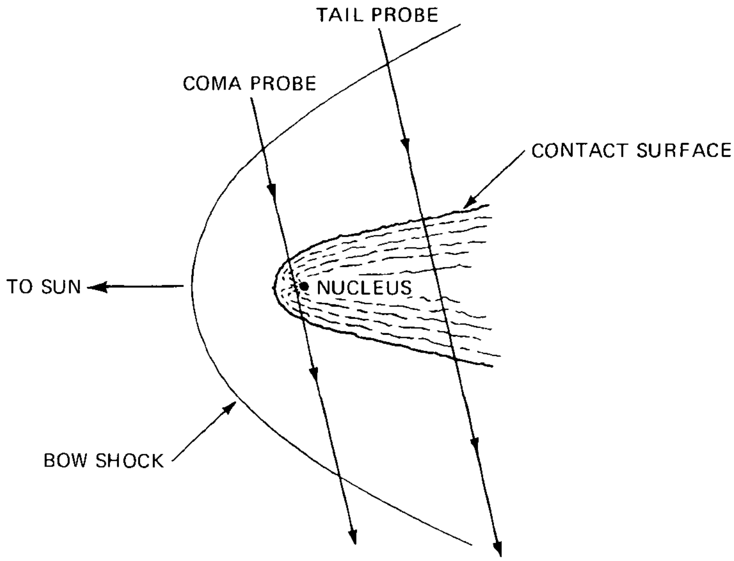


Figure 3. Dual-probe encounter geometry.

Table 1
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/s.
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/s.

applies a time-of-flight technique to determine the masses of the field ions.* Laboratory tests have demonstrated the feasibility of this concept, and a satisfactory flight instrument should be developed in time for the 1985-86 mission.

An important bonus of the ballistic Halley mission is the possibility of retargeting the spacecraft to another comet after the 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 those of Halley, and their physical characteristics are quite different (Appendix A). In general, the additional cometary encounters will have lower flyby speeds (13 → 21 km/s) and smaller miss distances (< 1000 km). Obviously, the scientific 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 significantly 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.

MISSION ALTERNATIVES

This section describes a number of attractive mission profiles for ballistic intercepts of Halley's comet. When comparing the relative merits of the alternative plans given in the following paragraphs, some attention should be given to.

- Encounter location. Spacecraft miss distances will be somewhat smaller in the preperihelion phase. For instance, estimated miss distances during the preperihelion 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, postperihelion encounters have the advantage that Halley's comet will probably be more active at this time.

- Encounter geometry. For early detection of solid nuclei, a small phase angle† is preferred. On the other hand, cross-sectional mapping of the cometary atmosphere is also desirable. Therefore, phase angles between 40° and 70° are probably optimal.

*K. C. Hsieh, "Report on the Time-of-Flight Field-Ionization Mass Spectrometer," presented to the Interplanetary Physics Science Working Group, January 1977.

†The phase angle is defined as the angle between the relative velocity vector at encounter and the Sun/comet line. A phase angle of 0° corresponds to an approach from the sunlit side of the nucleus.

- <u>Favorable geometry for Earth-based observations.</u> Encounters that take place close to the Earth and at large solar elongations are preferred.
- <u>Inclusion of additional targets in the mission profile.</u> If additional cometary intercepts can be carried out without major spacecraft modifications (e.g., excessive on-board propulsion capability), the mission will be very cost effective.
- <u>Mission cost and complexity.</u> 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 and 1.40 AU (i.e., 1.5 → 0.5 solar constants).

Because all missions discussed in this document 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 and 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. Note that the cost for a spin-stabilized upper stage will be approximately 20 percent of the price for the basic two-stage IUS.

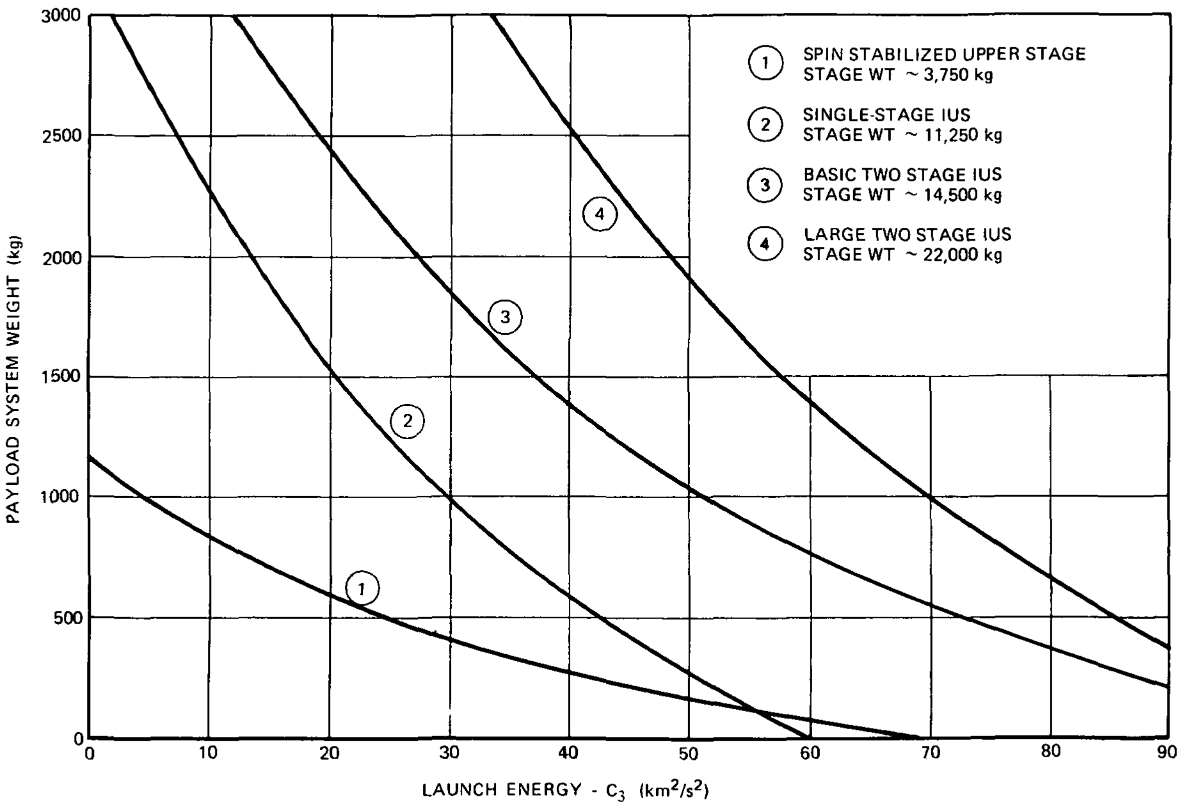


Figure 4 Payload capability of Shuttle with solid upper stage

Dual-launch Opportunities

It is possible to accommodate two independently-targeted interplanetary spacecraft with a single Shuttle launch by placing both spacecraft into an Earth parking orbit that contains the two required launch asymptotes. Each spacecraft can then be 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/s^2 for spacecraft weights of about 500 kg (figure 4). It is also beneficial, but not absolutely necessary, for the declinations of both launch asymptotes to be less than 55°.

