MISSION STRATEGY FOR COMETARY EXPLORATION IN THE 1980's

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I. INTRODUCTION

Ballistic intercept missions to comets have been strongly endorsed as the best way to initiate a program of cometary exploration (Roberts, 1971). This mission mode is the simplest and least expensive, and can provide a large science return. Currently, a near-perihelion intercept of Encke's comet in 1980 is receiving serious consideration for the initial cometary mission. Assuming that the 1980 Encke mission will be carried out as planned, a question that should be considered is: what is the next logical step in an evolutionary sequence of cometary missions? Two possibilities are:

- Investigate a particular comet in detail. That is, perform a rendezvous mission.

- Study the physical characteristics of several types of comets. This goal could be achieved by carrying out a series of intercept missions to comets that have exhibited diverse behavior.

A rendezvous mission is the ultimate goal of a cometary exploration program. However, it is felt that the most effective strategy would be to accomplish the intercept missions before attempting a rendezvous mission. Some of the arguments in support of this position are:

- Because physical characteristics can vary substantially between different comets, a number of precursor flyby missions will be needed to optimize the selection of a rendezvous target. The precursor missions will also lead to a better definition of the science objectives for the rendezvous mission.

- Exceptional opportunities for intercept missions to comets Halley and Giacobini-Zinner will be available in 1985. It is hard to imagine a cometary survey that would not include these unique targets.

- Fiscal constraints will be easier to satisfy if the comet survey plan is adopted. The 1985 mission set, which is described below, could be accomplished with a common spacecraft design and minimal launch-vehicle costs. On the other hand, a rendezvous mission will require the development of a solar-electric propulsion module or a high-energy chemical stage.

The main purpose of this paper is to present a specific plan for a sequence of cometary intercept missions in the 1980's. Each mission will be described in detail, and the supporting role of ground-based cometary observations will also be discussed.

II. SCIENCE OBJECTIVES

A brief summary of the scientific objectives for a cometary intercept mission is given here. For the comets' nuclear and coma region, the principal scientific objectives are to:

- Determine the existence and nature of the cometary nucleus. If it does exist as a single coherent body, determine its size, shape, albedo, rotation rate, and surface features. Study the material ejection dynamics, and attempt to confirm the postulated existence of a halo of ice grains surrounding the nucleus.

- Describe the structure, composition, and motions of the cometary atmosphere. Establish the abundance, spatial distribution, kinematic behavior, and production rate of all those particles that are present in the coma with a particular emphasis on spatial resolution within the inner coma. The identity of the stable parent molecules must be known in order to understand how the unstable species (radicals) are formed.

- Determine the nature of the solar-wind, comet interaction. Two radically different types of interactions have been proposed. One model postulates a bow shock and contact surface analogous to those of the earth and its magnetosphere. The other suggests that the transition from supersonic to subsonic flow is continuous, is over a very broad region, and occurs without a bow shock.

- Study the basic mechanisms which produce ions and radicals. To fully understand the ionization processes, it will be necessary to measure the ion density, electron density, and energy distribution of charged particles within the coma. A survey of high-frequency electric and magnetic field fluctuations is also essential to determine the importance of particle-wave interactions.

- Determine the extent of the coma constituents as a function of heliocentric distance. Spectrophotometric measurements during the approach and departure phases will yield invaluable data on the time variation of the coma's structure including its hydrogen halo. The principal advantages of a comet probe for spectrophotometric experiments are higher intensities and spatial resolution.

- Survey the characteristics of dust grains. The size distribution, velocity distribution, and composition of dust particles are of particular interest.

Correlative measurements in the coma and tail regions are needed to fully understand cometary phenomena. In addition to the latter two items listed above, which should be extended to cover the tail region, there are two specific aims for tail experiments:

- Determine the physical origin of the ion tail. This includes the determination of where and how the tail materials become ionized and the flux of charged particles through the tail. The electron distribution should be determined. Direct measurements of mass per unit charge or energy per unit charge are also required.

- Study the properties of the plasma and magnetic field. Possibly establish whether or not the stylized variations of the tail structures (a) are associated with an imbedded magnetic field entrapped from the interplanetary medium, (b) are related to waves along the contact surface, or (c) are structures imbedded within the multiple neutral sheets that may exist in the cometary tail.

Experimental payloads for cometary space probes would include an imaging system, neutral and ion mass spectrometers, UV spectrometer, dust detector, impact ionization mass spectrometer, magnetometer, plasma analyzer, and an electron analyzer. Further details of possible experimental payloads can be found in the literature (e.g., Roberts, 1971; NASA, 1973).

III. TARGET SELECTION CRITERIA

Many factors are involved in forming a cometary mission sequence. From a scientific viewpoint, the two most important guidelines are:

- The mission set should be made up of different types of comets. For example, both gaseous and dusty comets should be represented. A comet that has displayed physical characteristics associated with long-period comets should also be included (Halley is the logical choice).

- Comets with a long history of prior observations are preferred. Spectroscopic measurements are particularly useful.

Application of these standards leads to a drastic reduction in the number of candidate comets. The list of good mission opportunities is further reduced by programmatic considerations. For instance, to allow sufficient time for design feedback, a time span of at least three years is needed between the first and second cometary mission.

In addition to the scientific and programmatic criteria just mentioned, there are several mission-related characteristics that are also significant. The most important parameters for cometary intercept missions are:

1. Relative velocity at encounter. A small "flyby speed" will maximize the time available for in situ measurements of the cometary atmosphere, reduce smear in imaging experiments, and minimize the probability of neutral-molecule impact fragmentation.

2. Targeting errors at encounter. A sufficiently small miss distance is essential for adequate science return from the imaging and mass spectrometer experiments.

3. Launch energy requirement (C_3). Total mission cost is directly related to the launch energy requirement. Small values of C_3 permit the use of smaller and less-expensive launch vehicles.

4. Heliocentric distrance at encounter. Comets are generally more active at smaller heliocentric distances.

5. Geocentric distance at encounter. Data rates are higher for smaller earth distances.

6. Encounter geometry. Cross-sectional mapping of the cometary atmosphere is preferred.

7. Earth-based sighting conditions before and during encounter. Adequate dark time is required to ensure effective ground-based observational support. Recovery should occur at least three months before encounter.

Because of a widespread misconception concerning the recovery requirement, a short explanation is in order. Several authors (e.g., Kresak, 1973) have stated that a pre-launch recovery and orbit improvement is needed to minimize midcourse propulsion requirements. However, it is easy to show that a midcourse correction of less than 100 m/sec applied three months before encounter will compensate for a priori errors in the comet's perihelion passage time of as much as 0.3 days. Therefore, a recovery three months before encounter appears to be acceptable.

IV. MISSION SEQUENCE

Using the selection criteria from the previous section, it soon becomes obvious that really good cometary mission opportunities are quite rare. Fortunately, outstanding opportunities exist for missions to Encke in 1980 and Giacobini-Zinner and Halley in 1985. In terms of scientific interest, prior observations, and diversity of physical behavior this group of comets is an optimum set. Furthermore, in most instances, the mission parameters are also satisfactory.

A. Encke, 1980

As mentioned earlier, there is general agreement that the first mission to a comet should be a near-perihelion intercept of Encke's comet in 1980. This mission was originally proposed by Farquhar and Ness (1972), and has recently been endorsed by the Space Science Board of the National Academy of Sciences. The principal features of the 1980 Encke mission are given below. For a more-comprehensive discussion, see Farquhar et al. (1974).

