

Reports

The International Cometary Explorer Mission to Comet Giacobini-Zinner

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The International Cometary Explorer (ICE) became the first spacecraft ever to encounter a comet when it passed through the tail of comet Giacobini-Zinner. An overview of this encounter is presented, including highlights of the results.

ON 11 SEPTEMBER 1985, THE INTERNATIONAL Cometary Explorer (ICE) spacecraft passed through the tail of comet Giacobini-Zinner and made in situ measurements of particles, waves, and fields. The primary goal of this encounter was to study the interaction between the solar wind and the comet. This interaction was expected to be unlike any previously observed because the cometary atmosphere is not constrained by gravity. Neutral water molecules, sublimed from the comet nucleus by sunlight, freely escape at speeds of approximately 1 km sec^{-1} and are eventually ionized on a time scale of 10^6 seconds, leading to an extensive region of interaction millions of kilometers in diameter. Once ionized, the ions interact with the magnetic field of the solar wind and are carried radially outward from the sun. The acceleration of the "pick-up" ions causes the solar wind to slow significantly. The nature of this process was studied in situ and was found to be far stronger than had been anticipated.

At the time of launch in August 1978, the ICE spacecraft was known as the International Sun-Earth Explorer Number Three (ISEE-3). Little thought had been given to the possibility of its encountering a comet. Rather, ISEE-3 was part of a collaboration between the European Space Agency and NASA to study the interaction between the solar wind and Earth's magnetosphere. It was positioned in the solar wind some 240 Earth radii ($1.5 \times 10^6 \text{ km}$) upstream of Earth, where it observed disturbances and changes in the solar wind approximately 1 hour before they reached the outer magnetosphere. The ISEE-1 and -2 spacecraft, in orbit closer to Earth, then observed the magnetosphere's response to these changes. This first mission phase came to a close in the summer of 1982 when, following suggestions originated by R.W.F., two additional mission phases were undertaken: (i) exploration of the deep magnetic tail of Earth and (ii) a crossing of the tail of comet Giacobini-Zinner. The former was accom-

plished by gravitational flybys of Earth and the moon, and results have already appeared (1). A fifth and final lunar flyby on 22 December 1983 brought ISEE-3 within 120 km of the lunar surface and sent it out of the Earth-moon system. At this time the spacecraft was renamed ICE.

The ICE trajectory on the way to Giacobini-Zinner is depicted in Fig. 1, which also shows the comet headed toward the ecliptic plane. At the time of the encounter, Earth was in a good position for ground-based viewing. The cruise phase lasted almost 21 months. The on-board hydrazine propulsion system was vital to a successful intercept (2, 3), as was the astrometric support obtained from participants in the International Halley Watch. The ICE mission is complementary to the various comet Halley missions in that the latter are all targeted to pass on the sunward side of Halley. There was an estimated 10 percent chance of not successfully crossing the plasma ion tail. The uneven heating and removal of gas from the

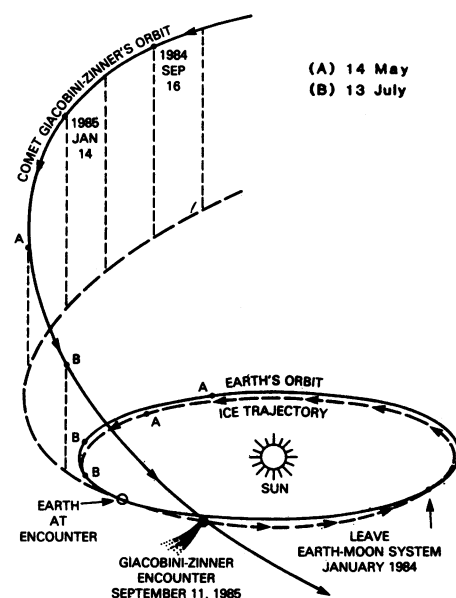


Fig. 1. Trajectories of the ICE spacecraft, comet Giacobini-Zinner, and Earth.

