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The International Cometary Explorer (ICE) Mission to Comets Giacobini-Zinner and Halley

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1. History and scientific mission objectives

The Third International Sun-Earth Explorer (ISEE-3) was launched on 12 August 1978 as one element of a three-spacecraft mission that began in 1977. The original purpose was to study the solar-wind interaction with the Earth’s magnetosphere. The spacecraft was maintained in a ’halo orbit’ about the libration point, L1, where it monitored the solar-wind input. It completed four years of uninterrupted operation at that location.

Several opportunities to use ISEE-3 in an extended mission phase were avallable. Among the most attractive scientifically were exploration of the distant geotail and an intercept of periodic Comet Giacobini-Zinner. Either or both of these options were available. The comet option was constrained to an intercept of Giacobini-Zinner in September 1985; specifically, an intercept of Comet Halley was not possible.

In order to explore the comet option, a subcommittee of the ISEE Science Working Team (SWT) was formed at the request of the ISEE-3 Project Scientist, T. von Rosen-vinge, and chaired by E. Smith. The subcommittee and the SWT as a whole found the option to be of considerable scientific interest, and a report entitled ’Intercept of Giacobini-Zinner by ISEE’ was issued in June 1982, and revised in May 1983.

An ad hoc subcommittee of the Space Science Board recommended that NASA pro-ceed with both the geotail option and the comet intercept. After an in-house review and a review of the readiness of the spacecraft to perform the intercept by the Goddard Space Flight Center, NASA approved the intercept with Comet Giacobini-Zinner.

The manoeuvres necessary to achieve the trajectory that would send the spacecraft into the distant geomagnetic tail and to an intercept of Comet Giacobini-Zinner are not simple. They are the brainchild of R. Farquhar, Flight Director for the Project. Basically, five gravitational encounters with the Moon were required to change the spacecraft’s orbit (Fig. 1). The last encounter (also see Fig. 6) was on 22 December 1983 when the spacecraft made a close swingby, passing only 120 km above the lunar surface. This manoeuvre effectively ’launched’ the spacecraft from the Earth-Moon system. At the same time, the spacecraft was renamed the Internationai Cometary Ex-plorer (ICE) to correspond to its new mission.

Figure 1. A colour-coded schematic showing the trajectory of the ISEE-3/ICE spacecraft. ICE returns to the vicinity of Earth in the year 2013 and, if retrievable, might provide comet dust for analysis

The first extensive survey of the distant geotail was accomplished by ISEE-3 in 1983. This survey achieved distances as great as 237 Earth radii in the tail. Aside from the scientific significance of the results obtained, the study of particle, field, and wave phenomena in the geotail provided an excellent rehearsal and scientific baseline for experiment operations during the cometary encounter. Results from the geotail excursion were presented in the October 1984 issue of Geophysical Research Letters (Vol. 11, No. 10).

The primary ICE scientific objective is to study the interaction between the solar wind and a cometary atmosphere by passing through the plasma tail. This will be accomplished by the intercept with Comet Giacobini-Zinner on 11 September 1985. Details of the targeting strategy are discussed below. Additional scientific objectives following the tail intercept of Comet Giacobini-Zinner include the support of Comet Halley studies through the measurement of solar-wind conditions upstream of P/Halley. Such opportunities occur in October 1985 and March 1986.

2. Comet Giacobini-Zinner (G/Z)

This short-period comet was discovered by M. Giacobini at Nice in 1900 and rediscovered in 1913 by E. Zinner at Bamberg. The discovery and recovery history of the comet is summarized in Table 1. The perihelion distance of 1.03 AU occurs near the ecliptic plane, making G/Z well suited to spacecraft encounters during its intervals of maximum nuclear and atmospheric activity. The orbital elements are listed in Table 2.

Typically, the plasma tail of G/Z is observed to begin developing at a heliocentric distance of about 1.7 AU. Conventional photographic observations at previous apparitions show that the plasma tail can exceed 500000 km in length. The coma, also observed photographically, reaches a typical diameter of about 50000 km (Fig. 2). G/Z is associated with the Draconid (Giacobinid) meteor showers. An analysis by D.K. Yeomans indicates that there is a limited possibility that a Giacobinid shower will occur on 8.5 October 1985, although it is unlikely to rival the great displays of this shower in 1933 and 1946. Ground-based observers and interplanetary-dust-particle experiments should attempt to observe this shower. Details are given in. the Comet Giacobini-Zinner Handbook.

The early recovery of Comet G/Z by ground-based observers was of special interest to the ICE-mission flight dynamicists. In the event that the observed orbit had differed significantly from the expected orbit of Comet G/Z, early detection of Comet G/Z would have been crucial to carefully schedule operation of the onboard propulsion capability in order to effect the flyby successfully. Fortunately, the first recovery photographs (Fig. 2) obtained on 3 April 1984, by S. Djorgovski, H. Spinrad, G. Will, and M. Belton with the 4 m Mayall telescope at Kitt Peak National Observatory, revealed that G/Z was within 4 arcsec of the anticipated position. Current projections indicate that further use of the propulsion system involves changes well within the available fuel capacity. The celestial mechanics of the encounter produces an intercept with the spacecraft travelling from south to north in the rest frame of the comet.