A short summary of Encke's physical characteristics is given in Table 1. The orbit of comet Encke is depicted in Figures 1 and 2. Note that Encke's perihelion is almost coincident with its descending node. The bipolar plot of Figure 2 shows Encke's motion with respect to a fixed sun-earth line for each apparition. With this plot, it is easy to verify that 1980 is a very good year for pre-perihelion observations of Encke.

The nominal mission profile is shown in Figure 3. A near-perihelion intercept was chosen because gas densities are highest in this region and the flyby speed is minimized here. Note that the launch occurs when the earth is almost coincident with Encke's nodal line. It is this condition that makes it possible for the spacecraft to follow a transfer trajectory in essentially the same plane as Encke's orbit, thereby reducing the out-of-plane component of the relative velocity vector. In Table 2, it can be seen that the flyby speed at encounter will be less than 9km/sec throughout a 10-day launch window.

Another aspect of the near-perihelion intercept strategy is that the spacecraft's orbital period almost exactly equals one-sixth Encke's period ($T_{ENCKE} \sim 6\ T_{S/C}$). Therefore, as shown in Table 2, only a small retargeting maneuver is needed to achieve a second encounter with Encke in 1984.*

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*A double encounter could also be accomplished by targeting for an intercept at P-19 days. In this case $T_{ENCKE} \sim 5\ T_{S/C}$, but the flyby speed would be about 21 km/sec.

Table 1

Comet Encke Summary

Observational History: Encke has been observed at more apparitions than any other comet. Since its discovery in 1786, it has been seen during fifty returns to perihelion, with only one apparition (1944) being missed after 1819. Due to Encke's 3.3-year period and its small perihelion distance, favorable geometric conditions for Northern-Hemisphere observers occur at 10-year intervals. Encke generally brightens perceptibly about six weeks before perihelion, and by the time it reaches perihelion, it often has enough brilliance to be classed as a naked-eye object. Indeed, 14 naked-eye observations of Encke have been recorded. A rapid decrease in brightness usually occurs about six to seven weeks after perihelion. Typical post-perihelion brightness estimates appear to be one magnitude fainter than pre-perihelion estimates for the same heliocentric distance.

Nuclear Region and Coma: Encke frequently displays a sharp nuclear condensation as it approaches perihelion. However, an unusual feature that seems to be unique to Encke is the eccentric location of the nuclear region at the antisolar apex of a fan-shaped coma. The observable coma diameter is approximately 10^5 km. Encke's spectrum is strong in CN, C_2, and C_3, but is especially faint in the continuum. Recently, a large hydrogen cloud surrounding Encke was detected by a Lyman-Alpha photometer on-board the OGO-5 satellite. The size of Encke's nucleus is still uncertain, but observations of Encke near aphelion ($\sim$4.1 AU) suggest a nuclear radius of 2-3 km.

Tail: A narrow type-I tail starts to develop about thirty days before perihelion. Typical observed tail lengths for Encke are $\sim 2 \times 10^6$ km.

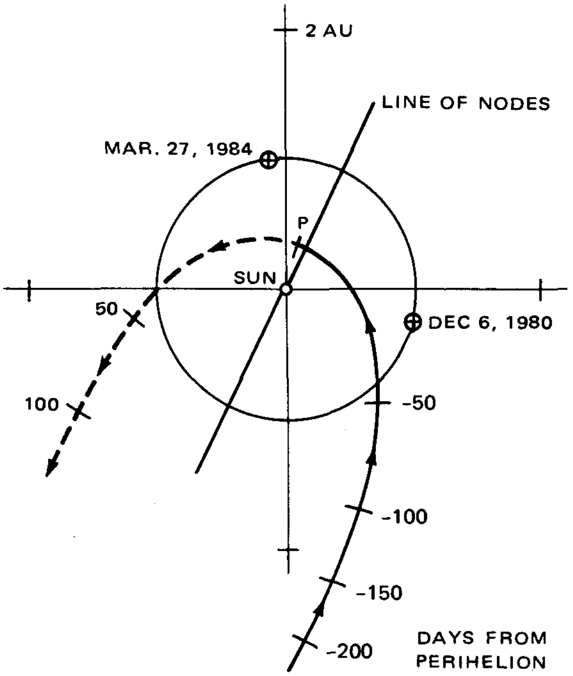
Dust: The faintness of a continuum in Encke's spectrum and the non-observability of a dust tail indicates that Encke's dust content is rather low. However, larger dust grains would not contribute appreciably to these observations and could be present. This seems likely because the Taurid meteor showers are associated with Encke's comet. The absence of fragmentation in the Taurid meteors argues for a rigid structure.

Nongravitational Effects on Orbital Motion: The comprehensive analysis of Marsden and Sekanina (1974) has shown that the transverse component of the nongravitational acceleration reached a maximum value around the year 1825, and has since decreased in magnitude by about a factor of ten. At present, the nongravitational effect on Encke's motion is quite small.

ORBITAL ELEMENTS (EQUINOX 1950.0)

EPOCH	1980 NOV. 17.0
T	1980 DEC. 6.57610
q	0.3399411 AU
e	0.8467578
Ω	334.19764°
ω	185.97967°
i	11.94599°

EPOCH	1984 APR. 10.0
T	1984 MAR. 27.68721
q	0.3410024 AU
e	0.8463305
Ω	334.18436°
ω	185.99329°
i	11.92738°