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

Halley Preperihelion and Postperihelion Encounters

The beginning of July 1985 is the best time for a dual launch to Halley. At that time, the launch energies for both trajectories will be less than 15 km^2/s^2. Figure 5 shows the basic plan for the dual launch to Halley, and table 2 summarizes the nominal mission parameters. Note 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 preperihelion encounter could be used to optimize the targeting strategy for the postperihelion encounter.

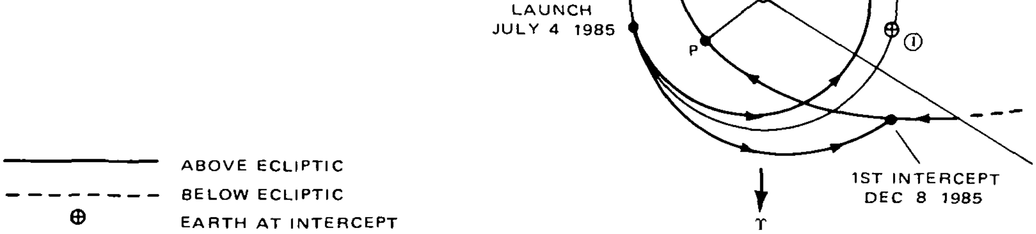


Figure 5. Dual launch to Halley's comet.

Table 2
Nominal Parameters for Dual Launch to Halley*

	Preperihelion Intercept (P -63 Days)	Postperihelion 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 (deg.)	57.7	112.2
Flyby speed (km/s)	55.3	64.5
Launch Parameters		
Launch energy–C_3 (km^2/s^2)	14.5	9.1
Declination of launch asymptote (deg.)	33.5	54.3
Spacecraft Transfer Orbit		
Perihelion (AU)	1.01	0.81
Aphelion (AU)	1.44	1.03
Inclination (deg.)	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 $< 15.1\ km^2/s^2$ for the preperihelion intercept and $< 9.4\ km^2/s^2$ for the postperihelion intercept.

Figure 6 shows the encounter geometries for both cases. Cross-sectional traverses occur in each instance, but the preperihelion encounter has a better phase angle. The geometry illustrated in figure 6 is similar to the other preperihelion and postperihelion Halley intercepts discussed in the following paragraphs.

Halley and Multicomet Mission

Another dual-launch opportunity will occur in March 1985. The nominal mission plan for this launch date is outlined in table 3. In this plan, one spacecraft will be targeted for a preperihelion encounter with Halley on December 13, 1985. The second spacecraft will be placed into a trajectory that will intercept comet Giacobini-Zinner on September 11, 1985, and return to the vicinity of the Earth on March 10, 1986. The Earth-return trajectory is shown in figure 7. Two Earth-swingby maneuvers will then be used to retarget the spacecraft toward an encounter with comet Borrelly on December 25, 1987. Details of these maneuvers are shown in figure 8. In May 1975, this mission was reviewed by the Comet

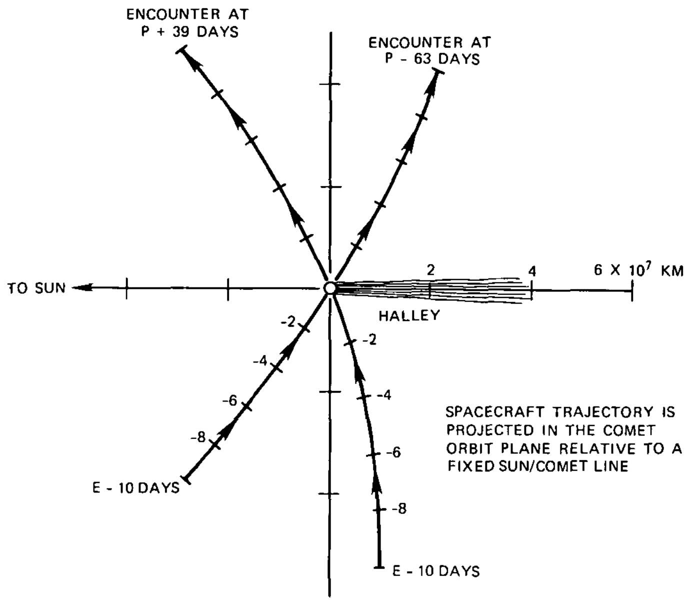


Figure 6. Halley encounter geometry.

Table 3
Dual-launch Multicomet Mission

Launch date: March 10, 1985

Launch vehicle: Shuttle with two spin-stabilized upper stages

Spacecraft 1: Intercept Halley at P-58 days
- Launch energy-C_3: 22.2 km^2/s^2
- Declination of launch asymptote: -51.7°

Spacecraft 2: Intercept Giacobini-Zinner and Borrelly
- Launch energy-C_3: 12.3 km^2/s^2
- Declination of launch asymptote: -4.1°

Encounter Date	Sun Distance (AU)	Earth Distance (AU)	Flyby Speed (km/s)
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