Table 1. Discovery and recovery of periodic Comet Giacobini-Zinner

Apparition	Designation		First observation	Observer/Institution	A m
1	1900III	(1900c)	20 Dec 1900	Giacobini/Observatoire de Nice	
2	l913V	(1913e)	23 Oct 1913	Zinner/Remeis-Sternwarte	9-
3	1926VI	(l926e)	l6 Oct 1926	Schwassmann/Hamburger Sternwarte	
4	1933III	(l933c)	23 Apr 1933	Schorr/Hamburger Sternwarte	
5	1940I	(19391)	15 Oct 1939	Van Biesbroeck/Yerkes Observatory ,	
6	1946V	(1946c)	29 May 1946	Jeffers/Lick Observatory	
7	1959VIII	(1959b)	8 May 1959	Roemer/US Naval Observatory	
8	1966I	(1965g)	17 Sept 1965	Roemer & Lloyd/US Naval Observatory	

9	l972VI	(1972d)	11 Mar 1972	Roemer & McCallister/University of Arizona
10	l979III	(1978h)	30 Apr 1978	Shao & Schwartz/Harvard College Observatory 20-
11	l985	(1984c)	03 Apr 1984	Djorgovski & Spinrad/Univ. Calif. Berkeley Will & Belton/Kitt Peak National Observatory

General references:

l. Baldet M F 1950, Liste Generale Des Cometes De L'Origine A l948

2. Marsden B G 1982, Catalogue of Cometary Orbits, 4th Edition, Smithsonian Astrophysical Obse

Table 2. Orbit parameters for Comet Giacobini-Zinner

q	= perihelion distance	1 .03 AU
Q	= aphelion distance	6.00 AU
e	= eccentricity	0.708
i	= inclination	31.9deg
OMEGA	= longitude of ascending node	194.7deg
omega	= argument of perihelion	172.5deg
P	= period	6.5 y
T	= time of perihelion	1985 Sept 5.25(ET)

Figure 2. Recovery photograph of Comet Giacobini-Zinner obtained on 3 April 1984 with a charge-coupled device at the prime focus of the 4 m telescope at the Kitt Peak National Observatory. The observers were S. Djorgovski and H. Spinrad of the Astronomy Department, University of California, Berkeley and G. Will and M. Belton of the Kitt Peak National Observatory

In order to develop the targeting strategy, a baseline tail model (Fig. 3) was developed. The starting point was a gas production rate of 2.3 X 10**28 molecules/s at perihelion (derived by N. Divine from the measured brightness of Comet G/Z during previous apparitions). The model suggests a plasma tail width of about 5000 km from the nucleus, consistent with the measured size on a photograph of Comet G/Z obtained by E. Roemer on 26 October 1959 (Fig. 4). Features of the model include a bow shock, a two-lobed magnetic tail, and neutral sheet separating the two magnetic lobes in the tail. The model-dependent nature of these features should be kept in mind.

Figure 3. Schematic of the baseline plasma-physics model for Comet Giacobini-Zinner near perihelion

Figure 4. Photograph of Comet Giacobini-Zinner, obtained by E. Roemer on 26 October 1959 (Official US Navy photograph). Linear and angular scales have been added

The targeting strategy is based on the desire to penetrate the central, denser, fully-formed plasma tail of Comet Giacobini-Zinner. Thus, the following elements must be considered in the formulation of a targeting strategy:

1. the dust hazard
2. full formation of the tail; directly in the wake of the nucleus conditions may be chaotic and it is thought that the tail may not be fully organized closer than a few thousand kilometres to the nucleus
3. the cross-section of the plasma tails tends to increase or 'flare' with increasing distance from the nucleus (Fig. 3)
4. the plasma tail tends to wag back and forth in response to variations in the solar-wind velocity.

Elements 1 and 2 set a lower bound to the distance from the nucleus at which the intercept occurs. Elements 3 and 4 conflict. The increasing cross-section 3 indicates that targeting away from the nucleus increases the probability of intersection the tail for a given targeting accuracy. The tail wagging 4 indicates that targeting away from the nucleus decreases the probability of a successful tail intercept. A probabilistic model has been developed for elements 3 and 4 and a solution sought for a 0.99 probability of successful intercepts for a range of reasonable targeting accuracies. A solution consistent with all presently available information and elements l through 4 indicates 3 tailward targeting distance of 10000 km from the nucleus.

The relative geometry of the intercept is shown in Figure 5. The spacecraft will pass essentially south to north through the tail of the comet. Clearly, we expect to pass through the bow shock, the contact surface separating the mixed solar-wind and cometary plasma, and the central plasma tail. As shown in Figure 5, the path of the ICE spacecraft is nearly parallel to the expected orientation of the neutral sheet separating the magnetic tail lobes. For the anticipated targeting accuracies, we cannot reasonably expect to intersect the neutral sheet. However, we may be able to detect the neutral sheet from the signatures of electromagnetic waves and plasma waves generated in the neutral sheet and detected by ICE in the plasma tail.

Figure 5. The geometry of the cometary encounter, as seen looking towards the Sun

Clearly, the maximum scientific return from the intercept depends on extensive, supporting ground-based observations of the comet. The appropriate observations have been requested through the International Halley Watch and a Comet Giacobini-Zinner Handbook has been prepared (Yeomans & Brandt, 1985). Because the 'Giacobini-Zinner Watch', with a focus on the time period of September 1985, comes before the time period of maximum effort for Halley, the Giacobini-Zinner Watch can serve as a valuable dress rehearsal for Halley's Comet.

The coverage requested can be divided into four levels of activity:

1. Light coverage: This time period would be approximately one year centred on the encounter date. The comet's development is to be monitored as it passes through perihelion. Observations would emphasize astrometry and photometry.
2. Moderate coverage: This level has the goal of obtaining one good-quality observation per observer per day during the time periods 28 August to 4 September and 18 to 25 September 1985. These weeks, together with the periods of heavy and

intense coverage (see below), provide good coverage for one month or a full solar rotation, which is important for establishing the comet's plasma environment. The comet's heliocentric distance is almost constant ($1.03 < r < 1.07$ AU), and the ecliptic latitude separation of the comet and the ICE spacecraft is less than 10deg for this month. Thus, ICE can serve as an excellent upstream monitor during this period, which is also one of excellent comet visibility from Earth. Therefore, we expect the following International Halley Watch networks - Astrometry, Radio Studies, Infrared Spectroscopy and Radiometry, Spectrophotometry and Spectroscopy, Photometry and Polarimetry, Near-Nuclear Studies, and Large-Scale Phenomena - to be actively involved.