——— ABOVE ECLIPTIC

– – – – BELOW ECLIPTIC

⊕ EARTH AT ENCKE PERIHELIA

Figure 1. Orbit of Comet Encke

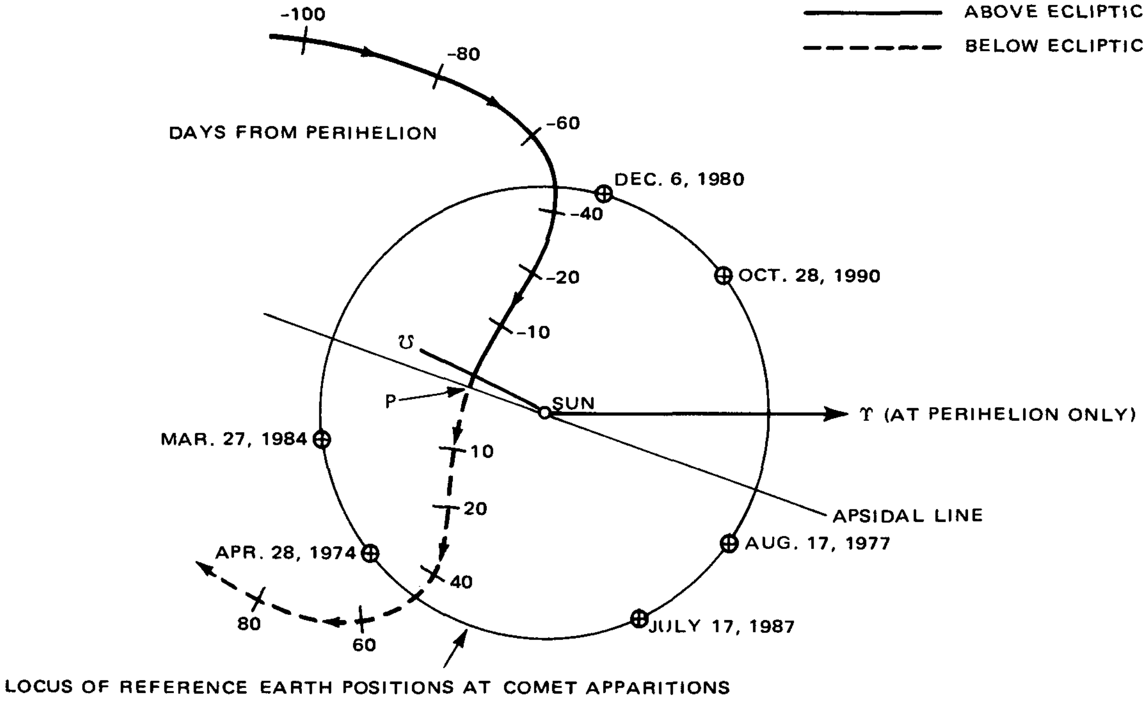
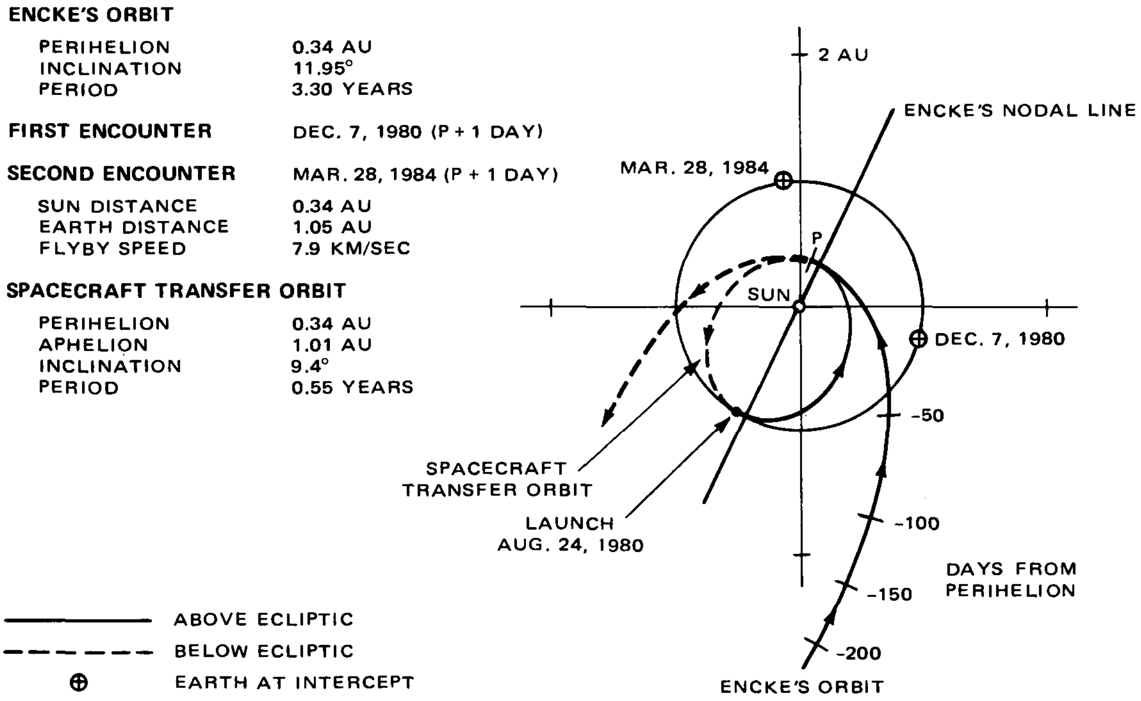


Figure 2. Orbit of Comet Encke in Bipolar Coordinates



ENCKE'S ORBIT	
PERIHELION	0.34 AU
INCLINATION	11.95°
PERIOD	3.30 YEARS
FIRST ENCOUNTER	DEC. 7, 1980 (P + 1 DAY)
SECOND ENCOUNTER	MAR. 28, 1984 (P + 1 DAY)
SUN DISTANCE	0.34 AU
EARTH DISTANCE	1.05 AU
FLYBY SPEED	7.9 KM/SEC
SPACECRAFT TRANSFER ORBIT	
PERIHELION	0.34 AU
APHELION	1.01 AU
INCLINATION	9.4°
PERIOD	0.55 YEARS

Figure 3. Encke Double Encounter, 1980-84

Table 2

Encke Mission Parameters for 10-Day Launch Window

	Nominal	Variation
Encounter Parameters		
Intercept Date	Dec. 7, 1980	Dec. 4 → 8, 1980
Sun Distance (AU)	0.34	0.34
Earth Distance (AU)	1.05	0.95 → 1.08
Phase Angle (Degrees)	77	53 → 86
Flyby Speed (km/sec)	7.9	7.6 → 8.9
Launch Parameters		
Launch Date	Aug. 24, 1980	Aug. 20 → 30, 1980*
Launch Energy-C_3 (km^2/sec^2)	89	87 → 92
Declination of Launch Asymptote (Deg.)	-0.9	-2.6 → 1.8
Payload System Weight (kg) (Titan-3E/Centaur)	845	760 → 900
Retargeting Maneuver for 2nd Encounter		
ΔV Requirement (m/sec)	130	120 → 162

*No Launch on August 27, 1980

The spacecraft trajectory near encounter is shown in Figure 4. Note the favorable geometry for spectrophotometric measurements of the coma/tail region before and after encounter. Mission plans call for a simultaneous intercept with two spacecraft (both probes are carried on the same launch vehicle). One probe will pass close to the nucleus on its sunward side, while the other traverses the tail region. The geometry for the dual-probe encounter is illustrated in Figure 5. The dual-probe scheme extends the mapping of Encke's structure to its longitudinal axis and prevents possible confusion between spatial and temporal variations.

The opportunity for a slow flyby of Encke near its perihelion in 1980 is truly exceptional. A comparable situation will not occur again until the year 2013.

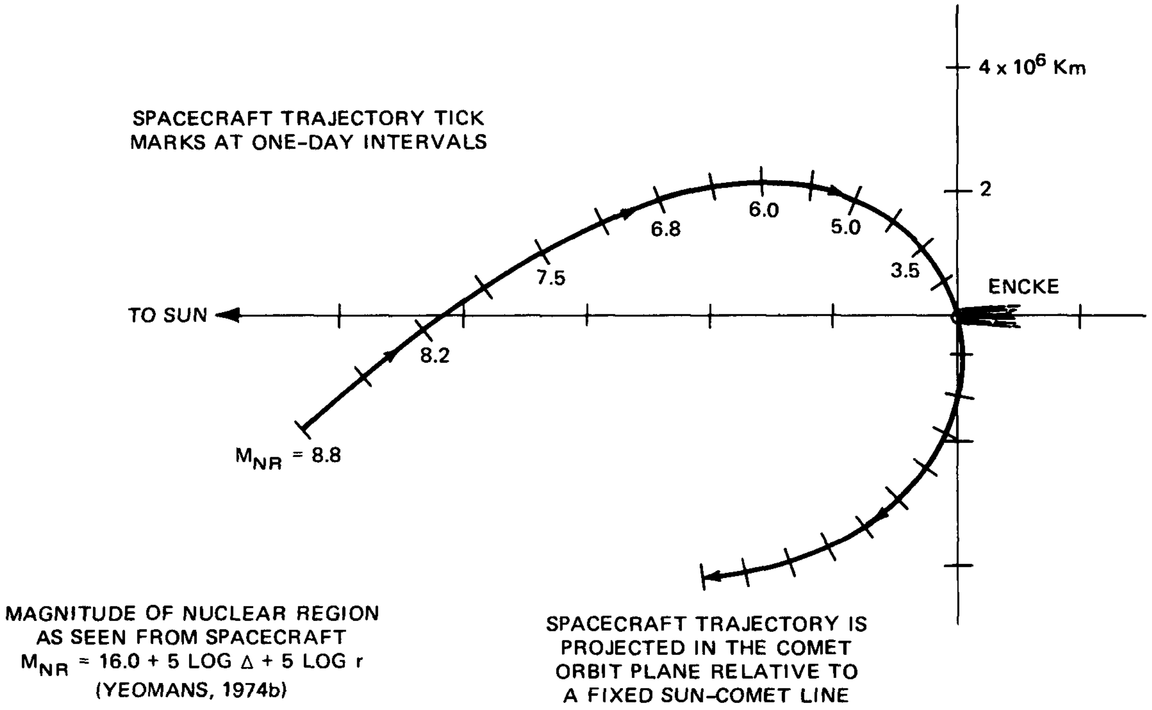
B. Giacobini-Zinner and Borrelly, 1985-87

The second mission of the proposed sequence will be an intercept of Giacobini-Zinner in 1985. This mission is a perfect complement to the 1980 Encke encounter, and is further enhanced by the possibility of intercepting another comet (Borrelly in 1987) with the same spacecraft. The additional cometary en-encounter is attained by employing a novel earth-swingby technique that is described below.