comet nucleus causes a net jetting action, the so-called nongravitational force, which is difficult to predict. The orbital adjustment in early August put the spacecraft directly on target for the then-existing comet orbit, and it was thought that the final maneuver scheduled for 4 September might not be necessary. However, as comet Giacobini-Zinner approached perihelion on 5 September, it became more active than expected, and it became evident that the comet orbit was shifting. Consequently the orbit maneuver was delayed until 8 September. The original plan had been to cross the comet ion tail 10,000 km downstream from the comet nucleus; the new comet orbit reduced this distance to 7800 km. A maneuver to restore the 10,000-km tail crossing was large and was deemed too risky. Consequently, on 8 September a smaller maneuver (a change in velocity of 2.3 m sec^{-1}) was performed to correct only the cross-tail error. This error, after correction, is estimated to have been approximately 600 km at a distance from Earth of $7.1 \times 10^7 \text{ km}$ [0.47 astronomical units (AU)].

At the time of the encounter the spacecraft was approximately 50 times farther from Earth than it was designed to go. This confronted the Deep Space Network with a very challenging task to recover the data. The telemetry stream was transmitted over two redundant transmitters in order to increase the power received at Earth. In addition, the bit rate was reduced to 1024 bits per second and 64-m dish antennas at Madrid, Spain, and at Goldstone, California, were arrayed with 34-m antennas to improve the signal margin. Backup coverage for 2 hours centered on closest approach was provided by the 300-m radio astronomy antenna at Arecibo, Puerto Rico (operated by Cornell University). Non-real-time data were also received from the new 64-m antenna at Usuda, Japan (operated by the Institute of Space and Aeronomy Science of Japan).

Before the encounter there was some concern that dust from the comet, impacting the spacecraft solar cells with a velocity of 21 km sec^{-1} , might cause a reduction in electrical power to the point that the spacecraft might go into undervoltage, that is, switch off all subsystems other than the command receiver. Consequently, 4 of the 13 instruments on board were switched off before the encounter and the heaters to the hydrazine

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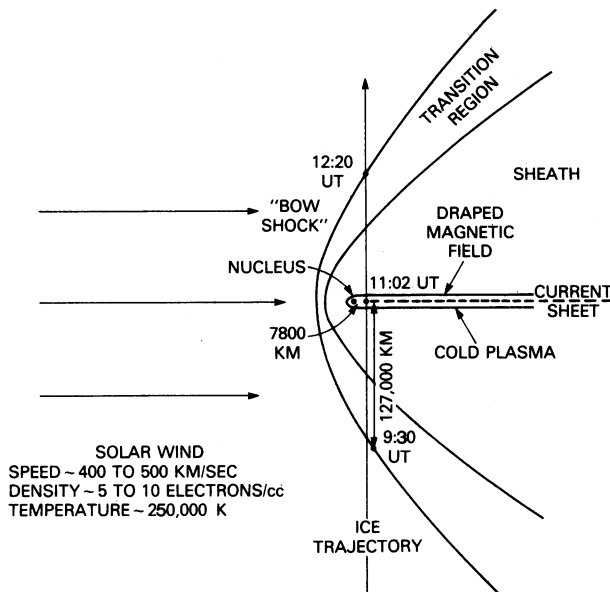


Fig. 2. Schematic of comet Giacobi-Zinner and the ICE trajectory crossing the comet ion tail 7800 km from the nucleus. The label "Bow shock" appears in quotes because the appropriateness of this label is not settled.

the other hand, it is associated with the Draconid (Giacobinid) meteor shower, which produced spectacular displays in 1933 and 1946.

The encounter. Figure 2 shows the encounter schematically, indicating the times different regions were crossed. The encounter geometry is further depicted in Fig. 3. Note that the spacecraft velocity vector, measured relative to the comet, made an angle of $\sim 93^\circ$ with respect to the plasma tail axis, that is, the trajectory was essentially perpendicular to the plasma tail axis.