3. Heavy coverage: This level has the goal of obtaining at least two observations per observer per day where appropriate, e.g. for time-sequence photographs. The period covers 4 September to 18 September 1985, and the same networks as in 2 would be involved.
4. Intense coverage: This period covers the night of the encounter, which is scheduled for 11.00 UT on ll September 1985. We have requested maximnm effort from all observers during this night.

Comet Giacobini-Zinner is well situated for viewing during the month of September 1985 for Northern-Hemisphere observers. An abbreviated ephemeris is included as Appendix 1. For a few days in September, Comets Giacobini-Zinner and Halley will be close together in the morning sky; on 14 September, they will be separated by less than 2deg. Comets Giacobini-Zinner and Halley should be roughly 8th and 12th magnitude, respectively, and present a historic opportunity for wide-field celestial photography.

For the possible Giacobini meteor shower on 8.5 October 1985, we will rely on the newly-formed IHW network for Halley Meteor Studies for coverage.

3. The ICE instruments

The spacecraft supports 13 scientific investigations, which are listed in Table 3. The line separates those experiments that will probably contribute useful measurements at a comet and those that probably will not. The latter are principally experiments that measure high-energy cosmic-ray nuclei and electrons. This division is, of course, somewhat arbitrary. All experiments are candidates for operation during the cometary encounter to the extent permitted by available spacecraft power and a suitable safety margin.

l. Solar-Wind Plasma

The plasma electron analyzer is a 90deg, spherical-section electrostatic analyzer. Electrons from secondary emitters are coupled into a discrete-dynode electron multiplier to provide spatial resolution in polar and azimuth angles. Electrons having $5 < E(e) < 1500$ eV are analyzed in 16 steps. A complete two-dimensional distribution is obtained in one spacecraft revolution and is read out every 24 s at 1024 bit/s.

Table 3. ICE experiments and status

	Title	Principal Investigator	Affiliation	Experiment status
1.	Solar-Wind Plasma	S. Bame	Los Alamos National Laboratory	Electrons only (ion portion falled)
2.	Plasma Composition	K. Ogilvie	NASA/Goddard Space Flight Center	Operational
3.	Energetic Protons	R. Hynds	Imperial College London	Operational

4.	X-Ray, Low-Energy Electrons	K. Anderson	Unlversity of California, Berkeley	X-rays and E(e)>200 keV (low-energy electron portion failed)
5.	Low-Energy Cosmic Rays	D. Hovestadt	Max-Planck-Institut fur Physik und Astrophysik	Partial failure
6.	Magnetometer	E. Smith	Jet Propulsion Laboratory	Operational
7.	Plasma Waves	F. Scarf	TRW Systems	Operational
8.	Radio Waves	J.-L. Steinberg	Paris Observatory, Meudon	Operational
9.	Medium-Energy Cosmic Rays	T. von Rosenvinge	NASA/Goddard Space Flight Center	Operational
10.	High-Energy Cosmic Rays	E. Stone	California Institute of Technology	Partial failure (isotope portion)
11.	High-Energy Cosmic Rays	M. Wiedenbeck	Unlversity of Chicago	Partial failure (drift chamber)
12.	Cosmic-Ray Electrons	P. Meyer	Ualversity of Chicago	Operational
13.	Gamma-Ray Bursts	B. Teegarden	NASA/Goddard Space Flight Center	Partial failure (PHA memory)

2. Plasma Composition

The ion-composition experiment consists of a Wien filter, whose magnetic and electric fields provide velocity selection, followed by an electrostatic analyzer which transmits ions based on the ratio of their energy to their charge. The range covered by the dual analyzer is normally 470 to 10500 V. In the solar wind, the corresponding mass/charge range extends from 1.0 to 5.6 AMU for singly ionized particles.

The mode of operation of the experiment is controlled by a microprocessor and will be adjusted to optimize the experiment’s performance for the comet flythrough. A suitable measurement programme could cover the mass range from 4 to 50 in 25 steps and a velocity range from 20 to 200 km/s in 25 steps. Normally, 20 min would be required for each readout of this portion of parameter space.

The performance of this instrument may be seriously degraded due to aberration caused by the encounter trajectory; for ion velocities believed to be reasonable, the bulk flow is not in the acceptance cone of the instrument. Nevertheless, the measurements are important and the microprocessor will be reprogrammed to an optimum cometary approach.

3. Energetic Protons

Energetic protons and heavy nucleons are detected by three identical charged-particle telescopes aligned at different angles (30deg, 60deg and 135deg) to the spin axis. Each telescope consists of a 1 cm**2 solid-state detector of 30 micro m thickness immediately followed by a 2 cm**2 detector of 150 micro m thickness in anticoincidence. Pulse-height analysis resolves the particle energies into eight channels between 35 keV and 1.6 MeV. The count rate from each telescope and each channel is resolved into eight sectors in the equatorial plane to measure the anisotropy of the particles. Shielding, a mechanical collimator, and a magnetic broom prevent electrons from entering the telescope. To sample the three telescopes, eight energies and eight sectors requires 32 s at 1024 bit/s.

4. X-Rays, Low-Energy Electrons

Photons in the energy range 5-1250 keV are measured with a proportional counter and a scintillation detector. A burst memory allows capture of fine timing detail both for solar flares and for cosmic-gamma-ray bursts. Electrons with energies greater than 200 keV are also detectable by the scintillation detector.

5. Low-Energy Cosmic Rays

The instrument now consists of two different sensor systems: (i) an electrostatic deflection analyzer system; and (ii) a thin-window flow-through proportional-counter/solid-state-detector telescope. The combination measures the elemental abundances, charge-state composition, energy spectra and angular distributions of ions over parts of the range 2 keV/charge to 80 MeV/nucleon and of electrons between 75 and 1300 keV.