Physical characteristics of Giacobini-Zinner are summarized in Table 3. A comparison of Tables 1 and 3 reveals sharp differences in the physical behavior of comets Encke and Giacobini-Zinner. Although scientific interest in Borrelly has not been as great as in Encke and Giacobini-Zinner, the information contained in Table 4 indicates that Borrelly is a well-observed comet.

The orbits of Giacobini-Zinner and Borrelly are given in Figures 6 and 7. From the bipolar plots, it can be seen that the geometry for earth-based observations of both comets will be quite good at these apparitions. It should also be noted that Giacobini-Zinner will be almost stationary with respect to the sun-earth line for approximately 100 days around its perihelion.

The mission profile for the Giacobini-Zinner intercept is shown in Figure 8. An encounter at the comet's descending node has been chosen to minimize the launch-energy requirement. By launching on March 10, 1985, the spacecraft will be placed into a trajectory that returns to the earth's vicinity after the Giacobini-Zinner intercept. As shown in Figure 9, this trajectory will be slightly modified by an earth swingby maneuver on March 10, 1986, and then more drastically changed by a second earth passage on August 20, 1987. After the second earth swingby, the spacecraft will be on its way towards an encounter with Borrelly on December 25, 1987. Mission parameters for the Borrelly encounter are listed in Figure 10. It is noteworthy that both encounters will take place fairly



MAGNITUDE OF NUCLEAR REGION AS SEEN FROM SPACECRAFT
$M_{NR} = 16.0 + 5 \text{ LOG } \Delta + 5 \text{ LOG } r$
(YEOMANS, 1974b)

SPACECRAFT TRAJECTORY IS PROJECTED IN THE COMET ORBIT PLANE RELATIVE TO A FIXED SUN-COMET LINE

Figure 4. Encke Encounter Geometry

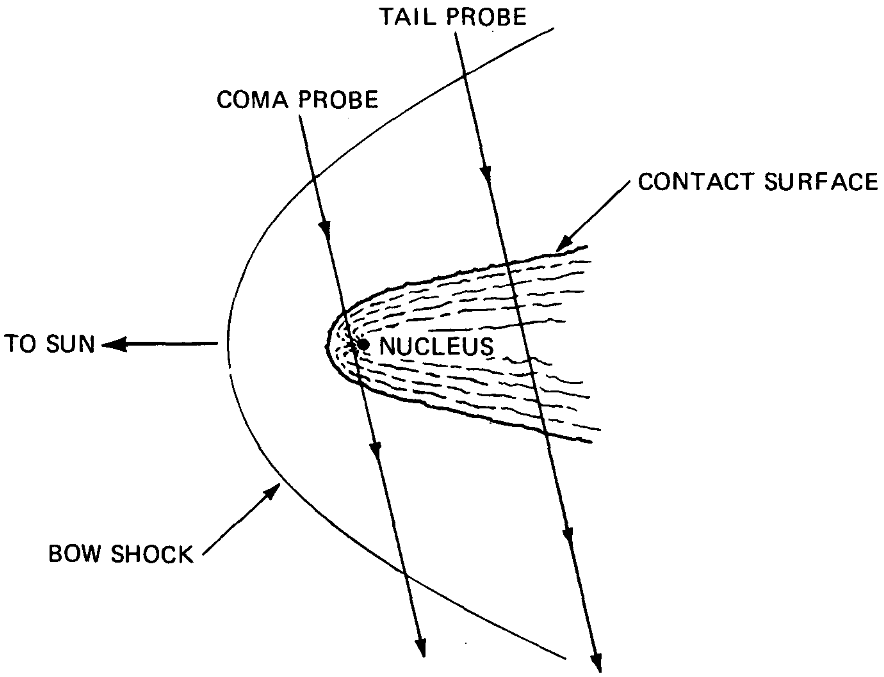


Figure 5. Dual-Probe Encounter Geometry

Table 3

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 by Jacchia et al. (1950) 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 (1971) 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 4

Comet Borrelly Summary

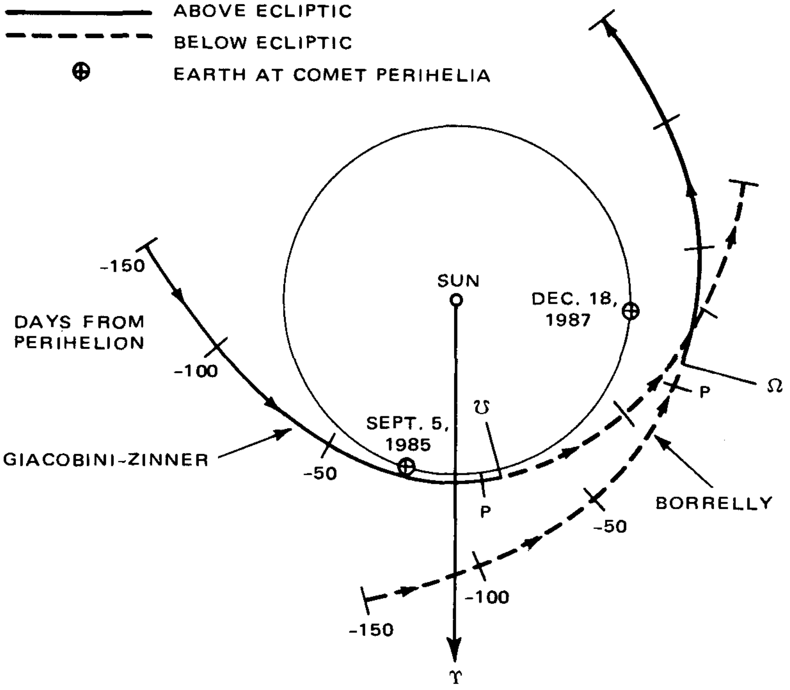
Observational History: Borrelly has been observed at nine apparitions since its discovery in 1904. Excellent orbital geometry during its first four apparitions (1905, 1911, 1918, 1925) produced a large number of observations. However, a perturbation by Jupiter in 1936 changed Borrelly's period, and the 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 (1971). It was found that although Borrelly is affected by substantial nongraviational forces, the transverse component of the nongravitational acceleration has remained constant over the entire 70-year observational interval.