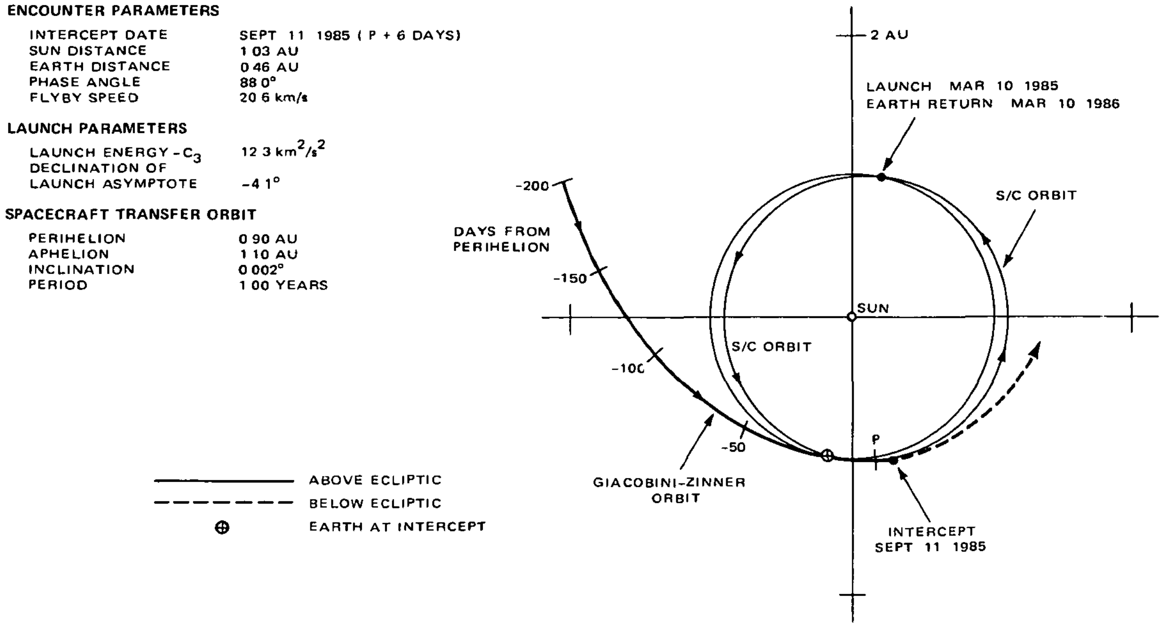


Figure 7. Giacobini-Zinner intercept with Earth-return.

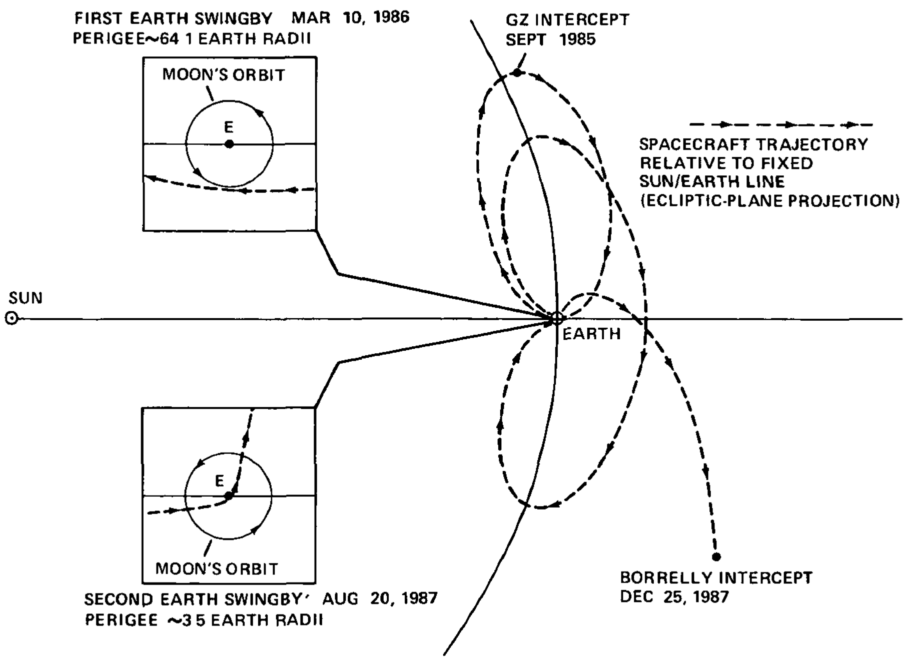
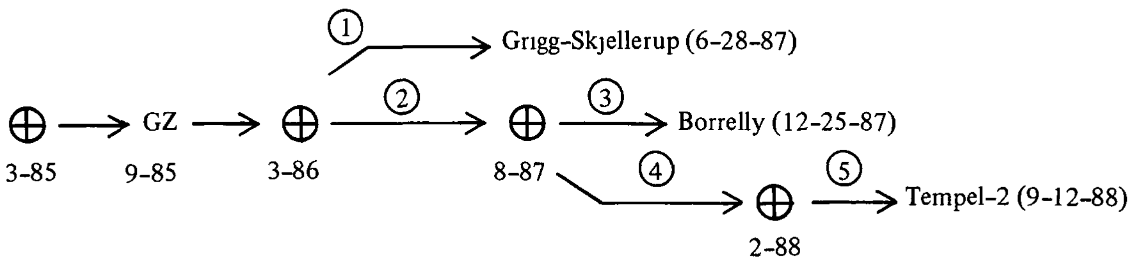


Figure 8. Spacecraft trajectory for multiple encounter mission to Giacobini-Zinner and Borrelly.

Working Group (sponsored by the National Aeronautics and Space Administration) and received its 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 5.

Recently, two alternative mission profiles for the multicomet mission have been found. The alternative profiles use different Earth-swingby maneuvers to retarget the spacecraft to either comet Grigg-Skjellerup or comet Tempel-2 instead of comet Borrelly. Table 4 presents details of these profiles, and Appendix B describes variations in mission parameters for all these options over a 10-day launch window.

Table 4
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/s)
GS	June 28, 1987	1.00	0.89	98.0	12.8
B	December 25, 1987	1.36	0.53	74.7	17.3
T2	September 12, 1988	1.38	0.95	83.4	11.7

Halley Intercept with Earth Return

Earth-return trajectories that include a Halley intercept are also possible. Table 5 lists launch dates of Earth-return trajectories for both preperihelion and postperihelion 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 5 will return to Earth approximately 1 year after launch.

To minimize the launch-energy requirement, nominal launch dates of July 21, 1985, for the preperihelion intercept and August 25, 1985, for the postperihelion intercept were selected. With the Earth-swingby technique, it is possible to retarget both of these trajectories to either Borrelly in January 1988 or to Tempel-2 in September 1988. The total mission duration of these encounters would be about 3 years, which is quite reasonable.