6. Magnetometer

The vector helium magnetometer is mounted on the end of a 3 m boom (Fig. 6) and makes in-situ measurements of the ambient magnetic field vector in the frequency range 0-3 Hz. The instrument automatically chooses one of eight ranges in which to operate, the four lowest full-scale ranges being +/-4, +/- 14, +/-42, and +/- 146 nT. The precision of measurement is 1/256 of the full-scale field values (0.016, 0.055 nT, etc.). The absolute accuracy is limited by knowledge of the spacecraft magnetic field, which is presently known to better than 0.1 nT. The time resolution corresponds to three triaxial samples per second at 1024 bit/s . The magnetometer contains a three-channel spectrum analyzer which is connected to the search-coil sensor of the plasma-wave investigation (see No. 7).

Figure 6. The ISEE-3/ICI spacecraft

7. Plasma Waves

The plasma-wave investigation measures fluctuating electric and magnetic fields associated with waves above the ion cyclotron frequency (1 - 100000 Hz). Spectral analysis is performed on signals from three detectors: a pair of long electric-field antennas, a short electric-field sensor and a search coil, both of which are mounted on one of the experiment booms (Fig. 6). Electric-field fluctuations between 20 and 100000 Hz are measured in 16 frequency channels once per second at 1024 bit/s.

Cometary dust particles hitting the spacecraft or the electric antennas are expected to cause detectable outputs similar to those detected when Voyager passed through Saturn’s ring-plane.

8. Radio Waves

Fluctuating electric fields are detected in three pairs of orthogonal antennas, one aligned with the spacecraft spin axis and the other two in the equatorial plane (Fig. 6). The antenna voltages are preamplified and then analyzed by a radiometer consisting of four superheterodyne receivers, which step through the frequency range from 30 kHz to 2 MHz. Two channels are narrow-band with a filter bandwidth of 3 kHz, and two have a filter bandwidth of 10 kHz. The narrow-band filters sweep between 30 kHz and 1 MHz in 12 steps, while the broadband filters cover frequencies between 40 kHz and 2 MHz, also in 12 steps. The frequencies are scanned in a nonlinear manner so that the highest frequencies are sampled 12 times as often as the low frequencies. The complete scan sequence consists of 72 steps; 56 s are required to read out all channels at 1024 bit/s.

9. Medium-Energy Cosmic Rays

The medium-energy cosmic-ray experiment measures the elemental composition of nuclear energetic particles over wide ranges in energy (~ 1-500 MeV/nucleon) and in charge (Z= 1-28). Electrons of ~0.2-10 MeV are measured as well. These measurements are accomplished using all-solid-state detector telescopes with detectors ranging in thickness from 15 to 3000 micro m. This experiment has been designed to study solar-flare particles, galactic cosmic rays, and particles accelerated by the interplanetary medium.

10. High-Energy Cosmic Rays

This experiment measures the isotopic composition of solar and galactic cosmic rays with 5-250 MeV/nucleon and for all elements with charge $Z \le 30$. It consists of two thin (50 micro m) solid-state detectors, which determine the entering particle trajectory, followed by solid-state detectors that measure the particle energy.

11. High-Energy Cosmic Rays

Similar to the preceding experiment, this instrument is a telescope constructed from trajectory-defining drift chambers, a large stack of solid-state detectors and a surrounding scintillator anti-coincidence detector. The experiment has been designed to measure the isotopic abundances of galactic cosmic rays from ~ 20 to ~500 MeV/nucleon for isotopes with masses from A = 1 to 64.

12. Cosmic-Ray Electrons

Eight active detectors are used to determine the energy spectrum of electrons in the range 5-400 MeV. The experiment also determines the energy spectrum and relative abundances of nuclei from protons to the iron group in the range ~ 30 MeV/nucleon to 15 GeV/nucleon. It may also be able to count cometary dust particles impinging on the front detector.

13. Gamma-Ray Bursts

The gamma-ray-burst experiment is designed to detect cosmic gamma-ray bursts with high spectral resolution (<3.5 keV at l MeV) and high temporal resolution (as fast as 4 ms). The primary sensor, an intrinsic germanium solid-state detector cooled to ~ l00 K by a two-stage radiative cooler, spans the energy range 0.05-6.5 MeV

Figure 7. The geometry of ’launch’ and the encounter on 11 September 1985. The range at encounter is 0.47 AU and the Sun-Earth Comet angle is 79.6deg.

Figure 8. ICE shortly before encountering Comet Giocobini-Zinner in September 1985.

These experiments, in particular, experiments 1 through 8, although not chosen with cometary research in mind, are well-suited for probing the plasma-tail environment. The ICE spacecraft has no imaging capability nor any experiments designed to study dust particles (but see descriptions for Nos. 7 and 12). For additional details of the instruments as launched, see the July 1978 issue of IEEE Transactions of Geoscience Electronics (Vol. GE-16, No. 3).

4. The spacecraft

The spacecraft (Fig. 6) is a developed version of the earlier Interplanetary Monitoring Platform (IMP). Spacecraft weights are listed in Figure 6.

The spacecraft body is a 16-sided cylinder, 1.74 m in diameter and 1.6 m high. Solar arrays mounted on the faces of the cylinder provide 160 W of primary power at 28 V. A distinctive feature is a superstructure, or tower, which elevates the telemetry antenna above the spacecraft body and provides a clear field of view for several cosmic-ray detectors.

The spacecraft body supports a total of ten appendages. Two equatorial experiment booms (3 m long) support the magnetometer and plasma-wave sensors. Four wire antennas (each 49 m long) are deployed in the spin plane as part of the radio-wave and plasma-wave investigations. Two axial antennas (7 m each) extend above and below the spacecraft parallel to the spin axis to render the radio-wave measurements three dimensional. Finally, two short inertial booms provide stability.

