The International Cometary Explorer (ICE) Wallsheet Teacher's Guide

edited by
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National Aeronautics and
Space Administration
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Preface

On September 11, 1985, the veteran NASA spacecraft ISEE-3, which has been renamed the International Cometary Explorer, will make the first visit of a spacecraft to a comet. This pamphlet is designed as a teachers' guide to the NASA wallsheet on the International Cometary Explorer (ICE) and its mission. The chapters have been extensively edited and the responsibility for any error inadvertently introduced is mine and not the respective authors'.

Teachers and their students should be aware that a large number of new books on comets have been published and that many of these are available in public libraries and bookstores. This circumstance, of course, results from the current interest in the return of Halley's Comet. This teacher's guide will be equally helpful in understanding scientists' strong interest in sending the ICE spacecraft to investigate the tail of a much less famous object, Comet Giacobini-Zinner.

For vital support of the ICE mission to Comet Giacobini-Zinner, the participating scientists are indebted to many individuals. This includes the staff of the Deep Space Network (DSN), operated by the NASA Jet Propulsion Laboratory in Pasadena, CA. The DSN has been augmented to track ICE. Two of its large antennas in Madrid, Spain and in California, will be receiving the data as ICE passes through the comet. The great 300 meter radio telescope of the Arecibo Observatory in Puerto Rico, operated by Cornell University, has also been especially equipped to receive the comet encounter data. The encounter has been timed for 11:00 a.m. EDT on September 11 when the comet and the spacecraft will be nearly overhead at Arecibo.

Appreciation is expressed also to the dozens of astronomers of the International Halley Watch Astrometry Net who have been photographing Comet Giacobini-Zinner and sending data on its changing position to Dr. Donald Yeomans of the Jet Propulsion Laboratory. From these data, Dr. Yeomans has kept track of changes in the comet's orbit, enabling controllers at the Goddard Space Flight Center, Greenbelt, MD, to plan the necessary mid-course maneuvers to keep the ICE spacecraft on course.

In the first chapter, John C. Brandt and I describe some basic properties of comets and summarize the observational history of Comet Giacobini-Zinner and its associated meteor showers. Next, flight director Robert Farquhar briefly describes the use of lunar gravity to redirect, accelerate, or decelerate a spacecraft. Lunar gravitational assist played a key role in sending ICE (or ISEE-3, the two spacecraft names are used almost interchangeably throughout this publication) on to Comet Giacobini-Zinner. Dr. Farquhar then provides a brief description of the original, unique "halo orbit" of ISEE-3 and the concept of libration points. In the chapter on History and Discoveries of ISEE-3, Tycho von Rosenvinge mentions just a few of the many interesting findings on the space environment and the terrestrial magnetosphere that have resulted from analysis of data gathered by this spacecraft. Malcolm Niedner, in "The ICE Mission to Comet Giacobini-Zinner," describes the instruments carried on the ICE spacecraft that are expected to contribute to our understanding of comets. Niedner describes some key features, according to present theory and knowledge, of the interaction of a comet with the solar wind. The teachers' guide concludes with a short contribution by Dr. Farquhar, on the future of the ICE spacecraft after it passes beyond Comet Giacobini-Zinner: first will come two opportunities to sample the solar wind upstream of Comet Halley, then in the year 2013, perhaps an opportunity to recover the aging spacecraft when it returns to the vicinity of Earth. This assumes that ICE will survive its likely bombardment by high-speed dust particles in the tail of Comet Giacobini-Zinner, and remain in operable condition.

For help in designing and producing the ICE poster and teachers' guide, special thanks are due to Elva Bailey, Howard Golden, Sam Haltom, Steve Meszaros, Arthur Shilstone, and Janet Wolfe.

Stephen P. Maran
July 1985

Comet Giacobini-Zinner, Target of The International Cometary Explorer

John C. Brandt
Stephen P. Maran

Selection of Comet Giacobini-Zinner

Comet Giacobini-Zinner was chosen as the target for the first voyage of a spacecraft to a comet because its orbit was found to take it within reach of an existing operational spacecraft, ISEE-3 (now renamed ICE, the International Cometary Explorer), that is suitably instrumented to study the magnetic fields and plasma phenomena that are known or believed to occur in comets.