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 6. Orbits of Comets Giacobini-Zinner and Borrelly

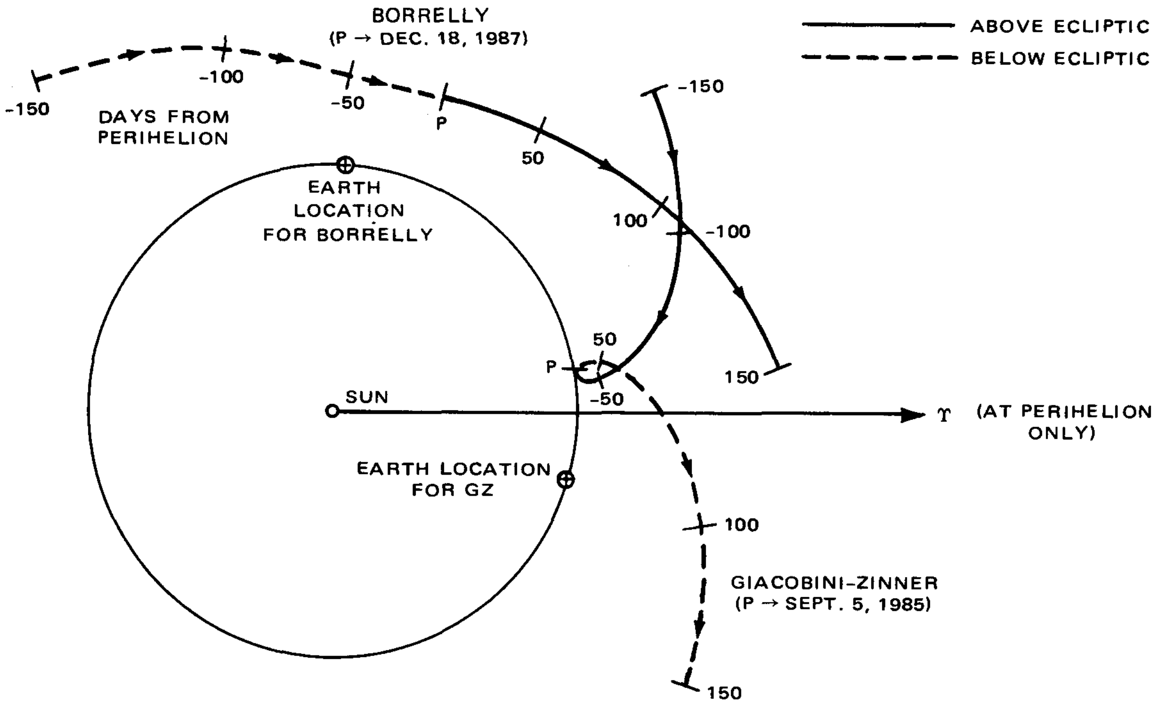


Figure 7. Orbits of Comets Giacobini-Zinner and Borrelly in Bipolar Coordinates

ENCOUNTER PARAMETERS

INTERCEPT DATE	SEPT. 11, 1985 (P + 6 DAYS)
SUN DISTANCE	1.03 AU
EARTH DISTANCE	0.46 AU
PHASE ANGLE	88.0°
FLYBY SPEED	20.6 KM/SEC