Preperihelion Encounter

Figure 9 shows the trajectory for the preperihelion Halley intercept with Earth-return, and table 6 summarizes alternative mission profiles to Borrelly and Tempel-2. Appendix B contains launch-window variations. Figure 10 shows complete trajectories for both options. Note the similarity of the encounter locations with respect to the Sun/Earth line.

Table 5
Launch Dates for Halley Intercept with Earth-Return

Launch Parameters			Halley Encounter Parameters				
Launch Date	Launch Energy (km^2/s^2)	Declination of Launch Asymptote (degrees)	Intercept Date	Sun Distance (AU)	Earth Distance (AU)	Phase Angle (degrees)	Flyby Speed (km/s)
Preperihelion 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
Postperihelion Encounter							
6-26-85	70.5	53.2	4-4-86	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	45.3	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	18.3	3-18-86	0.96	0.86	107.0	64.3

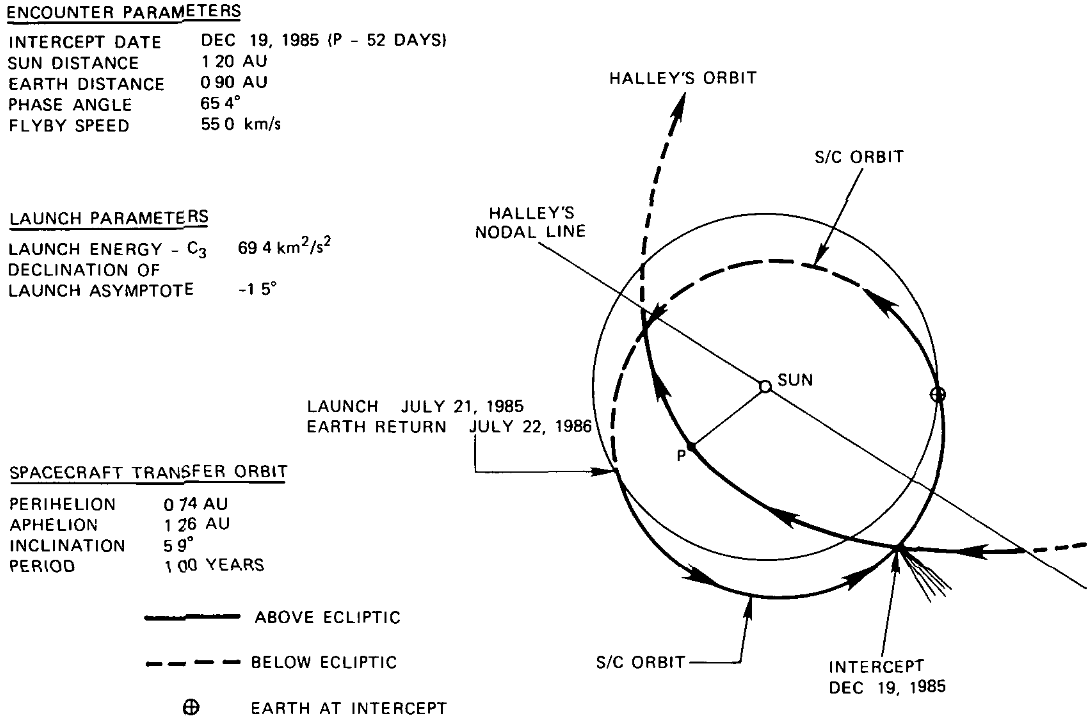
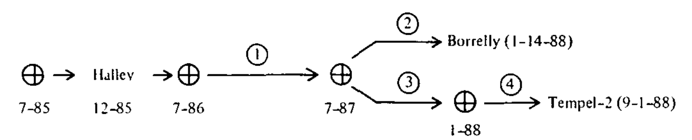


Figure 9. Halley preperihelion intercept with Earth-return.

Table 6
Alternative Mission Profiles Following the Preperihelion 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	14 8
② July 22 1987	1 57	42 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/s)
(B) January 14, 1988	1 39	0 68	91 1	21 1
(T2) September 1, 1988	1 39	0 91	78 3	15 5

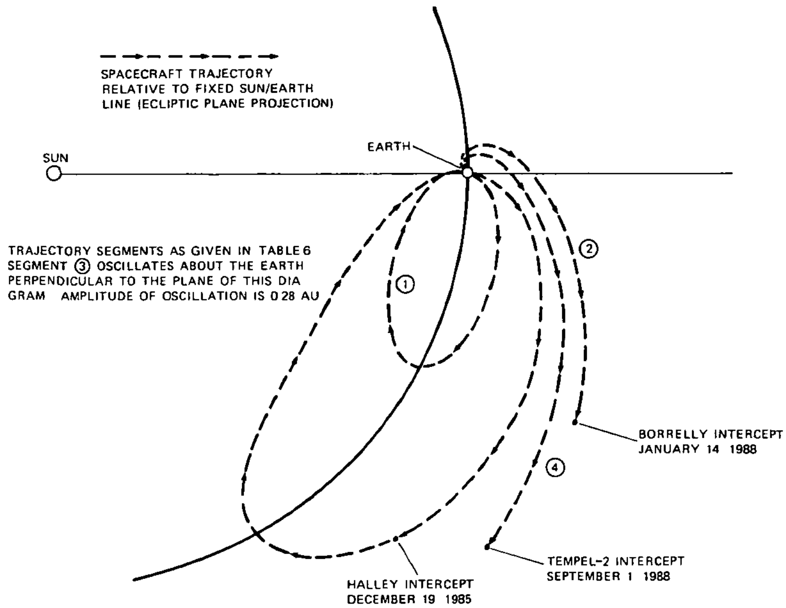


Figure 10. Alternative spacecraft trajectories following the preperihelion Halley intercept.

A preperihelion intercept trajectory with an Earth-return 2 years after launch is also possible. Appendix C contains details of this trajectory, which includes retargeting options to comets Borrelly and Reinmuth-1. This mission profile is not considered to be as attractive as the 1-year Earth-return case mainly because the aphelion distance for the 2-year Earth-return trajectory is 2.2 AU, which is rather large.