The orbit of Comet Giacobini-Zinner takes it around the Sun about once every 6.6 years. The plane of the comet's orbit is tilted by 32° with respect to the plane of the orbit of the Earth. It is much easier to send an interplanetary spacecraft to points located in or near Earth's orbital plane than to destinations located well outside the plane, because much more energy is needed to travel out of the plane. On September 11, 1985, Comet Giacobini-Zinner will pass through the Earth's orbital plane at a distance of 0.47 astronomical units (about 70 million kilometers or 43 million miles) from Earth, and will be intercepted by ICE. This single-pass flyby of the comet is called the "encounter."

At the present time, the orbit of Comet Giacobini-Zinner has a perihelion (point closest to the Sun) of 1.03 astronomical units, about 154,000,000 kilometers or 96 million miles, from the Sun. However, the perihelion distance has been slowly changing as the comet is affected by gravitational perturbations by the planet Jupiter. The so-called nongravitational force, meaning the reactive force on the comet due to the escape of gases in a preferential direction, also affects the exact parameters of the comet's orbit.

A key point in planning a spacecraft voyage to a comet is that you must have adequate knowledge of the comet's orbit several years in advance of the proposed encounter, in order to plan and develop the mission. This explains why, for example, no spacecraft was sent to Comet IRAS-Araki-Alcock, which came very close to Earth in 1983. That comet was discovered only shortly before its close pass by Earth, whereas Comet Giacobini-Zinner has been under study since the beginning of the twentieth century.

Basic Facts About Comets

Although comets have been the subject of observation and speculation for thousands of years, modern cometary research dates to the early 1950s, when a consistent physical model for the nature of comets began to emerge.

The basic features of a comet, most of them shown in the sketch on the accompanying International Cometary Explorer poster, are the nucleus, coma, hydrogen cloud, and the two kinds of tail—dust tail and plasma or ion tail. Some comets display both types of tail, while some only have one or the other. The chapter on The ICE Mission to Comet Giacobini-Zinner describes some additional, mostly theoretical features of a comet and its interaction with the solar wind. Through the ICE mission, we hope to verify the existence of these additional features.

The *nucleus* is believed to be a "dirty iceball," composed mostly of water ice, but with some other frozen gases ("ices") and with interspersed interplanetary dust, that is, microscopic particles of rock. When a comet is far from the Sun, the nucleus is inactive, just an orbiting iceball. As such, it is the only permanent or quasi-permanent structure in a comet. However, as a comet follows its orbit and comes closer to the Sun, sunlight heats the surface layers. As heating continues, the temperature of the surface layers of the nucleus rises until *sublimation*, the transformation of matter from solid to gas without passing through the liquid state, begins. The sublimation of dry ice, a familiar phenomenon in which the frozen substance turns directly to gaseous carbon dioxide, is a good example of this process. For completeness, students should recall that transformation from solid to liquid is melting, while transformation from liquid to gas is called evaporation.

As the comet continues to approach the Sun, sublimation becomes more and more efficient, so that essentially all the energy of the sunlight absorbed by the nucleus results in the release of gas. As the frozen water and other substances sublimate, the escaping gases blow away the interplanetary dust particles that were trapped near the surface of the ice. Some dust particles may form a temporary, porous, crust at the surface of the nucleus. Ultimately, these particles are also blown away. The escaping gas and dust are forever lost to the comet, although they form temporary features, such as the coma (atmosphere) and the tails. It has been estimated that a typical comet making a pass through the inner solar system loses about one percent of its mass. Therefore (assuming no other fate befell the comet), comets with orbits that take them within the inner solar system (defined as within about the orbit of Mars) will eventually die out as repeated passages strip them of their frozen matter.

The dust and gases released from the nucleus of a comet form the *coma*, an expanding, roughly spherical atmosphere that surrounds the nucleus. Water molecules (H_2O) are the primary component of the gas released from the nucleus. However, the water molecules are dissociated (separated into smaller components, hydrogen atoms, OH molecules, oxygen atoms) by ultraviolet radiation from the Sun. The hydrogen atoms form a huge *hydrogen cloud* that surrounds the nucleus and is much larger than the coma. Unlike the coma, the hydrogen cloud is not visible in ordinary photographs, because it glows detectably only in ultraviolet light. The existence of hydrogen clouds around comets was discovered in 1970 with ultraviolet telescopes carried on two Earth-orbiting satellites.