The radio system consists of two redundant S-band transponders operating at 2217 and 2270 MHz. There are two low-gain antennas and a telemetry antenna having medium gain (7 dB) and a fan beam of +/-6deg. The radiated power is 5W. The standard telemetry rate in halo orbit was 2048 and 512 bit/s.

The spacecraft is spin-stabilized at 19.75 rpm. Attitude information and control is provided by two fine Sun sensors and a panoramic attitude sensor. The spin axis is maintained perpendicular to the ecliptic plane to within <1deg.

Propulsion and attitude control use monopropellant hydrazine. The system contains eight propellant tanks and 12 thrusters, including redundancy. A large amount of propellant was carried at launch (94 kg) as a safeguard against large errors associated with the launch vehicle. As a result of a nominal launch, gas usage has been much lower than anticipated, resulting in a substantial amount of excess gas still being available.

5. Mission description

The 'effective launch' of ICE took place on 22 December 1983. As the spacecraft distance from Earth increased, tracking and data acquisition involved the NASA Deep Space Network (DSN). The necessity for this involvement is apparent if one considers that the ISEE-3 radio system was designed to transmit from the halo orbit at a geocentric distance of 0.01 AU, whereas the distance to the spacecraft at cometary encounter will be 0.47 AU. A major effort required for the ICE mission was the outfitting of antennas in the DSN to operate at the ICE frequencies.

Current plans are to utilize the 64 m DSN (Goldstone, Madrid, Canberra) and the 300 m dish at Arecibo as the prime station. The anticipated data rate at encounter will be 1024 bit/s, although 512 bit/s may be used at other times. The acceptable performance is based on a bit error rate of 10**-4. There will be additional coverage by the 64 m station at Usuda, Japan. Operations outside the month centred on the encounter date of 11 September 1985 are basically cruise-science measurements, which will be discussed in the next section.

On 11 September 1985, Comet Giacobini-Zinner will be at the location shown in Figure 7. The ICE spacecraft will be approaching the aim point on the main plasma tail axis 10000 km from the nucleus, as shown schematically in Figure 8.
Some idea of the spatial scales associated with key instruments and their sampling times is given in Table 4 for the expected data rate of 1024 bit/s. For the sampling period indicated, the 'spatial resolution' is the distance travelled at the relative encounter speed of 20.7 km/s. These dimensions should be compared with the estimated distance between bow-shock crossings of about 175 000 km and a measured main tail diameter of 5000 km. Expressed in terms of time, we expect the spacecraft to be inside the bow shock for about 2 h 20 min and in the maln plasma tail for about 4 min.

The magnetometer will produce many measurements during the encounter period and we use it to illustrate possible scientific product. Current models of comets do not indicate a major amplification of the cometary magnetic field over the solar-wind value. However, major changes in field-line direction are expected. Well away from the comet the magnetic field should, on average, show the Archimedian spiral angle of 135deg or 315deg to the radial appropriate for normal solar-wind fiow. Interior to the bow shock we expect a different, possibly somewhat chaotic, orientation tending to the ordered two-lobed configuration along the axis of the plasma tail. If the neutral sheet is encountered, a magnetic reversal should be recorded. The model-dependent nature of this description must be stressed. For example, the bow shock may or may not exist. We should know after 11 September 1985, and the model will be tested in this and in other respects. Obviously, we need data from as many different experiments as possible to complete our model testing.

To enhance the science return from the encounter, a Guest Investigator Program has been established by NASA.

Table 4. Spatial resolution of the scientific meaurements (assuming 1024 bit/s)

Instrument	Sampling period (s)	Spatial resolution (km)

Magnetometer	1/3	7
Plasma Waves		
16 channel E	1	21
8 channel E, B	16	330
Plasma Electrons		
Two-dimensional distribution	24	500
Energetic Protons	32	660
Radio Waves	56	1200
Plasma Ions	1200	25000

6. ICE and Comet Halley

The ICE mission should be of direct benefit to the missions to explore Halley's Comet in two general ways. The first is through the spin-off and synergism of the encounter, and the second is through the use of ICE as an upstream monitor of solar-wind conditions.

The ICE experience at encounter will give the first indications of spacecraft problems in a cometary environment. For example, the dust emitted by Comet Giacobini-Zinner is thought to be extremely fluffy and possibly one hundred times less dense than the dust associated with Halley's Comet. Dust fluences from Comet Giacobini-Zinner are estimated to be lower than for Halley's Comet. Thus, a relatively benign dust environment is expected for the ICE encounter. If spacecraft problems are encountered and ascribed to dust, some revision of strategy for the Halley encounters may be indicated.

On the scientific side, the Comet Giacobini-Zinner encounter is highly complementary to the Halley encounters. In-situ data will have been obtained for two comets within a very short time, permitting intercomparisons. All the Halley probes are targeted for the sunward side of the comet versus the tailward targeting for ICE. Both data sets are probably necessary to sketch a moderately complete picture of a comet's plasma and magnetic field.

Finally, experience with the 'Giacobini-Zinner Watch' carried out by the International Halley Watch in September 1985 could lead to more efficient coverage of Halley's Comet in March of 1986. The opportunity to observe both comets simultaneously around 14 September 1985 has already been mentioned.

The second role of ICE in Halley studies involves its use as an upstream monitor of solar-wind conditions. In late March 1986, the ICE spacecraft can be considered a 'fairly distant' probe to Halley's Comet (Table 5). A bipolar plot of the ICE trajectory showing the alignments is given in Figure 9.

Two near-radial lineups are available, and relevant facts are assembled in Table 5.

Tracking of ICE at these times should not be a problem because the range from Earth is approximately the same as the range at Comet Giacobini-Zinner encounter. Furthermore, when ICE is in the cruise mode making solar-wind measurements, the lower data rate of 512 bit/s would be acceptable.