Postperihelion Encounter

Figure 11 shows the Earth-return trajectory for the postperihelion Halley intercept. Table 7 summarizes the alternative mission profiles to Borrelly and Tempel-2. A comparison of tables 6 and 7 shows that the flyby speeds for the Borrelly and Tempel-2 encounters are somewhat lower for the trajectories associated with the postperihelion intercept. Figure 12 illustrates the trajectory options listed in table 7. Appendix B contains variations of the key mission parameters for a 10-day launch window.

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

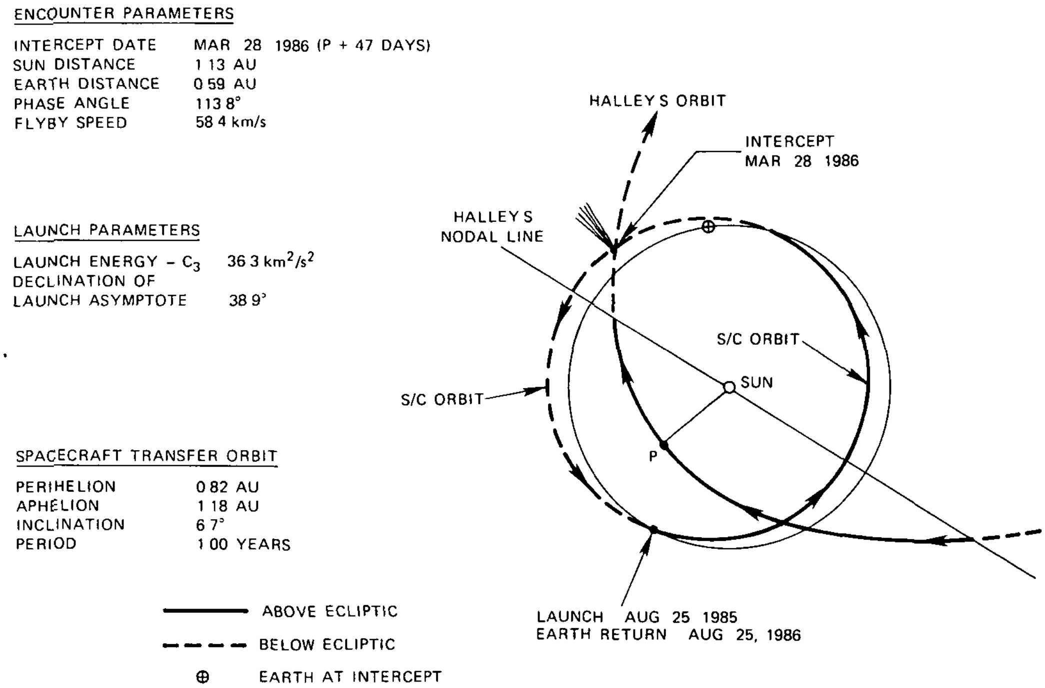
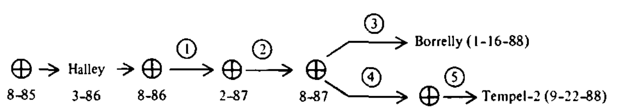


Figure 11. Halley postperihelion intercept with Earth-return.

Table 7
Alternative Mission Profiles Following the Postperihelion 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/s)
Ⓑ 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

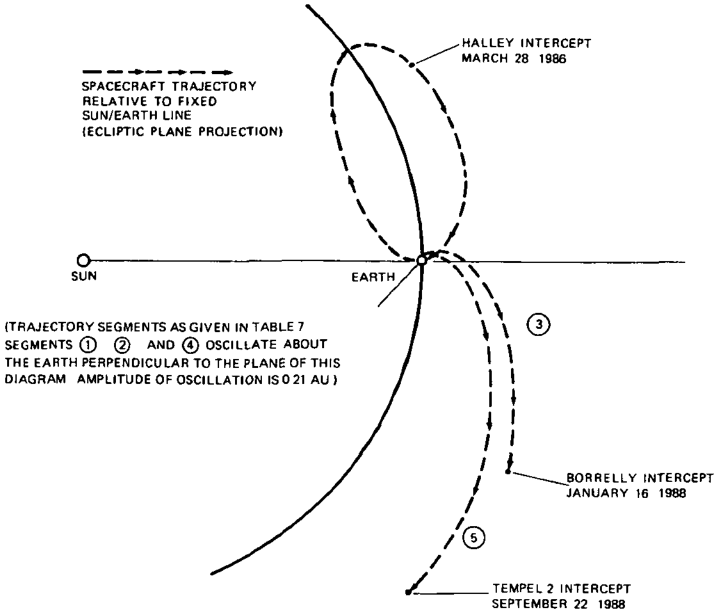


Figure 12. Alternative spacecraft trajectories following the postperihelion Halley intercept.

POSSIBLE SCENARIOS

Numerous mission strategies could be formulated with the trajectory alternatives described in the previous section. Four particularly interesting possibilities are:

- A dual launch in July 1985 with preperihelion and postperihelion Halley intercepts. This plan is outlined in figure 5 and table 2. Launch requirements can be satisfied by a single Shuttle with two spin-stabilized upper stages.
- A dual launch in March 1985 with a preperihelion Halley intercept and a multiple-encounter mission to Giacobini-Zinner and Borrelly. Table 3 summarizes this mission. A single Shuttle with two spin-stabilized upper stages will satisfy launch requirements.
- A single launch in July 1985 with a preperihelion Halley intercept, followed by a Borrelly encounter. (See table 6.) The July mission would be augmented by another solo launch in August 1985 that would include a postperihelion Halley intercept, followed by a Tempel-2 encounter. (See table 7.) This plan would require two Shuttle launches with appropriate IUS stages.
- A dual launch in August 1985 with both spacecraft targeted for postperihelion 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 Borrelly, and the other would be sent to Tempel-2. (See table 7.) A single Shuttle launch with one IUS stage would be sufficient.

All of the scenarios previously outlined would require two cometary spacecraft. However, a simple spin-stabilized spacecraft that could function at heliocentric distances between 0.8 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.

The third alternative would be somewhat more expensive than the other mission strategies because two Shuttle launches would be required rather than one. However, with this plan, the scientific return would be maximized, and a high degree of redundancy and mission flexibility would be attained. Four independent cometary intercepts including preperihelion and postperihelion encounters with Halley would be achieved.