LAUNCH PARAMETERS

LAUNCH ENERGY - C_3	12.3 KM^2/SEC^2
DECLINATION OF LAUNCH ASYMPTOTE	-3.9°

SPACECRAFT TRANSFER ORBIT

PERIHELION	0.90 AU
APHELION	1.10 AU
INCLINATION	0.002°
PERIOD	1.00 YEARS

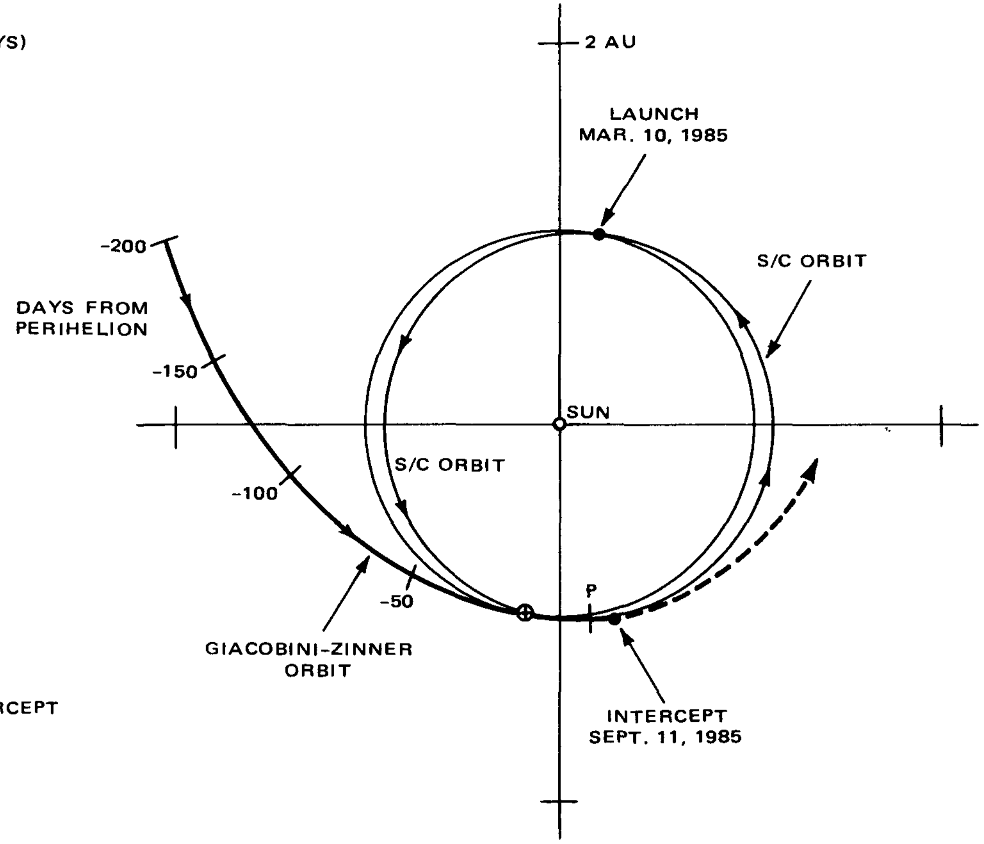


Figure 8. Mission to Giacobini-Zinner, 1985

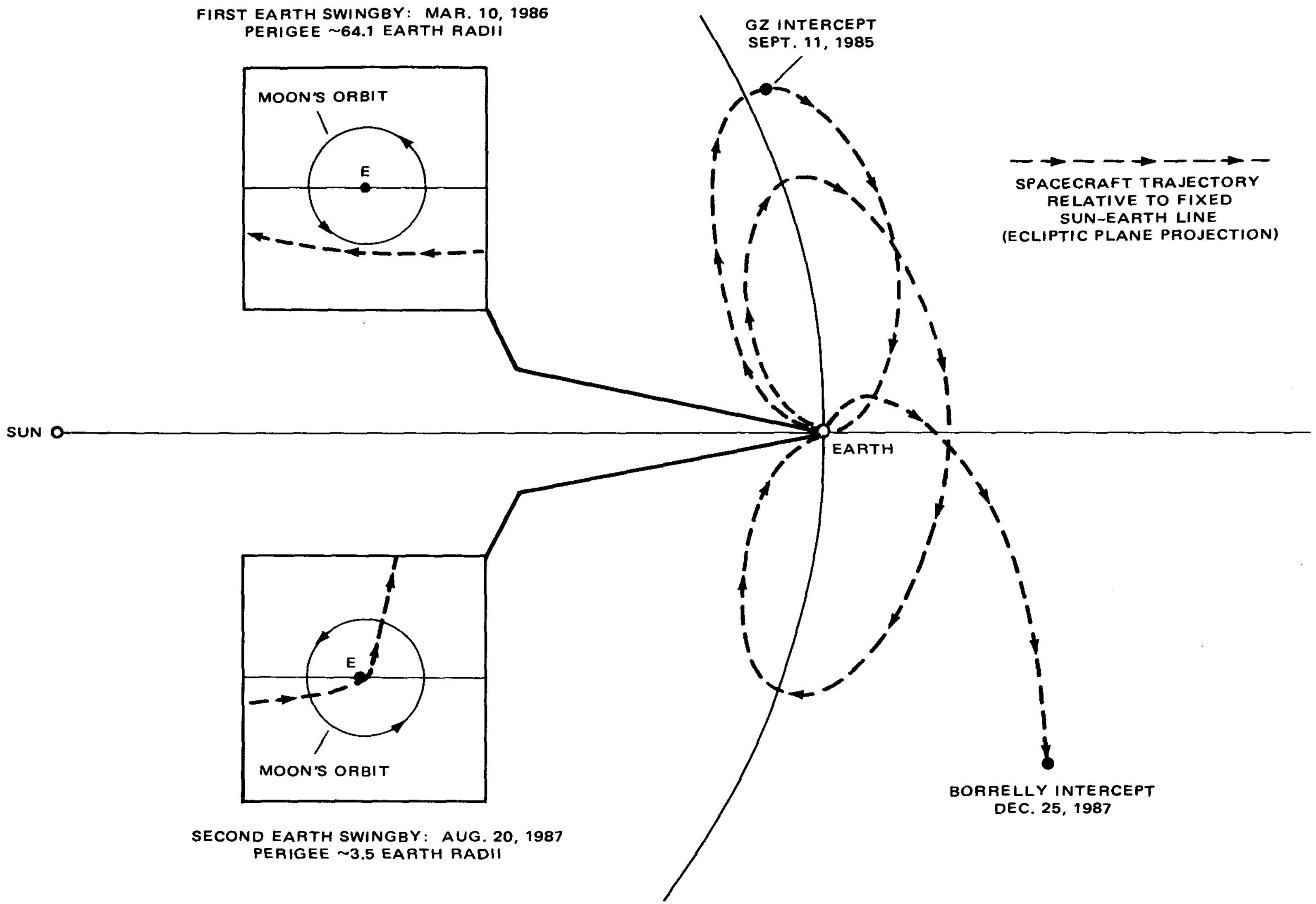
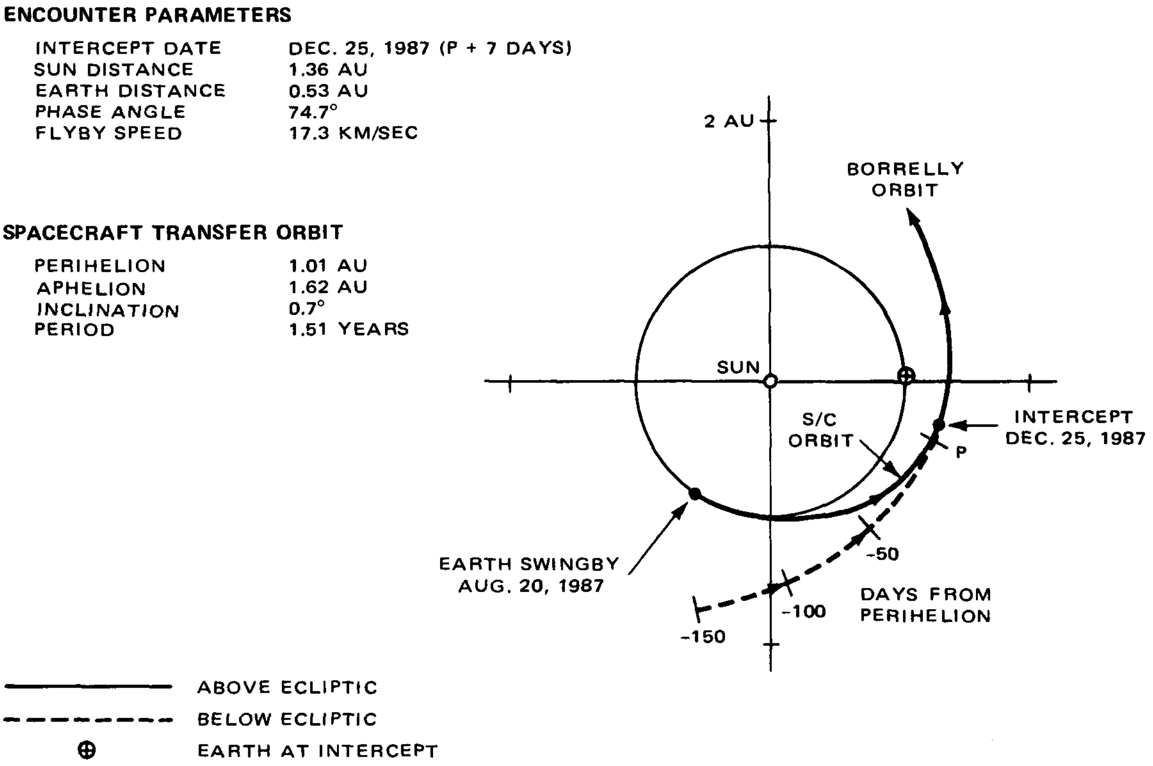


Figure 9. Nominal Mission Profile GZ → Borrelly, 1985–87



ENCOUNTER PARAMETERS

INTERCEPT DATE	DEC. 25, 1987 (P + 7 DAYS)
SUN DISTANCE	1.36 AU
EARTH DISTANCE	0.53 AU
PHASE ANGLE	74.7°
FLYBY SPEED	17.3 KM/SEC

SPACECRAFT TRANSFER ORBIT

PERIHELION	1.01 AU
APHELION	1.62 AU
INCLINATION	0.7°
PERIOD	1.51 YEARS

Figure 10. Borrelly Encounter, 1987

close to the earth (~0.5 AU) and will also be near the cometary perihelia. Further details of this attractive multi-comet mission have been treated by Farquhar et al. (1975).

C. Halley, 1985-86

At present Halley is the only dramatically bright comet whose return can be accurately predicted. Unfortunately, flyby speeds for ballistic intercept missions to this comet will be very fast (>50km/sec) due to Halley's retrograde orbit. However, because Halley is an extremely large comet, the time available for in situ measurements will be comparable to slow flybys of smaller comets. Of course, the fast flyby speed will create major problems for neutral mass-spectrometer measurements, but other experiments should not experience serious difficulties. Again, because Halley is a huge comet, it is uniquely suited for experiments concerning large-scale cometary phenomena.

Halley's physical characteristics are discussed in Table 5 and its orbit has been plotted in Figure 11. Nominal mission parameters are summarized in Figure 11 and Table 6. The exceptionally favorable orbital geometry in 1985-86 makes

Table 5

Comet Halley Summary

Observational History: Halley's comet has been seen at every apparition since at least 86 B.C., 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 50km 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 specta. 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 nongravitation 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 (Kiang, 1972).