The first signs that the comet was approaching were apparently detected by the plasma wave instrument, which started to detect mid-frequency electric field turbulence near 0400 U.T. (universal time) on 10 September, when ICE was 2.3×10^6 km from the nucleus. This turbulence is ascribed to the pickup of cometary ions described earlier (7). The first direct detection of these ions was made by the energetic proton experiment near the middle of the same day (8). The levels of activity in both instruments continued to increase with decreasing distance from the comet until they equaled the highest levels seen by these instruments at any time in the preceding 7 years in space. The low-energy cosmic ray experiment also began seeing cometary ions near midday on the 10th (9). It had not been anticipated that these low-energy ions (typically < 4 keV per nucleon) would be so readily observed.

Considerably closer to the comet ($\sim 2 \times 10^5$ km), the plasma electron instrument detected the comet's approach by observing enhanced fluxes of energetic (> 100 eV) electrons streaming along the interplanetary magnetic field in the direction opposite to the heat flux from the solar corona. Similar counterstreaming heat fluxes are observed upstream from Earth's bow shock when the interplanetary magnetic field connects to the hot magnetosheath plasma behind the shock. Ion acoustic waves and enhanced ion fluxes were observed in conjunction with the cometary electrons.

Before the encounter it was asked whether a bow shock would be found at all. It was thought that the gentle deceleration of the solar wind by the ion pickup process, distributed over a large region of space, might inhibit the formation of a bow shock. The evidence on this question is mixed. Essentially where a possible bow shock had been predicted to be, there does begin a "transition region" inside which the solar wind has been heated, compressed, and slowed (10). Within and outside the transition region, the magnetometer and plasma wave measurements reveal extreme hydromagnetic turbulence. There appears, however, to be

propellant system were also switched off in order to conserve power. As it turned out, the dust impact rate was extremely low and there was no detectable loss of power during the encounter.

There are 13 different scientific instruments on ICE. Of these, only seven were expected to give useful results about the comet, and reports corresponding to each of these follow. A brief description of the spacecraft and the instruments is given by von Roseninge and Brandt (4), while detailed descriptions of each instrument may be found in (5). The seven instruments are the plasma electron, magnetometer, plasma waves, radio waves, plasma composition, low-energy cosmic ray, and energetic proton instruments.

Comet Giacobi-Zinner. This short-period comet (6.5 years) was discovered in 1900 by M. Giacobi at Nice, France, and was "rediscovered" in 1913 by E. Zinner at

Bamberg, Germany. It is in a prograde orbit inclined to the ecliptic at an angle of 31.9° and with perihelion at 1.03 AU. At encounter the comet's velocity was 38.3 km sec^{-1} and the solar wind speed varied between 400 and 500 km sec^{-1} , leading to an aberration angle in the comet's orbit plane between 5.5° and 4.4° , respectively (the comet tail lags the radial line from the sun to the comet nucleus by this amount) (Fig. 3). The coma near 1 AU typically has a diameter of approximately 60,000 km and the plasma tail can reach lengths of 500,000 km or more. By late August, observations obtained from the IUE spacecraft indicated that the comet was releasing over 10^{29} water molecules per second. Observations on the day of encounter from IUE and the Pioneer Venus Orbiter (6) indicate that by then this figure had fallen to between 2×10^{28} and 5×10^{28} . Infrared observations suggest that Giacobi-Zinner is not particularly dusty. On