RELATIONSHIP TO PROPOSED RENDEZVOUS AND SLOW-FLYBY MISSIONS

Recently, two highly unusual schemes for a rendezvous mission to Halley's comet have been proposed (References 6 through 8). Both plans will require advanced propulsion capability that may 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 concept uses an "ion-drive" system (advanced solar-electric propulsion) to produce a rendezvous with Halley about 50 days before perihelion (Reference 6). Figure 13 shows the mission profile. 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 7). Unfortunately, the solar-sail technique would not be capable of accomplishing the rendezvous until about 50 days *after* Halley's perihelion passage.

Assuming that a Halley rendezvous mission using one of the propulsion systems previously mentioned 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:

- 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. This would be true of 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.

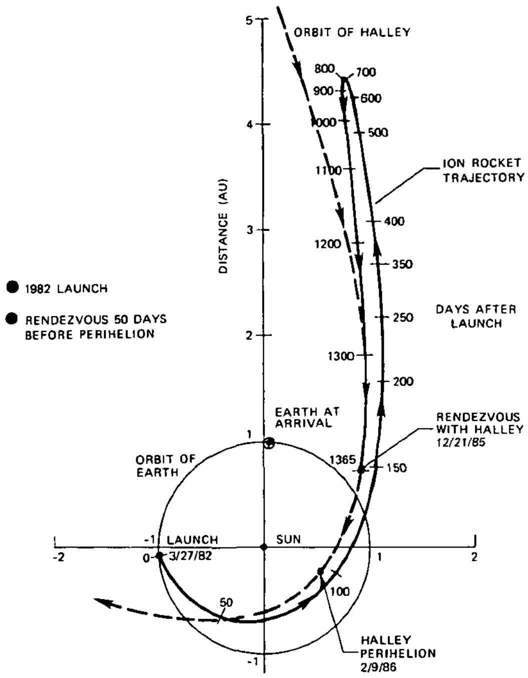


Figure 13. Rendezvous trajectory of Halley's comet, using ion drive (from Reference 6).

- 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 another nation, with the United States providing the Shuttle launch capability.

- 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. Because another Halley opportunity will not occur until 2062, provision for some redundancy for the 1985-86 apparition would be wise.

If, for some reason, the development of the advanced propulsion technology takes longer than expected, it has been suggested that the rendezvous mission be replaced by a "slow" flyby of Halley at about 15 km/s (Reference 7). 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 authors, this proposal 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 the section on "Science Objectives and Experiments," the scientific 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/s). Therefore, it could be argued that the total scientific 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., third alternative of the "Possible Scenarios" section) would still be considerably less expensive than the slow-flyby proposal.

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 described. One particularly attractive plan would require only two spacecraft (probably of identical design) to carry out preperihelion and postperihelion 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 permit 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 postperihelion 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 or tail probes.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, June 1977

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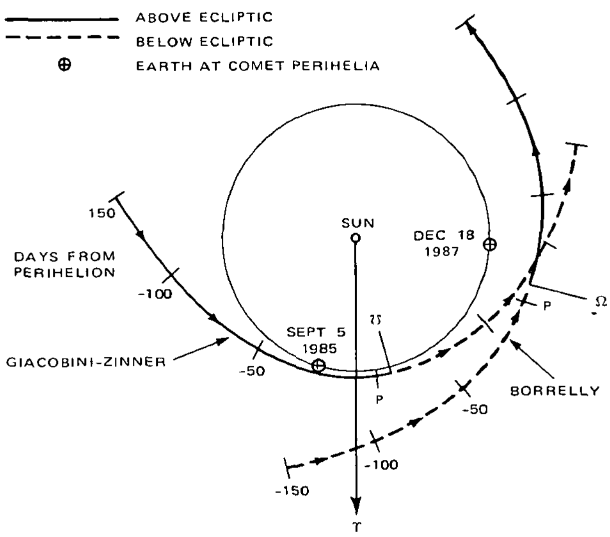
APPENDIX A

ORBITAL AND PHYSICAL CHARACTERISTICS OF SECONDARY COMET TARGETS

Figures A-1 and A-2 show the orbital parameters of four comets that are cited in the "Mission Alternatives" section of the main text as candidate mission targets. Physical characteristics of these comets are as follows

COMET GIACOBINI-ZINNER

- 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 and 1966) and was 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. When it is near perihelion, Giacobini-Zinner is one of the brightest periodic comets. 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.



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.

- Nuclear region and coma. A well-defined nuclear condensation develops near perihelion. Observations in 1972 suggest that Giacobini-Zinner possesses both an inner and an outer coma. The observable diameter of the outer coma is $\sim 5 \times 10^4$ km, and the diameter of the inner coma is about 2×10^4 km. The spectrum of Giacobini-Zinner shows a strong continuum that indicates a large dust component. The abundances of CN and C_2 radicals have been compared with Encke, and, although 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 3 months before 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 that of Encke, but it is probably 1000 times smaller than that of Halley. The Giacobinid (or Draconid) meteor showers that are associated with Giacobini-Zinner have probably been the most spectacular meteor displays of this century. These showers were particularly strong in 1933 and 1946. Studies of the 1946 shower indicate that the Giacobinid meteors are abnornally fragile compared to meteors from other showers.

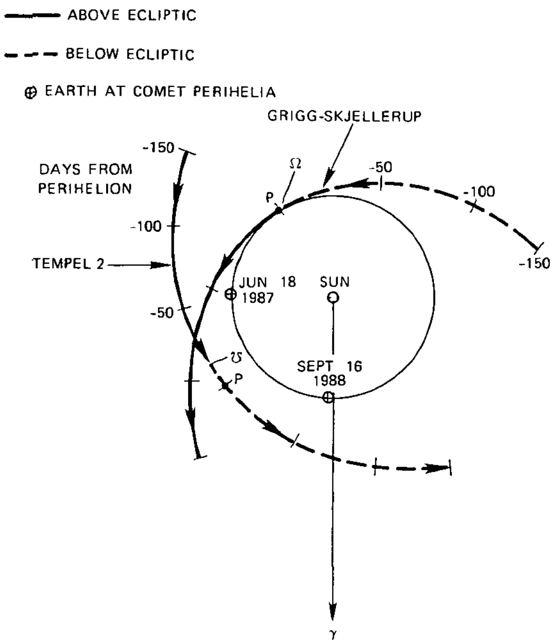
- Nongravitational effects on orbital motion. A rigorous investigation by Yeomans* has shown that Giacobini-Zinner's nongravitational forces have increased with time over the 1900 to 1965 interval. (This unusual characteristic is shared with Biela's comet, which disappeared in 1852.) The orbital motion 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.