There are two distinct types of comet tails, formed by the interaction of the coma with light and atomic particles from the Sun. The radiation pressure of sunlight pushes dust particles from the coma in the anti-sunward direction. They form a smooth, curved *dust tail* that shines by reflecting sunlight and therefore appears yellow in color photographs. *Plasma tails*, also called ion tails, are less smooth; they generally appear highly structured, sometimes with linear features, blobs, kinks, or other noticeable details. The plasma tails are formed when molecules and atoms in the coma are ionized and then accelerated out of the coma by a complex, incompletely understood interaction with the solar wind, the continuous, high-speed outpouring of ions and electrons from the Sun's outer atmosphere. Ionization is the removal of an electron from an atom or molecule; it produces a positively charged ion and the newly-freed, negatively charged electron.

Typical sizes for the parts of a comet are: nucleus—diameters of a few kilometers; coma—diameters of tens to hundreds of thousands of kilometers; hydrogen cloud—diameters of hundreds of thousands to a few million kilometers; tails—lengths of millions to hundreds of millions of kilometers. There are approximately 1.609 kilometers to one mile. For a given comet, the size of the coma depends on the distance of the comet from the Sun and also on the measurement method that is used. In fact, the coma is an atmosphere and thins out gradually to very large distances. Diameters are usually quoted primarily for illustrative purposes.

As a comet recedes from the Sun and solar heating becomes negligible, the coma, hydrogen cloud, and tail(s) gradually dissipate into space so that only the nucleus remains. When the comet returns to the inner solar system on its next trip toward the Sun, a new coma, hydrogen cloud, and tail(s) will form.

History of Comet Giacobini-Zinner

This moderate-sized comet has been photographed at several apparitions in this century. Some of the best photographs were obtained at the comet's 1959 apparition; one is shown on the accompanying International Cometary Explorer poster. Spectroscopy and measurements of polarization of light from the comet have also been accomplished. However, it will best be remembered as the first comet to be visited by a spacecraft. The comet is generally too dim to be observed without telescope or binoculars. Until now it has been better known for the associated meteor showers than for its display of cometary forms.

Meteors from the Comet

Comet Giacobini-Zinner is associated with the famous Giacobinid meteors, now known by international convention as the Draconid meteor shower. This meteor shower can occur in October as the Earth passes near the orbit of the comet. In most years, this meteor shower is not observed, but occasionally it is truly spectacular. Meteors or "shooting stars" are the brief streaks of light caused as interplanetary dust particles fall at high speed through the Earth's atmosphere and are heated by friction, just as the nose cone of a rocket is heated during reentry.

The most famous display of the Draconid meteors occurred over Europe on October 9, 1933. During a few minutes at the peak of the shower, an estimated 350 meteors per minute were visible from a given point on the ground. On that occasion, the Earth passed near the orbit of Comet Giacobini-Zinner just 80 days after the comet had gone by. In contrast, in 1949 and 1940, the Earth passed by about six months early and about six months late, respectively, and in each case no Draconid meteors were seen. Radar observations have, on occasion, registered a weak Draconid meteor shower when the Earth passed its intersection point with the comet's orbit long before or after the comet passed that point, which indicates that some dust from the comet has spread well around the orbit. The Draconid shower is named for the location in the sky, in the constellation Draco the dragon, from which the meteors seem to arrive. It is the direction from which Comet Giacobini-Zinner would seem to come if it were approaching the intersection point at the same time as the Earth.

Although the actual size of the nucleus of Comet Giacobini-Zinner is unknown, a recent study suggests that it is about 2.5 kilometers (about 1.6 miles) in diameter, and possibly severely flattened at the poles, so that it is much larger in the equatorial plane than along the line between the poles. A dirty iceball of this size would yield a few times 10^{28} gas molecules per second under solar heating at a distance of 1 astronomical unit (about 150 million kilometers, or 93 million miles) from the Sun. The actual gas production rate of Comet Giacobini-Zinner is now being determined by astronomers using groundbased telescopes and a NASA satellite called the International Ultraviolet Explorer.