Investigations of cometary phenomena utilizing input parameters from solar-wind measurements have been carried out successfully for some years. However, we note that three-dimensional plasma ion speeds have been quite important in these investigations. The challenge will be to fully exploit the ICE data.

With the caveat mentioned just above, ICE could provide important solar-wind data during cruise-mode operations, which would include the 'week' of the five spacecraft encounters with Halley's Comet in March 1986. The time delay between ICE and Halley's Comet on 13/14 March 1986, calculated according to standard formulas, is only two days, considered quite reasonable by scientists working in this field. If suitable ion-velocity coverage is obtained from ICE or another spacecraft, solar-wind data for the Halley encounters could be reasonably complete.

Finally, there is the near-radial alignment of ICE, Pioneer Venus Orbiter, Vega-1 and 2, and MS-T5 in the interval 15 May to 15 June 1985, which presents an opportunity for multispacecraft investigation of comet-like phenomena over large scale lengths (described in Galeev & Scarf, 1985).

Table 5. Radial alignments with Comet Halley

Date	Radial separation (AU)	Angular separation (deg)	Solar-wind travel time (d)	Range (AU)
31 October 1985	0.93	l	4	0.41
28 March 1986	0.21	6	1	0.56

Figure 9. A bipolar plot of the ICE trajectory showing the radial alignments with Halley's Comet

Appendix 1. Ephemeris for Comet Giacobini-Zinner

EXPLANATI0N OF EPHEMERIS ENTRIES *

J.D. = JULIAN DATE (TIMES IN THIS EPHEMERIS ARE EPHEMERIS TIMES)
R.A. 1950.0 DEC. = GEOCENTRIC RIGHT ASCENSION AND DECLINATION REFERRED TO THE MEAN EQUATOR AND EQUINOX OF 1950.0 - LIGHT TIME CORRECTI0NS HAVE BEEN APPLIED.
R.A. APPN DEC. = APPARENT RIGHT ASCENSION AND DECLINATION - LIGHT TIME, ANNUAL ABERRATION, AND NUTATION CORRECTIONS HAVE BEEN APPLIED AND R.A. AND DEC. HAVE BEEN PRECESSED TO THE EPHEMERIS DATE.
DELTA = GEOCENTRIC DISTANCE OF OBJECT IN AU.
DELDOT = GEOCENTRIC VELOCITY OF OBJECT IN KM/SEC.
R = HELIOCENTRIC DISTANCE OF OBJECT IN AU.
RDOT = HELIOCENTRIC VELOCITY OF OBJECT IN KM/SEC.

TMAG = TOTAL MAGNITUDE ESTIMATES AFTER THE ANALYSIS BY C.S. MORRIS.
PRE-PERIHELION
TMAG = 8.90 + 5*LOG(DELTA) + 11.00*LOG(R)   FOR R > 1.3 AU
TMAG = 9.60 + 5*LOG(DELTA) + 4.73*LOG(R)   FOR R = 1.3 TO 0.99 AU
POST-PERIHELION
TMAG = 9.65 + 5*LOG(DELTA) + 10.48*LOG(R)   FOR R = 0.99 TO 1.71 AU
IN CASES WHERE TMAG IS NOT COMPUTED, IT IS SET EQUAL TO ZERO.
NMAG = NUCLEAR MAGNITUDE = 16.5 + 5*LOG(DELTA) + 5*LOG(R) + 0.03*BETA

THETA = SUN-EARTH-OBJECT ANGLE IN DEGREES.
BETA = SUN-OBJECT-EARTH ANGLE IN DEGREES.
MOON = OBJECT-EARTH-MOON ANGLE IN DEGREES.

THE FOLLOWING OSCULATING ORBITAL ELEMENTS ARE C0NSISTENT WITH THE EPHEMERIS:

EPOCH	2446320.5	1985	SEPT. 12.0 (E.T.)
PERIHELION PASSAGE	2446313.74907	1985	SEPT. 5.24907 (E.T.)
PERIHELION DISTANCE	1.0282614 AU		

ECCENTRICITY 0.7075300
ARG. OF PERIHELION 172.48887
LONG. OF ASCENDING NODE 194.70595
INCLINATION 31.87829

IN THE ABOUE ORBITAL ELEMENTS, THE ANGLES ARE IN DEGREES AND REFERRED TO THE ECLIPTIC AND EQUINOX OF 1950.0.

THE N0NGRAVITATIONAL PARAMETERS ARE AS FOLLOWS:
A1 = -0.0543
A2 = -0.0465
FOR THE DEFINITION OF A1 AND A2 SEE: MARSDEN ET AL, ASTRONOMICAL JOURNAL, 1973, VOL. 78, PP. 211-225.

COMPUTATIONS BY D.K. YEOMANS - JPL

* For an expanded ephemeris. see The Comet Giacobini-Zinner Handbook Yeomans & Brandt, 1985.