COMET BORRELLY

- 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, and 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 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. Numerous early observations show 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 usually persists for several months. Observed tail lengths are ~ 5×10^5 km.
- Dust. No data are available.
- Nongravitational effects on orbital motion. The nongravitational forces that affect the motion of Borrelly have been investigated by Yeomans.* 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.



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.

COMET GRIGG-SKJELLERUP

- 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 each 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 preperihelion 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 since 1942 for viewing this comet.

*D. K. Yeomans, "Nongravitational Forces Affecting the Motions of Periodic Comets Giacobini-Zinner and Borrelly," *Astron. J.*, 76 (1), February 1971.

- 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 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. Although these negative results are not conclusive, they 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.

COMET TEMPEL-2

- 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 was 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 2 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 Å. 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 was approximately 1.5×10^5 km. The tail persists for about 3 months about 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 MULTICOMET OPTIONS

The multicomet missions described in the main text use 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 10-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/s^2)	10.8	12.3	14.1
Decl. of launch asymp. (deg.)	-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 (deg.)	88.1	87.9	87.8
Flyby speed (km/s)	20.6	20.6	20.6
Earth-return ΔV (m/s)	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 (deg.)	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 (deg.)	97.7	98.0	98.4
Flyby speed (km/s)	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 (deg.)	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 (deg.)	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 (deg.)	77.0	74.7	73.5
Flyby speed (km/s)	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 (deg.)	8.0	8.4	8.8

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

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 (deg.)	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 (deg.)	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 (deg.)	83.5	83.4	83.2
Flyby speed (km/s)	11.6	11.7	11.7

Table B-2
Ten-Day Launch Window for Preperihelion 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/s^2)	69.4	69.4	70.1
Decl. of launch asymp. (deg.)	−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 (deg.)	66.2	65.4	64.7
Flyby speed (km/s)	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 (deg.)	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 (deg.)	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 (deg.)	90.4	91.1	91.7
Flyby speed (km/s)	21.4	21.1	20.8
Tempel-2 Option			
Second Earth swingby date	7-17-87	7-22-87	7-27-87
Perigee (Earth radii)	3.44	3.17	2.89
Bend angle (deg.)	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 (deg.)	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 (deg.)	75.9	78.3	80.7
Flyby speed (km/s)	15.6	15.5	15.5

Table B-3
Ten-Day Launch Window for Postperihelion 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/s^2)	36.4	36.3	36.5
Decl. of launch asymp. (deg.)	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 (deg.)	114.2	113.8	113.3
Flyby speed (km/s)	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 (deg.)	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 (deg.)	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 (deg.)	90.0	90.0	90.0
Flyby speed (km/s)	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 (deg.)	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 (deg.)	89.5	91.6	93.7
Flyby speed (km/s)	13.4	13.2	13.1

*Standoff encounter.

APPENDIX C

ADDITIONAL MISSION ALTERNATIVES

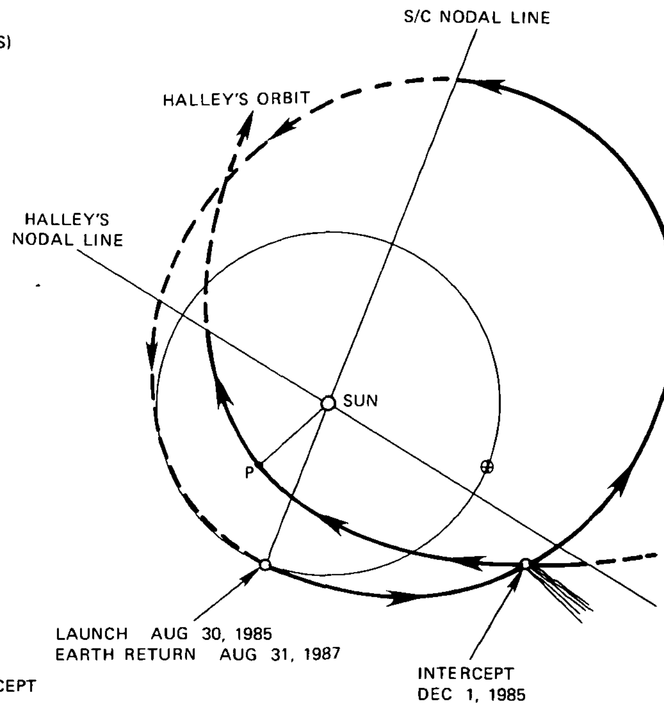
Figure C-1 shows the nominal trajectory for a preperihelion Halley intercept with an Earth-return 2 years after launch. Table C-1 lists the retargeting options to other comets and launch-window variations for this trajectory. Figures C-2 and C-3 show orbital parameters for comets Borrelly and Reinmuth-1, respectively.

The postperihelion Halley intercept with an Earth-return 1 year after launch can be retargeted to either comet Encke or comet Pons-Winnecke. The orbits for these comets are illustrated in figures C-3 and C-4. 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 7 of the main text. However, a different nominal launch date was chosen for the Encke option because ΔV maneuvers are required for earlier launch dates. Note also that, at later launch dates, the launch window for the Encke option is further restricted by small perigee distances.

ENCOUNTER PARAMETERS	
INTERCEPT DATE	DEC 1, 1985 (P - 70 DAYS)
SUN DISTANCE	1 48 AU
EARTH DISTANCE	0 63 AU
PHASE ANGLE	51 1°
FLYBY SPEED	57 0 km/s