The hydrogen atoms in the hydrogen cloud of Comet Giacobini-Zinner are so-called first-generation products, meaning that they are not present in the same form in the nucleus of the comet but are produced by the breakup of molecules that sublimated from the nucleus. The larger molecules actually present in the nucleus are called "parent molecules." The presence of atoms and molecules in comets, until now, has been determined by recording the spectrum of the coma and the plasma tail. It is believed that most of the substances detected in this manner are first-generation products and that only a few parent molecules have been detected thus far.

Discovery and Rediscovery of Comet Giacobini-Zinner

Comet Giacobini-Zinner is named for two astronomers who discovered it independently of each other 13 years apart. First, M. Giacobini of the Nice Observatory in France found the comet on December 20, 1900, and it was named Comet Giacobini. The comet, with its roughly 6.5-year orbital period, must have reappeared in about mid-1907, but it went unseen at that time. After a second orbital revolution about the Sun, the comet was found on October 23, 1913 by E. Zinner at the Remeis Observatory in Bamberg, Germany. Zinner thought that he had discovered a new comet, but it was soon recognized that the orbit of "Comet Zinner" was essentially the same as that of Comet Giacobini and that the two objects were in fact one and the same comet. Since then, it has been known as Comet Giacobini-Zinner.

Apparitions of the Comet

The arrival and appearance of a comet in the inner solar system, where it may be relatively bright for a few weeks or months, is termed an apparition. The first finding of a comet is, of course, the "discovery." The first spotting of the same comet on each subsequent apparition is called the "recovery" of the comet at the corresponding apparition. The discovery and subsequent apparitions of Comet Giacobini-Zinner are listed in Table 1. Tabulated there are the dates of discovery or recovery, the observers' names and institutions, and the approximate apparent magnitude of the comet at the time it was found. "Observatoire" and "Sternwarte" are the French and German terms, respectively, for "Observatory." As can be seen from the Table, there have been eleven observed apparitions to date; the apparitions that must have occurred around 1907, 1921, and 1953 went unseen. Magnitude is an astronomer's term for brightness; the smaller the magnitude numerically, the brighter the object. Bright stars are about magnitude 1; the faintest stars usually visible with the unaided eye from a dark location are magnitude 6; the faintest objects currently observable with sensitive electronic detectors on the world's largest telescopes are about magnitude 25. Note that there seems to be a clear trend toward numerically larger or fainter magnitudes with time in Table 1. This does not mean that Comet Giacobini-Zinner has been getting fainter. Instead, the trend reflects improvements in the technology of observation, which have allowed astronomers to spot the comet at greater and greater distances (*i.e.*, earlier and earlier) on successive apparitions, before it reached maximum apparent brightness. For example, the earliest apparitions listed in the Table were observed visually, the astronomers simply peering through their telescopes. Next, as photography became a sensitive method of observation, the apparitions of Comet Giacobini-Zinner were photographed through telescopes; time exposures allowed astronomers to reach fainter magnitudes. Finally, in the latest apparition, the recovery observation was made with a sensitive electronic detector operating near the state-of-the-art of modern technology.

The most recent recovery of Comet Giacobini-Zinner was accomplished, as listed in Table 1, when the comet was at magnitude 23, well before it reached perihelion. That's twelve magnitudes fainter than the 1900 discovery magnitude of 11, or a factor of about 60,000 times fainter, a dramatic illustration of the improvement of observational technology since the beginning of the century.

The Solar Wind and Comets

The solar wind is an ionized gas that flows radially outward from the Sun at a speed of about 400 kilometers per second (about 240 miles per second). The density of the solar wind is less than that of the best laboratory vacuum: at the Earth's distance from the Sun, there are just 5 to 10 electrons and an equal number of protons per cubic centimeter in the solar wind (about 60 to 160 electrons or protons per cubic inch). Yet this very tenuous wind has pronounced effects on the plasma tails of comets. The tails respond to the solar wind like windsocks in a stiff breeze. In fact, the existence of the solar wind was inferred in the early 1950s from the behavior of comet plasma tails as revealed by telescopic photographs.

The solar wind carries solar magnetic field lines along as it flows out into space. Because these field lines are anchored in the Sun, the combination of the solar wind outflow and the rotation of the Sun produces a spiral pattern of magnetic field lines in interplanetary space, much in the way that a rotating lawn sprinkler produces what an observer perceives as a spiral pattern of water streams.