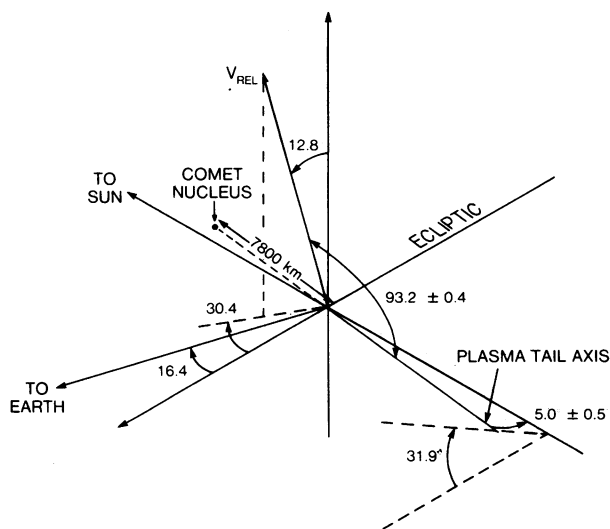


Fig. 3. Schematic of the ICE encounter geometry. The coordinate system shown has its origin at the point of closest approach to the comet; one axis points to the sun and another points to the north ecliptic pole. The comet orbital plane is inclined 31.9° to the ecliptic plane. The comet tail lags the comet-sun line by about 5° in the comet orbital plane. This angle has been exaggerated in the figure for clarity. V_{rel} is the velocity vector of the spacecraft relative to the comet.

no evidence of a conventional bow shock at the edge or within the region (10, 11). The appropriate scale on which to look for such a shock might be the gyroradius of singly charged water molecules in the solar wind frame (about 8000 km ahead of the transition region; by comparison, the gyroradii of protons and electrons were about 25 and 1 km, respectively). The transition region was entered inbound at approximately 0930 U.T. and was exited outbound at about 1220 U.T. This region was roughly 50,000 km thick where it was crossed.

Closer to the time of closest approach (that is, forward from ~ 1007 U.T. and backward from ~ 1148 U.T.), another plasma regime was found in which the average plasma flow velocity continued to decrease, but the average density and temperature began to decrease from their elevated values in the transition region. This regime has been termed a sheath (10). [The word sheath may also be used to include the transition region (11).] Within both the transition region and the sheath, the magnetometer experiment sees average magnetic field orientations consistent with draping of interplanetary field lines around the comet and possibly large ray-like structures parallel to the tail (11). Electron density spikes also suggest possible ray-like structures, although they may be density fluctuations associated with magnetohydrodynamic turbulence.

The spacecraft crossed the center of the comet ion tail at ~ 1102 U.T. Although the measurements from different experiments are consistent, there is no unanimity of terminology as applied to the tail. The plasma electron experimenters identified a boundary layer adjacent to an inner coma region containing a plasma tail only 2.4 minutes wide. By contrast, the magnetometer team identified, in approximately corresponding time intervals, a folded ray adjacent to an ion tail with an embedded current sheet. This situation reflects the fact that the various experimental data sets are only beginning to be analyzed jointly.

The radio wave and plasma electron instruments found a cold, dense plasma near the center of the tail. The radio wave instrument has wire antennas 90 m long (tip to tip) to measure electric fields in the plasma. By observing the spectrum of thermal electric field fluctuations, it is possible to deduce both the local electron density and temperature. These measurements are unaffected by changes in the spacecraft potential and the presence of photoelectrons removed from the sunlit side of the spacecraft, effects that limit the accuracy of the plasma electron instrument in the central region of the tail. Fortunately, the characteristics of the radio