EPHEMERIS (WITH PERTURBATIONS) FOR P/GIACOBINI-ZINNER

YR	MN	DY	HR	J.D.	R.A. 1950.0		DEC.		R.A. APPN		DEC.		DELTA	DELDOT	R	RDOT
1985	3	15	.0	2446139.5	18	35.523	+ 4	8.24	18	37.251	+ 4	9.82	2.38	-32.19	2.34	-14.88
1985	3	25	.0	2446149.5	18	51.870	+ 6	29.50	18	53.571	+ 6	31.89	2.19	-31.48	2.25	-15.11
1985	4	4	.0	2446159.5	19	8.273	+ 9	13.69	19	9.943	+ 9	16.88	2.01	-30.40	2.16	-15.33
1985	4	14	.0	2446169.5	19	24.783	+12	22.08	19	26.417	+12	26.06	1.84	-29.04	2.08	-15.52
1985	4	24	.0	2446179.5	19	41.454	+15	55.70	19	43.050	+16	.47	1.68	-27.41	1.99	-15.69
1985	5	4	.0	2446189.5	19	58.413	+19	54.61	19	59.968	+20	.14	1.53	-25.56	1.89	-15.82
1985	5	14	.0	2446199.5	20	15.905	+24	18.27	20	17.416	+24	24.57	1.38	-23.61	1.80	-15.89
1985	5	24	.0	2446209.5	20	34.262	+29	4.80	20	35.729	+29	11.87	1.25	-21.60	1.71	-15.89
1985	6	3	.0	2446219.5	20	54.078	+34	10.19	20	55.504	+34	18.04	1.13	-19.66	1.62	-15.79
1985	6	13	.0	2446229.5	21	16.342	+39	29.04	21	17.734	+39	37.69	1.03	-17.88	1.53	-15.55
1985	6	23	.0	2446239.5	21	42.588	+44	52.86	21	43.966	+45	2.35	.93	-16.33	1.44	-15.12
1985	7	3	.0	2446249.5	22	15.443	+50	8.48	22	16.851	+50	18.84	.84	-15.03	1.35	-14.44
1985	7	13	.0	2446259.5	22	59.057	+54	55.08	23	.586	+55	6.24	.75	-13.95	1.27	-13.44
1985	7	18	.0	2446264.5	23	26.582	+56	56.06	23	28.231	+57	7.52	.71	-13.44	1.24	-12.79
1985	7	23	.0	2446269.5	23	58.803	+58	32.21	0	.620	+58	43.80	.68	-12.90	1.20	-12.03
1985	7	28	.0	2446274.5	0	35.984	+59	33.08	0	38.017	+59	44.53	.64	-12.30	1.17	-11.14
1985	8	2	.0	2446279.5	1	17.576	+59	46.31	1	19.847	+59	57.25	.60	-11.59	1.14	-10.12
1985	8	7	.0	2446284.5	2	1.895	+58	59.35	2	4.378	+59	9.34	.57	-10.71	1.11	- 8.97
1985	8	12	.0	2446289.5	2	46.356	+57	2.41	2	48.979	+57	11.07	.54	- 9.62	1.08	- 7.69
1985	8	17	.0	2446294.5	3	28.340	+53	51.22	3	31.006	+53	58.33	.52	- 8.24	1.06	- 6.27
1985	8	22	.0	2446299.5	4	6.077	+49	28.17	4	8.700	+49	33.70	.50	- 6.53	1.05	- 4.75
1985	8	27	.0	2446304.5	4	38.927	+44	1.87	4	41.454	+44	5.89	.48	- 4.52	1.04	- 3.13
1985	8	28	.0	2446305.5	4	44.918	+42	50.15	4	47.423	+42	53.89	.48	- 4.09	1.03	- 2.80
1985	8	29	.0	2446306.5	4	50.724	+41	36.57	4	53.205	+41	40.03	.47	- 3.65	1.03	- 2.47
1985	8	30	.0	2446307.5	4	56.349	+40	21.26	4	58.806	+40	24.45	.47	- 3.20	1.03	- 2.13
1985	8	31	.0	2446308.5	5	1.799	+39	4.35	5	4.231	+39	7.29	.47	- 2.74	1.03	- 1.79
1985	9	1	.0	2446309.5	5	7.078	+37	46.00	5	9.485	+37	48.68	.47	- 2.28	1.03	- 1.45
1985	9	2	.0	2446310.5	5	12.191	+36	26.35	5	14.573	+36	28.78	.47	- 1.81	1.03	- 1.11
1985	9	3	.0	2446311.5	5	17.144	+35	5.54	5	19.501	+35	7.73	.47	- 1.34	1.03	- .77
1985	9	4	.0	2446312.5	5	21.943	+33	43.73	5	24.274	+33	45.69	.47	- .87	1.03	- .43
1985	9	5	.0	2446313.5	5	26.591	+32	21.07	5	28.898	+32	22.80	.47	- .40	1.03	- .09
1985	9	6	.0	2446314.5	5	31.095	+30	57.70	5	33.377	+30	59.21	.47	.08	1.03	.26
1985	9	7	.0	2446315.5	5	35.460	+29	33.79	5	37.718	+29	35.08	.47	.55	1.03	.60
1985	9	8	.0	2446316.5	5	39.690	+28	9.46	5	41.924	+28	10.54	.47	1.02	1.03	.94
1985	9	9	.0	2446317.5	5	43.790	+26	44.88	5	46.000	+26	45.76	.47	1.49	1.03	1.28
1985	9	10	.0	2446318.5	5	47.765	+25	20.17	5	49.952	+25	20.85	.47	1.95	1.03	1.62
1985	9	11	.0	2446319.5	5	51.620	+23	55.48	5	53.783	+23	55.97	.47	2.40	1.03	1.96
1985	9	12	.0	2446320.5	5	55.357	+22	30.93	5	57.499	+22	31.24	.47	2.85	1.03	2.30