The interaction of the rapidly flowing, ionized and thus electrified solar wind and its embedded magnetic fields with a comet can produce spectacular effects and is thought to involve many important processes of plasma physics. In some cases, these interactions cause a plasma tail to break off and float away from a comet, which then grows a new plasma tail, like a lizard with the ability to regenerate a lost tail.

The principal features of the interaction of a comet with the solar wind are described in the accompanying chapter on The ICE Mission to Comet Giacobini-Zinner. However, it must be emphasized that nearly all of the structures and phenomena in this described interaction are theoretical; our first chance to test the theories involved will come on September 11, 1985, when the International Cometary Explorer makes the first visit of a spacecraft to a comet.

Table 1
Observed Apparitions of Comet Giacobini-Zinner

Date	Observer Institution	Approximate Magnitude
Dec. 20, 1900	Giacobini/Observatoire de Nice	11
Oct. 23, 1913	Zinner/Remeis-Sternwarte	9-10
Oct. 16, 1926	Schwassmann/Hamburger Sternwarte	14
Apr. 23, 1933	Schorr/Hamburger Sternwarte	15
Oct. 15, 1939	Van Biesbroeck/Yerkes Observatory	15
May 29, 1946	Jeffers/Lick Observatory	17
May 8, 1959	Roemer/U.S. Naval Observatory	20
Sept. 17, 1965	Roemer & Lloyd/U.S. Naval Observatory	20
Mar. 11, 1972	Roemer & McCallister/University of Arizona	19
Apr. 30, 1978	Shao & Schwartz/Harvard College Observatory	20-21
Apr. 3, 1984	Djorgovski & Spinrad/Univ. of California, Berkeley	
	Will & Belton/Kitt Peak National Observatory	23

Lunar Swingbys and the First Orbit of ISEE-3

Robert W. Farquhar

Most artificial satellites follow orbits around the Earth that are tightly bound by the Earth's gravity. Therefore, large propulsive maneuvers ("rocket burns") are needed to move these satellites into significantly different orbits. In contrast to this situation, the spacecraft ISEE-3 originally followed a so-called "halo orbit" around a point in space where the respective gravitational attractions of the Sun and Earth on an object such as a spacecraft are equal. Therefore, relatively small propulsive maneuvers were capable of making major changes in the flight path of ISEE-3, for example to send it from the halo orbit on a trajectory approaching the Moon. Even so, the increase in the orbital energy of the spacecraft needed to send it off to a comet was beyond the capability of the on-board propulsion system. The solution that we adopted was to use the propulsion system to maneuver ISEE-3 close to the Moon and to use the gravity field of the Moon to achieve the required spacecraft orbital energy. In other words, we used the Moon's gravity to accelerate ICE toward the comet. In preparation for doing this, we also used the Moon's gravity to help send the spacecraft on its voyage through and around the Earth's magnetic tail.

As the Moon follows its orbit around the Earth, the side that faces forward on the orbit is called the "leading hemisphere," while the side that faces backward on the orbit is called the "trailing hemisphere." When a spacecraft flies past the Moon on the trailing side, the craft is accelerated with respect to the Earth (meaning that its velocity with respect to the Earth increases). On the other hand, when a spacecraft flies past the Moon's leading hemisphere, the craft is decelerated with respect to the Earth. The closer a spacecraft approaches the Moon during a lunar swingby (other things being equal), the greater the pull of gravity and the greater the acceleration or deceleration that occurs.

ISEE-3 made four lunar swingbys in the course of its survey of the Earth's magnetic tail. By directing the craft past the appropriate side of the Moon in each case, the first and third maneuvers were designed to decelerate the spacecraft, while the second and fourth maneuvers accelerated it. These first four lunar swingbys of ISEE-3 all occurred with closest lunar approaches that were fairly large, about 20,000 kilometers (over 12,000 miles) each. However, the fifth and final lunar swingby, which sent ISEE-3 out toward Comet Giacobini-Zinner, occurred with a closest lunar approach of only 120 kilometers (about 75 miles), so that the substantial increase in speed required to leave the Earth-Moon system and reach the comet was attained. As ISEE-3 departed from the Earth-Moon system on the date of the fifth lunar swingby, December 22, 1983, it was renamed the International Cometary Explorer by NASA.