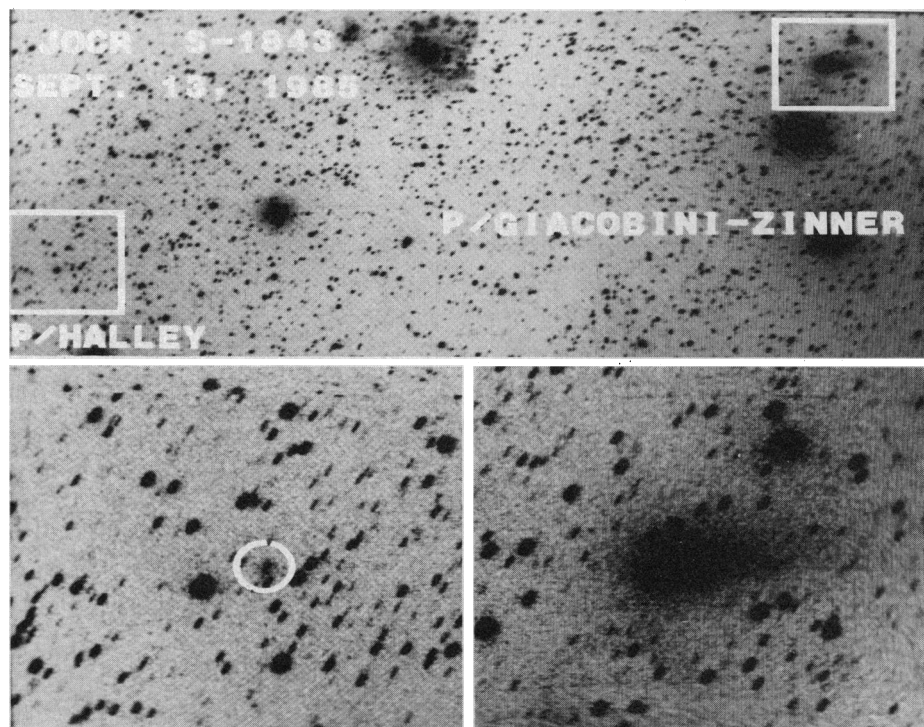


Fig. 4. Comets Giacobini-Zinner and Halley, as photographed on 13 September 1985. The upper part shows the portion of the Schmidt plate covering the two comets and the lower part shows an enlargement of the boxes around each comet. [Original photograph from the Joint Observatory for Cometary Research, operated by the Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center, and the New Mexico Institute of Mining and Technology]

wave instrument were nearly ideally matched to the tail plasma parameters. At the very center of the tail this instrument observed a temperature of only 13,000 K and a density of 670 electrons per cubic centimeter (12). These figures may be contrasted with interplanetary values observed by the plasma electron instrument before encounter of 250,000 K and less than ten electrons per cubic centimeter.

One of the more significant results obtained was confirmation of Alfvén's (13) model of the formation of a comet tail. Specifically, it was found that a magnetic lobe composed of magnetic field lines of one polarity extends from the coma on one side of the plasma tail, while a lobe of oppositely directed field lines is located on the opposite side of the tail (11). The two lobes are separated by a current sheet. This results from capture of interplanetary magnetic field lines by the cometary ionosphere. The outward motion of the solar wind carrying magnetic field lines causes the field lines to be bent around the nucleus like spaghetti around a fork. It had been thought that the spacecraft might move nearly parallel to the current sheet and hence pass through only one lobe. Passage through both lobes apparently occurred due to the current sheet being inclined to the ecliptic plane, although back and forth motion of the tail may also

have contributed. A similar field pattern has been observed at Venus. At Venus, however, the lobe field strength is approximately the same as for the interplanetary field, whereas at the comet the magnetic field peaked at about 60 nT, more than six times higher than the values observed just before and after encounter.

The ion composition experiment obtained direct measurements of the composition of a comet (14). Water group ions (HO^+ , H_2O^+ , H_3O^+) are the dominant component, and there is probably CO^+ or HCO^+ or both. These measurements verify that the major volatile constituent of Whipple's (15) "icy conglomerate" model of the nucleus is water ice. In addition, there are unidentified ions in the mass range 23 to 24; possible candidates are Na^+ and C_2^+ . A difficulty with the C_2^+ identification is that ground-based spectrometric observations of Giacobini-Zinner show very weak C_2 lines (3, 16). On this same basis, Na^+ is also an unlikely candidate. It is thought that C_2 will dissociate before it becomes ionized. Sodium could possibly be sputtered off the comet surface or off dust particles by ions energized by solar wind pickup.

Finally, the plasma wave experiment detected pulses attributable to dust particles hitting the spacecraft. The dust impact rate was low ($<0.5 \text{ sec}^{-1}$ peak), with the maxi-

imum rate occurring at closest approach (7). The radio waves group reported an upper limit to the dust flux for particles with mass exceeding 10^{-10} g that is 100 times lower than the predicted flux (3).

Shortly after the ICE encounter, comets Giacobini-Zinner and Halley were near each other in the sky. Figure 4 shows the symbolic changing of the guard.