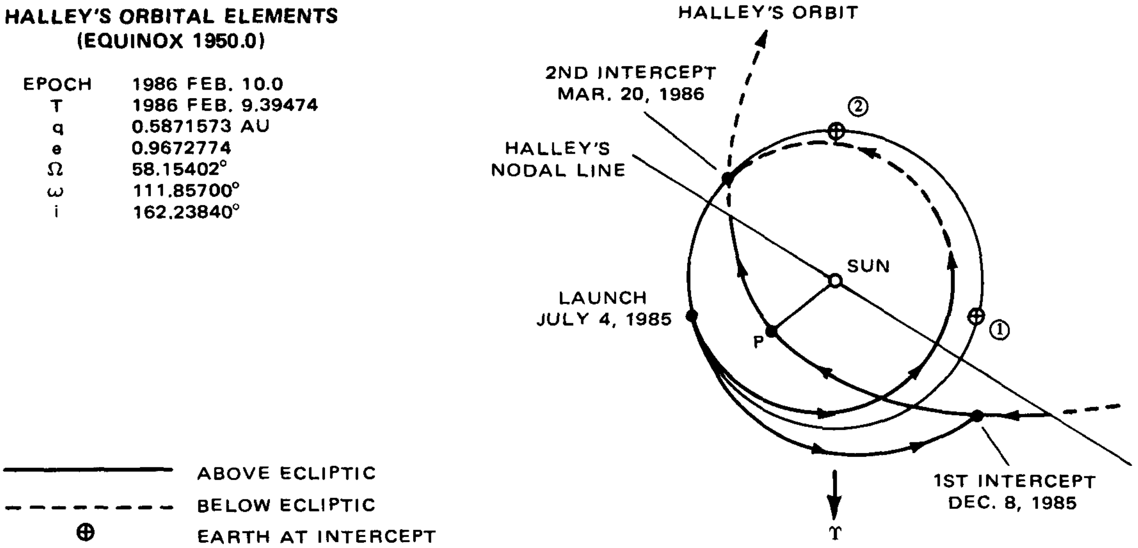


Figure 11. Dual Launch to Halley's Comet

Table 6

Nominal Parameters for Halley Mission*

	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.

it possible to intercept Halley before and after its perihelion passage (Michielsen, 1968). A common launch date has been selected for both the pre-perihelion and post-perihelion intercept trajectories to take advantage of the multi-payload launch capability of the "space shuttle" which should be operational in the early 1980's. The basic mission plan is to use a single shuttle launch to place two cometary spacecraft with attached solid rocket motors into a low earth parking orbit. Each solid rocket motor (fuel weight <2000 kg) will be capable of injecting a 500-kg spacecraft into the specified Halley intercept trajectory.

Due to a lower flyby speed and a more favorable encounter geometry (see Figure 12), imaging science will be emphasized during the pre-perihelion intercept. Less dust obscuration of Halley's nucleus is also anticipated. Preliminary results from the pre-perihelion encounter will probably be used to optimize the targeting strategy for the post-perihelion encounter which will take place about 100 days later.

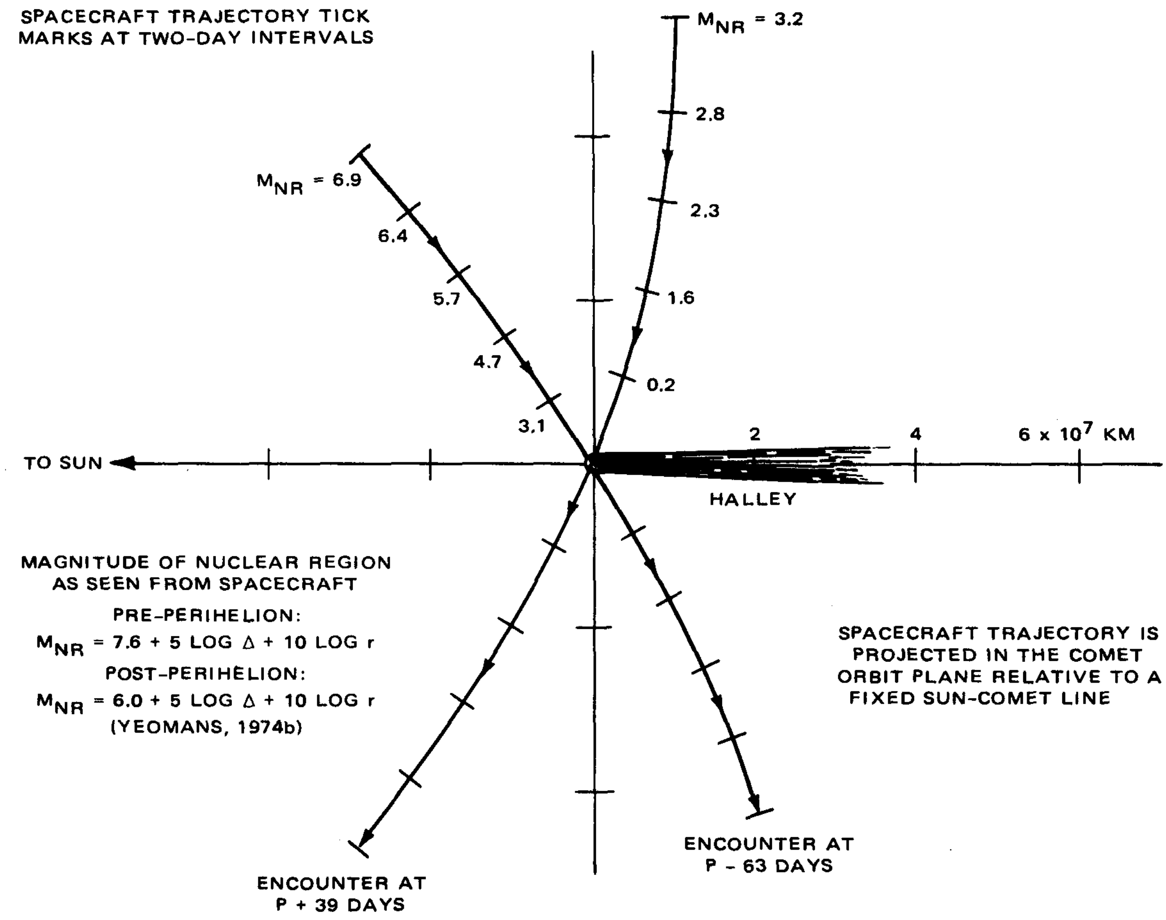


Figure 12. Halley Encounter Geometry

Correlative measurements in the coma and tail regions as well as dust experiments will have priority during the post-perihelion encounter. It is planned to release one or more small tail probes from the main spacecraft to effect a simultaneous multi-probe encounter (cf. Figure 5). Conditions for spectrophotometric measurements will probably be better during the post-perihelion encounter because Halley is expected to brighten considerably after perihelion.

V. GROUND-BASED OBSERVATIONAL SUPPORT AND TARGETING ERRORS

Observational support from earth-based telescopes can contribute significantly to the success of a cometary intercept mission. Space probe results will be complemented and better understood if ground-based measurements of the physical behavior of the target comet are recorded throughout the comet's apparition. Spectral coverage is especially desirable. For a large comet like Halley, photographs of the coma and tail regions, with a time resolution that is fast enough to track the motions of tail condensations, should be obtained.

Sighting conditions for all of the cometary encounters that were mentioned in the previous section are listed in Table 7. Notice the excellent conditions for northern-hemisphere observations of Giacobini-Zinner, Borrelly, and Halley (pre-perihelion). Post-perihelion observations of Halley must be obtained at southern-hemisphere sites, but adequate dark time is available. The lack of prime dark time at the Encke encounter is not surprising because it is always difficult to observe Encke near its perihelion.

Of major importance, are the astrometric measurements which will be needed to reduce cometary ephemeris errors. At least one measurement every ten days from recovery to encounter will suffice, but more-frequent measurements are recommended. To be useful during the mission, these measurements should be processed within a few days time.