Gravity-assist maneuvers to make major adjustments in the trajectory of a spacecraft have been used before as NASA space probes flew past the planets Jupiter and Saturn. In one such maneuver, the probe Pioneer 10 was sent on a new path that permitted it to leave the solar system and depart into interstellar space. However, the ISEE-3/ICE mission represents the first case in which the Moon has been used to redirect a spacecraft. ISEE-3 was also the first spacecraft to be placed in a halo orbit.

ISEE-3's Halo Orbit

In 1771, the French mathematician J. Lagrange demonstrated that in the combined gravitational field of two attracting bodies such as the Earth and the Moon (or the Earth and the Sun), there are five special locations, the libration points. These locations have the interesting property that if a spacecraft is placed at a libration point with just the right velocity, the craft will remain in a fixed geometrical relationship with the two attracting bodies. For example, a spacecraft placed at the L_1 libration point in the Earth-Sun system, located on the line from the Earth to the Sun, at about one per cent of the distance to the Sun, will remain on that line as the Earth orbits around the Sun. As the Earth moves around the Sun, the Earth-Sun line rotates, but our hypothetical spacecraft would remain on the line.

The L_1 point, about 1,500,000 kilometers (roughly 930,000 miles) from the Earth, is seemingly an ideal location to study the solar wind as it approaches the Earth. Since this was the original scientific goal of ISEE-3, why was the spacecraft placed in an orbit around L_1 rather than at L_1 itself? The answer relates to the fact that the Sun produces strong radio wave emissions. If ISEE-3 had been positioned right at L_1, it would have been directly in line with the Sun, as seen from Earth-based tracking antennas, and the solar radio waves would have interfered with reception of the radio telemetry from the spacecraft.

Lagrange's mathematical discovery of libration points in the eighteenth century is a good illustration of the importance of basic research. His work was purely theoretical at the time, but in the twentieth century, NASA could plan the stationing of ISEE-3 near a libration point as a practical application of Lagrange's work.

History and Discoveries of ISEE-3

Tycho von Rosenvinge

The Solar Wind and the Earth's Magnetotail

The Sun's outer atmosphere or corona expands radially outward into space and pervades the entire solar system as a "solar wind" of ionized gas, flowing at speeds typically between 300 and 800 kilometers per second (about 200 to 500 miles per second). The solar wind is a consequence of the million degree K temperature of the corona, which produces a pressure so high that not even the powerful gravity of the Sun can prevent gas from escaping. The wind carries energy in the form of the kinetic energy of the gas particles; it also carries along magnetic field lines drawn out from the Sun.

The solar wind interacts with the Earth and the Earth's magnetic field in a complex manner, which has been under study since the earliest days of space exploration. For example, a bow shock forms around the Earth, outside the Earth's magnetosphere (which contains the famous trapped radiation zones or Van Allen Belts). The bow shock is present because the solar wind flows faster than the speed with which magnetic disturbances can propagate through it. Thus, the bow shock is analogous to the shock wave that we hear as a sonic boom when an airplane passes by at faster than the speed of sound. The solar wind also stretches the Earth's magnetic field lines in the direction opposite the Sun, thereby forming the Earth's long magnetic tail. This "magnetotail" is thought to resemble the plasma tail (ion tail) of a comet. ISEE-3 has successively studied the solar wind and the magnetotail; as the International Cometary Explorer, it will explore a comet's plasma tail.

Purpose of the ISEE Project

The International Sun-Earth Explorer (ISEE) Project, a joint effort of NASA and the European Space Agency, has the primary goal of investigating the interactions of the solar wind with the Earth. Previous studies were based on measurements by a single satellite at a time. Thus, it was impossible to distinguish between changes in measured quantities that were due to differences in the location of a moving satellite and those that were due to temporal changes in the Earth/solar wind interactions. The ISEE Project, with its three satellites, was a major step towards eliminating this ambiguity. The ISEE-1 and ISEE-2 spacecraft were launched together into the same highly elliptical orbit around the Earth; their separation along the orbit could be controlled by remote command. The orbit was chosen specifically to study the bow shock and the magnetopause. The latter, located within the bow shock, is a surface within which the magnetic field lines are connected to the Earth at one or both of their ends. On the other hand, ISEE-3 was put into an orbit which kept it in the solar wind upstream (*i.e.*, toward the Sun) of the Earth and its bow shock, at a distance of about 240 Earth radii (R_e) from the Earth (see "Lunar Swingbys and the First Orbit of ISEE-3"). The role of ISEE-3 at this location was to observe the solar wind before it encountered the Earth, while ISEE-1 and ISEE-2 observed the response of the Earth to changes in the wind. As an example of solar wind-induced changes, the bow shock moves considerably in and out with respect to the Earth as the pressure exerted by the solar wind changes. It took about one hour for a typical solar wind feature to travel from ISEE-3 to the bow shock.