The ICE spacecraft will be about 0.2 AU upstream from comet Halley in late March 1986. Disturbances and changes in the solar wind observed by ICE should be related to the behavior of Halley's ion tail observed from Earth by members of the International Halley Watch. Given the large distance from

which comet Giacobini-Zinner was first detected by ICE and the expected factor of 10 larger gas production rate for comet Halley, it is possible that ICE will detect comet Halley itself.

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Comet Giacobini-Zinner: Plasma Description

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A strong interaction between the solar wind and comet Giacobini-Zinner was observed on 11 September 1985 with the Los Alamos plasma electron experiment on the International Cometary Explorer (ICE) spacecraft. As ICE approached an intercept point 7800 kilometers behind the nucleus from the south and receded to the north, upstream phenomena due to the comet were observed. Periods of enhanced electron heat flux from the comet as well as almost continuous electron density fluctuations were measured. These effects are related to the strong electron heating observed in the cometary interaction region and to cometary ion pickup by the solar wind, respectively. No evidence for a conventional bow shock was found as ICE entered and exited the regions of strongest interaction of the solar wind with the cometary environment. The outer extent of this strong interaction zone was a transition region in which the solar wind plasma was heated, compressed, and slowed. Inside the inner boundary of the transition region was a sheath that enclosed a cold intermediate coma. In the transition region and sheath, small-scale enhancements in density were observed. These density spikes may be due to an instability associated with cometary ion pickup or to the passage of ICE through cometary ray structures. In the center of the cold intermediate coma a narrow, high-density core of plasma, presumably the developing plasma tail, was found. In some ways this tail can be compared to the plasma sheet in Earth's magnetotail and to the current sheet in the tail at Venus. This type of configuration is expected in the double-lobe magnetic topology detected at the comet, possibly caused by the theoretically expected draping of the interplanetary magnetic field around its ionosphere.

THE RESULTS OF THE LOS ALAMOS plasma electron experiment obtained during the encounter of comet Giacobini-Zinner with the International Cometary Explorer (ICE) on 11 September 1985 indicate that the solar wind interacted strongly with the comet. During the encounter, the spacecraft passed through several distinctive plasma regimes. Some preliminary interpretations of the plasma electron data are presented here. It is expected that these interpretations will be refined as more in-depth analyses become available. In particular, future analyses that make use of

the combined data of various experiments on ICE should lead to more detailed interpretations of the phenomena observed.

Instrumental details. Electron measurements were made with an electrostatic analyzer (I) composed of a spherical section analyzer with a 135° bending angle, followed by a system of secondary electron emitters and an electron multiplier that gives two- and three-dimensional capability. Only two-dimensional measurements of plasma electrons were made during the encounter so as to maximize the measurement repetition rate. A measurement cycle consists of

16 energy sweeps spaced uniformly throughout a 3-second spacecraft revolution. During each sweep, measurements are made at each of 15 energy levels. The experiment has two energy ranges: a "normal" range of 10 to 1000 eV and an infrequently used "photoelectron" range of 1.9 to 190 eV. The latter range was included for studying spacecraft charging, since a knowledge of the spacecraft potential is essential for analyzing low-energy electron data. At the encounter telemetry rate, one measurement cycle was obtained every 24 seconds, so the data format consists of 3-second data sets followed by 21-second gaps. In this report the data are presented in histograms in which the actual 3-second data acquisition times occur during the first 3 seconds of the 24-second-wide bars representing derived data points. In a few cases, abrupt changes in electron distributions occurred in times comparable to or less than the time between energy sweeps (~0.1 second). The plasma electron bulk flow speed, temperature, and density are determined by numerical integration of the entire plasma distribution.

The comet's plasma structure. Figure 1 shows a 10-hour plot of the electron moments during the solar wind-comet interaction (Fig. 1). The data extend from 0600 universal time (U.T.), when ICE was in the solar wind, through the central passage at ~1102 U.T., to 1600 U.T., when ICE was again in the solar wind. Shown are electron density (n), temperature (T), and plasma bulk speed (V), computed from the electron distributions. (The subscript e is to be understood for all the plasma moments throughout the text.) The data in Fig. 1 were processed through a three-point run-

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