Cometary ephemeris inaccuracies are the principal source of spacecraft targeting errors at encounter. Using simulated cometary observations, targeting errors for all the proposed encounters have been determined and the results are presented in Table 8. Analyses and assumptions used to obtain the error ellipses given in Table 8 are discussed in various papers (Farquhar et al., 1974, 1975; Yeomans, 1974a; Yeomans and Laubscher, 1975). Computations of the error ellipses for Encke, Giacobini-Zinner, and Borrelly have assumed that only earth-based measurements will be used to reduce the cometary ephemeris errors. If smaller errors are desired, it will be necessary to augment the earth-based measurements with measurements taken from the spacecraft (on-board navigation). It is clear that on-board navigation will be required for the Halley encounters. However, with the possible exception of Encke 1984, the targeting errors for the remaining cases are quite acceptable.

Table 7

Ground-Based Observations

Comet Encounter	Estimated Recovery Date	Site Latitude	Prime Dark Hours*		
			E -50 Days	Encounter	E +50 Days
Encke Dec. 7, 1980	July 9, 1980 Magnitude = 20.5 r = 2.43 AU Δ = 2.33 AU	35°N	6.0	—	—
		35°S	—	—	—
Encke Mar. 28, 1984	Oct. 5, 1983 Magnitude = 19.1 r = 2.54 AU Δ = 1.55 AU	35°N	—	—	—
		35°S	—	—	2.5
Giacobini-Zinner Sept. 11, 1985	Apr. 19, 1985 Magnitude = 18.2 r = 2.03 AU Δ = 1.76 AU	35°N	6.0	2.7	1.6
		35°S	—	0.2	3.8
Borrelly Dec. 25, 1987	Aug. 10, 1987 Magnitude = 16.7 r = 1.97 AU Δ = 1.42 AU	35°N	10.5	6.3	5.0
		35°S	—	2.4	—
Halley Dec. 8, 1985	Feb. 14, 1985 Magnitude = 17.7 r = 4.87 AU Δ = 4.43 AU	35°N	5.5	5.0	—
		35°S	2.0	2.0	—
Halley Mar. 20, 1986	Same as above	35°N	—	—	2.2
		35°S	—	1.9	5.6

*The comet is more than 25 degrees above the observer's horizon and the sun is simultaneously below the horizon by more than 18 degrees.

Table 8

Targeting Errors

Comet Encounter		Targeting Error Ellipse (1-σ)*		Miss Distance** (km)	
		Semi-Major Axis (km)	Semi-Minor Axis (km)	Nominal	Maximum
Encke Dec. 7, 1980		574	141	582	824
Encke Mar. 28, 1984		1712	154	608	1817
Giacobini-Zinner Sept. 11, 1985		427	250	800	1050
Borrelly Dec. 25, 1987		894	360	1020	1380
Halley Dec. 8, 1985	Without On-Board Navigation	3537	1297	2894	4570
	With On-Board Navigation†	1614	350	1000	1872
Halley Mar. 20, 1986	Without On-Board Navigation	10254	2349	4998	11410
	With On-Board Navigation†	637	421	1142	1563

*The error ellipse is located in the impact plane which is normal to the relative-velocity vector at encounter.

**An exclusion zone with a radius of 300 km has been assumed.

†A measurement noise of 10 arcseconds (1-σ) was assumed. Measurements are taken once every 12 hours from E-10 days to E-3 days.

The spacecraft miss distance at encounter is a function of the targeting strategy as well as the size of the cometary error ellipse. As shown in Figure 13, the nominal aim point has been chosen to guarantee that the spacecraft will not enter an exclusion zone around the nucleus even when targeting errors reach 2-σ levels. The exclusion zone has been specified to prevent possible damage to the spacecraft from large dust grains in the vicinity of the nucleus. To minimize the miss distance, the error ellipse should be oriented so that its minor axis passes through the nucleus.

VI. CONCLUDING REMARKS

The proposed mission sequence is outlined in Table 9. Notice that only three launches are required for the six cometary encounters. Additional features of this mission sequence are:

- Physical characteristics of the target comets cover a wide range of cometary behavior.
- The observational history of the target comets is extensive.
- There is ample time following the 1980 Encke encounter to incorporate the knowledge gained from the first mission into the design of an optimum science payload for the 1985 missions.

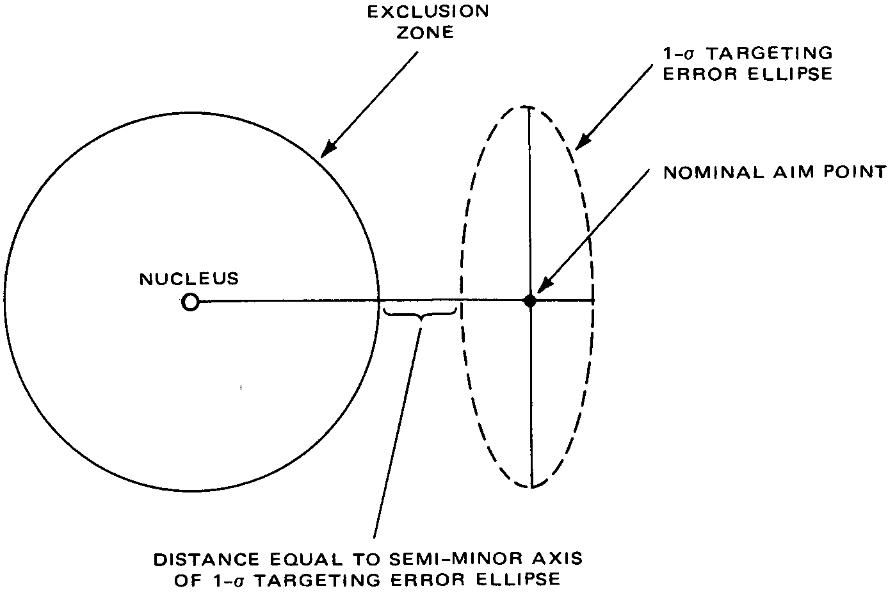


Figure 13. Targeting Geometry in Impact Plane

Table 9

Proposed Mission Sequence

Launch	Encounter	Flyby Speed (km/sec)
August 1980 Titan-3E/Centaur	Encke → Dec. 7, 1980 Encke → Mar. 28, 1984	7.9 7.9
March 1985 Shuttle/Solid Stage	Giacobini-Zinner → Sept. 11, 1985 Borrelly → Dec. 25, 1987	20.6 17.3
July 1985 Shuttle/Solid Stage (2)	Halley Pre-Perihelion → Dec. 8, 1985 Halley Post-Perihelion → Mar. 20, 1986	55.3 64.5

- Because of favorable earth-comet orbital geometry for Encke 1980, Giacobini-Zinner 1985, and Borrelly 1987, cometary ephemeris errors can be reduced to very small values with earth-based measurements alone. In other words, mission success will not be dependent on an on-board navigation system.

- Excellent earth-based sighting conditions exist for the entire 1985 mission set. All of the target comets are very bright.

- The 1985 mission set could be carried out at a relatively small cost. A common design could be used for the required spacecraft (three in all) because the operating range for all of these missions will be between 0.8 and 1.4 AU from the sun (~0.5 to 1.5 solar constants). Furthermore, the launch-vehicle costs will also be rather modest. Only two shuttle flights (or equivalently, three Delta-3914 launch vehicles) will be needed.

Finally, I wish to make a special plea for early consideration of the very-rare Halley mission opportunity by appropriate science advisory groups. The appearance of this famous comet in 1985-86 will generate considerable scientific and public interest. Therefore, it is imperative that serious planning for sending space probes to Halley begin in the near future.

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