Spacecraft Description

The ISEE-3 spacecraft is a 16-faceted drum, approximately 5'8" in diameter and 5'3" high. Most of its payload of scientific instruments are mounted in the midsection. Solar panels, located above and below the midsection, convert sunlight into electricity to power the spacecraft. Originally, power generated from sunlight also could be stored in batteries on board, but the batteries are now dead. Thus, if ISEE-3 travels through a shadow, such as the shadow of the Moon, its electrical equipment goes dead until the spacecraft reemerges into sunlight. The spacecraft rotates around the central axis of the drum (the "spin axis") once every three seconds. The spin axis is maintained in an orientation perpendicular to the plane of the Earth's orbit around the Sun.

Magnetic fields encountered by ISEE-3 are measured by the magnetometer instrument and by a device called the search coil, each of which is located at the end of separate, 3-meter-long booms that extend in opposite directions out from the drum. The purpose of the two booms is to support the sensitive magnetic detectors at positions away from the magnetic fields that arise in the metallic spacecraft itself. Thus, interference by the spacecraft magnetic fields with measurements of the magnetic fields present in space is minimized. Four long wires extend radially outward into the spin plane of the spacecraft (the plane passing through the center of the drum, perpendicular to the spin axis). These are antennas that measure 91 meters tip-to-tip; a third antenna is formed by thin metallic tubes that extend above and below the spacecraft along the spin axis. These three antennas have been used primarily to observe bursts of radio waves from disturbances on the Sun. A tower, mounted atop the spacecraft, carries two instruments and also a fourth antenna. This "medium-gain antenna" is used to receive commands transmitted from ground controllers and to transmit measurement data and information on spacecraft status back to the Earth. For most of its operational life, ISEE-3 has steadily transmitted at a rate of 2000 bits per second. During the encounter with Comet Giacobini-Zinner, the planned data rate will be 1024 bits per second. The spacecraft carries a hydrazine-fueled rocket propulsion system. At the time of launch, on August 12, 1978, ISEE-3 weighed about 450 kilos, including about 90 kilos of hydrazine propellant.

Shocks, Flares and Foreshocks

The initial location of ISEE-3, upstream of the Earth in the solar wind, was ideal for observing the plasma particles and magnetic fields in the solar wind for correlation with measurements made by ISEE-1 and ISEE-2. It was also ideal for observing X-rays, energetic particles, and radio bursts emitted by solar flares, powerful eruptions on the Sun. Since ISEE-3 was always located close to the line from the Earth to the Sun, it was never behind the Earth when a solar flare occurred. Besides instruments to measure the above solar wind and solar flare phenomena, ISEE-3 was equipped to study high energy particles (cosmic rays) and high energy photons (gamma rays) arriving from beyond the solar system.

The sunspot cycle reaches a broad maximum, when there are many spots on the Sun, once every eleven years. The frequency with which solar flares erupt also peaks during this maximum. The August, 1978 launch of ISEE-3 took place as solar activity was building toward the maximum that occurred around 1981. Using the measurements from ISEE-3, investigators studied the acceleration of atomic particles and other phenomena that were associated with transient shock waves that sweep out through the solar system from solar flares. The highly elliptical orbit of ISEE-1 and ISEE-2 took those satellites periodically dipping deep inside the Van Allen Belts, then sailing well beyond the bow shock. Outside the bow shock, ISEE-1 and ISEE-2 explored a little known region located in the direction toward the Sun, the foreshock. From measurements by ISEE-3, physicists learned that sometimes an analogous foreshock is located in front of the fast-moving shock waves from solar flares.