LAUNCH PARAMETERS	
LAUNCH ENERGY -C_3	53 8 km^2/s^2
DECLINATION OF LAUNCH ASYMPTOTE	19 2°

SPACECRAFT TRANSFER ORBIT	
PERIHELION	0 97 AU
APHELION	2 20 AU
INCLINATION	2 8°
PERIOD	2 00 YEARS

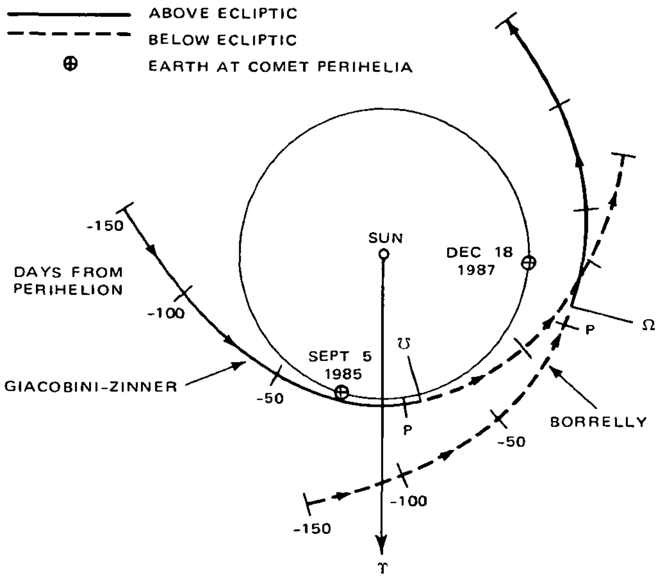


———— ABOVE ECLIPTIC
– – – – – – BELOW ECLIPTIC
⊕ EARTH AT INTERCEPT

Figure C-1. Halley preperihelion intercept with 2-year Earth-return.

Table C-1
Preperihelion Halley Intercept with 2-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/s^2)	45.2	53.8	65.1
Decl. of launch asymp. (deg.)	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 (deg.)	51.4	51.1	50.8
Flyby speed (km/s)	57.0	57.0	57.1
Earth-return ΔV (m/s)	–	–	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 (deg.)	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 (deg.)	91.7	93.2	94.5
Flyby speed (km/s)	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 (deg.)	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 (deg.)	80.8	85.9	89.5
Flyby speed (km/s)	10.7	10.8	11.0



ORBITAL ELEMENTS FOR GIACOBINI-ZINNER AND BORRELLY (EQUINOX 1950 0)

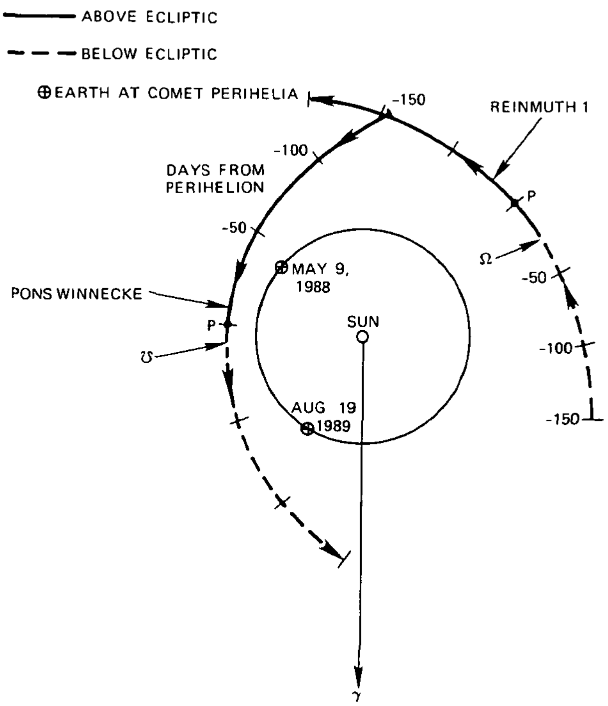
GIACOBINI-ZINNER

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 C-2. Orbits of comets Giacobini-Zinner and Borrelly.



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

PONS-WINNECKE

EPOCH	1989 AUG 22 0
T	1989 AUG 19 8577
REF	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 16154°
ω	13 00104°
i	8 14016°

Figure C-3. Orbits of comets Reinmuth-1 and Pons-Winnecke.

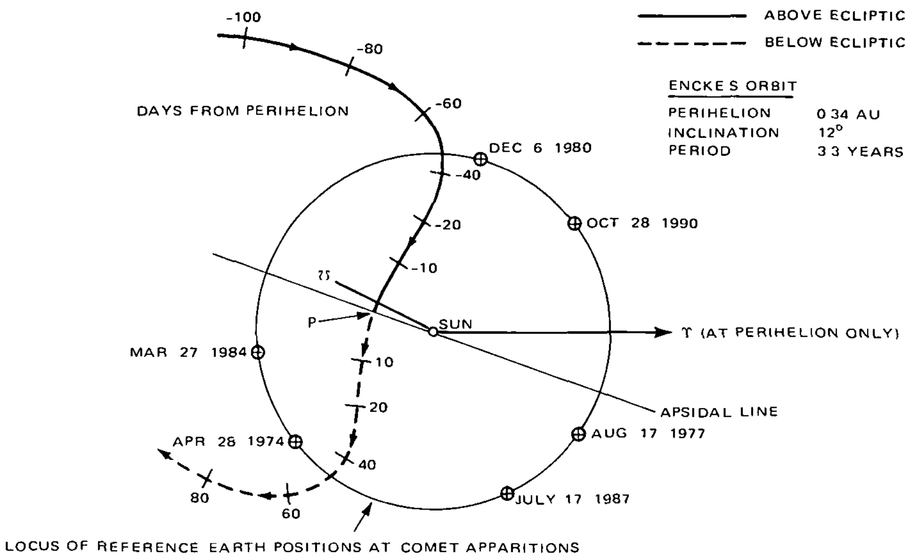


Figure C-4. Orbit of comet Encke in bipolar coordinates.

Table C-2
Postperihelion 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/s^2)	36.4	36.3	36.5
Decl. of launch asymp. (deg.)	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 (deg.)	114.2	113.8	113.3
Flyby speed (km/s)	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 (deg.)	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 (deg.)	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 (deg.)	57.0	58.7	67.3

*Standoff encounter.

Table C-2 (Continued)

	N - 5 Days	Nominal	N + 5 Days
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 (deg.)	113.3	116.0	117.8
Flyby speed (km/s)	15.6	16.3	16.7

Table C-3
Postperihelion Halley 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/s^2)	36.5	37.1	38.1
Decl. of launch asymp. (deg.)	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 (deg.)	113.3	112.9	112.4
Flyby speed (km/s)	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 (deg.)	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 (deg.)	166.5	166.1	165.8
Flyby speed (km/s)	31.2	31.1	31.1

*Powered swingby (ΔV = 130.6 m/s) required for launch at N - 5 Days.

NASA-Langley, 1977

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