1985	9	13	.0	2446321.5	5 58.983	+21 6.66	6 1.102	+21 6.79	.47	3.29	1.03	2.64
1985	9	14	.0	2446322.5	6 2.499	+19 42.77	6 4.596	+19 42.74	.48	3.72	1.04	2.97
1985	9	15	.0	2446323.5	6 5.911	+18 19.39	6 7.987	+18 19.19	.48	4.14	1.04	3.30
1985	9	16	.0	2446324.5	6 9.221	+16 56.62	6 11.276	+16 56.26	.48	4.55	1.04	3.63
1985	9	17	.0	2446325.5	6 12.433	+15 34.56	6 14.468	+15 34.04	.48	4.95	1.04	3.95
1985	9	18	.0	2446326.5	6 15.551	+14 13.30	6 17.565	+14 12.62	.49	5.34	1.04	4.27
1985	9	19	.0	2446327.5	6 18.576	+12 52.91	6 20.571	+12 52.08	.49	5.71	1.05	4.59
1985	9	20	.0	2446328.5	6 21.513	+11 33.48	6 23.489	+11 32.51	.49	6.08	1.05	4.91
1985	9	21	.0	2446329.5	6 24.365	+10 15.07	6 26.322	+10 13.96	.50	6.42	1.05	5.22
1985	9	22	.0	2446330.5	6 27.133	+ 8 57.74	6 29.072	+ 8 56.49	.50	6.76	1.06	5.53
1985	9	23	.0	2446331.5	6 29.820	+ 7 41.54	6 31.742	+ 7 40.16	.50	7.08	1.06	5.83
1985	9	24	.0	2446332.5	6 32.429	+ 6 26.51	6 34.334	+ 6 25.01	.51	7.38	1.06	6.13
1985	9	25	.0	2446333.5	6 34.961	+ 5 12.69	6 36.849	+ 5 11.07	.51	7.67	1.07	6.42
1985	9	30	.0	2446338.5	6 46.544	- 0 37.46	6 48.354	- 0 39.64	.54	8.88	1.09	7.82
1985	10	5	.0	2446343.5	6 56.454	- 5 55.38	6 58.194	- 5 58.03	.56	9.74	1.11	9.09
1985	10	10	.0	2446348.5	7 4.808	-10 41.94	7 6.485	-10 44.98	.59	10.30	1.14	10.23
1985	10	15	.0	2446353.5	7 11.668	-14 59.21	7 13.289	-15 2.58	.62	10.61	1.17	11.23
1985	10	20	.0	2446358.5	7 17.073	-18 49.57	7 18.642	-18 53.20	.65	10.75	1.20	12.11
1985	10	25	.0	2446363.5	7 21.055	-22 15.35	7 22.578	-22 19.16	.68	10.76	1.24	12.86

EPHEMERIS (WITH PERTURBATIONS) FOR P/GIACOBINI-ZINNER

YR	MN	DY	HR	J.D.	R.A. 1950.0	DEC.	R.A. APPN	DEC.	DELTA	DELDOT	R	ROOT	TMAG	N
1985	10		.0	2446368.5	7 23.635	-25 18.68	7 25.114	-25 22.61	.72	10.68	1.28	13.50	10.0	1
1985	11		.0	2446373.5	7 24.816	-28 1.26	7 26.225	-28 5.25	.75	10.55	1.32	14.04	10.3	1
1985	11		.0	2446378.5	7 24.599	-30 24.19	7 26.000	-30 28.17	.78	10.42	1.36	14.48	10.5	1
1985	11		.0	2446388.5	7 20.084	-34 12.51	7 21.419	-34 16.30	.84	10.30	1.44	15.15	10.9	1
1985	11		.0	2446398.5	7 10.764	-36 43.67	7 12.048	-36 47.04	.90	10.49	1.53	15.56	11.4	1
1985	12		.0	2446408.5	6 57.943	-37 56.51	6 59.196	-37 59.29	.96	11.11	1.62	15.80	11.8	1
1985	12		.0	2446418.5	6 43.530	-37 51.12	6 44.782	-37 53.24	1.03	12.26	1.72	15.89	12.2	1
1986	12		.0	2446428.5	6 29.752	-36 34.16	6 31.028	-36 35.64	1.10	13.88	1.81	15.89	12.6	1
1986	1		.0	2446438.5	6 18.353	-34 19.16	6 19.672	-34 20.10	1.19	15.92	1.90	15.81	12.9	1
1986	1		.0	2446448.5	6 10.369	-31 22.94	6 11.745	-31 23.52	1.29	18.26	1.99	15.68	13.3	1
1986	1		.0	2446458.5	6 6.128	-28 3.72	6 7.562	-28 4.12	1.40	20.72	2.08	15.51	13.7	1
1986	2		.0	2446468.5	6 5.389	-24 36.99	6 6.881	-24 37.37	1.52	23.20	2.17	15.32	14.1	1
1986	2		.0	2446478.5	6 7.733	-21 14.28	6 9.279	-21 14.80	1.67	25.54	2.26	15.10	14.5	2
1986	2		.0	2446488.5	6 12.653	-18 3.90	6 14.246	-18 4.68	1.82	27.64	2.34	14.87	14.8	2
1986	3		.0	2446498.5	6 19.638	-15 10.49	6 21.273	-15 11.64	1.98	29.46	2.43	14.63	15.2	2
1986	3		.0	2446508.5	6 28.283	-12 36.43	6 29.955	-12 38.02	2.16	30.93	2.51	14.39	15.5	2

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References

Brandt J C, Farquhar R W, Maran S P, Niedner M B & von Rosenvinge T 1983, The Third International Sun-Earth Explorer (ISEE-3) Mission to Comet Giacobini-Zinner (G/Z), Bull. Am. Astron., Soc., 15, No. 4, p. 960.

Brandt J C, Farquhar R W, Maran S P, Niedner M B & von Rosenvinge T, The International Cometary Explorer (ICE) Mission to Comet Giacobini-Zinner, Proc. IAU Colloquium No. 83, Dynamics of Comets, in press.

Farquhar R W & Dunham D W 1983, A late Entry in the Great Comet Chase, Astronautics and Aeronautics, 21, No. 9, p. 50.

Galeev A A & Scarf F L 1985, Coordinated Multispacecraft Plasma Science in the Solar-Wind and Comet-Plasma Environments (IACG WG-2), p. 233-243, ESA Publications Office, Noordwijk, The Netherlands, ESA SP-1066.

Ogilvie K W, von Rosenvinge T & Durney A C 1977, International Sun-Earth Explorer: A Three-Spacecraft Program, Science, 198, No. 4313, p. 131.
Yeomans D K & Brandt J C 1985, The Comet Giacobini-Zinner Handbook, International Halley Watch (IHW)/NASA-JPL Publication.