Exploring the Magnetotail

Before the voyage of ISEE-3, the Earth s magnetotail had mainly been studied only to about the distance of the Moon's orbit around the Earth (about 60 earth radii, 60 R_e). However, in mid-1982, ISEE-3 was redirected from its position on the sunward side of the Earth, upstream in the solar wind, into a series of looping trajectories downstream, which allowed the spacecraft to spend much of 1983 in the distant magnetotail, at 60 R_e to 240 R_e. Before this survey began, even the basic structure of the distant magnetotail was unknown. One possibility under consideration was that the distant magnetotail is structured much like the near portion, whch had already been established by studies with other spacecraft. Specifically, it was proposed that the distant magnetotail is formed from two magnetic lobes, one in the north comprising magnetic field lines that are directed toward the Sun, and one in the south with oppositely-directed field lines. Between the two lobes, according to this theory, is the region called the plasma sheet and, inside that, a thin zone known as the neutral sheet. An alternative theory proposed that the distant magnetotail is divided into multiple magnetic filaments, resembling the filamentary structure shown in many photographs of the plasma tails of comets. The ISEE-3 1983 survey showed that the first theory is correct. Detailed studies of the magnetotail data gathered by ISEE-3 are improving our understanding of the process by which solar wind plasma enters the magnetotail and revealing how magnetic field lines in the solar wind connect and disconnect with field lines of the magnetotail, which originate at the Earth.

ISEE-3 made important new observations pertaining to geomagnetic storms, world wide disturbances that sometimes follow the occurrence of a large flare on the Sun. The magnetotail was found to swell, increasing in diameter just prior to the onset of a geomagnetic storm as observed at the Earth. This swelling corresponds to a buildup of stored magnetic energy in the tail that is derived from the solar wind. When this energy is suddenly released, the plasma sheet in the magnetotail apparently is severed close to the Earth, causing the release of a large blob of plasma (plasmoid) that sweeps down the magnetotail away from the Earth.

The plasmoids observed by ISEE-3 (one such event is illustrated in the accompanying International Cometary Explorer poster) typically passed the spacecraft in the magnetotail twenty to thirty minutes after the onset of a geomagnetic storm at the Earth. This arrival delay is consistent with the measurements of a plasma speed, which ranged from 500 to 1000 kilometers per second (about 300 to 600 miles per second). As a plasmoid flies down the magnetotail, the blob grows larger because it is moving through regions of systematically decreasing magnetic pressure.

A few of the major findings on the magnetotail from ISEE-3 are summarized above. Continued analysis of the extensive data set gathered in the tail should lead to additional significant findings. This careful study of the Earth's magnetic tail should also help us in interpreting measurements made by the same instruments when ISEE-3, in its role as ICE, passes through the plasma tail of Comet Giacobini-Zinner on September 11, 1985.

The ICE Mission to Comet Giacobini-Zinner

Malcolm B. Niedner, Jr.

Scientific Rationale for the ICE Mission

A comet's interaction with the solar wind—a hot (100,000 K), rarefied (5-10 particles per cubic centimeter), and ionized gas flowing supersonically (400 kilometers per second, or about 250 miles per second) away from the Sun—is an extremely complex process which is incompletely understood today. It is an important area of inquiry because of its large role in determining a comet's structure, because of its application to the general study of planetary/solar wind interactions, and also because of the desirable use of comets as "natural probes" of the solar wind. Moreover, some of the most exciting plasma physics processes we know of today probably occur, and can be studied, in comets. Ironically, despite our incomplete understanding, it was the observed properties of cometary plasma tails that were largely responsible, in the 1950s, for the "discovery" of the solar wind before the advent of direct interplanetary exploration by spacecraft.

Gaps exist in our knowledge because remote observations of comets, both from the ground and even from Earth orbit, are incapable of measuring some of the physical variables of maximum interest, such as electric and magnetic fields, plasma densities, temperatures, flow speeds, and so on. The only method for determining these physical conditions is to visit a comet with an appropriately-instrumented spacecraft and to make *in situ* measurements. ICE is such a craft and its encounter with Comet Giacobini-Zinner promises to supply unique data which will answer many of our present questions, and undoubtedly pose new ones.

Definitions and Basic Features of the Comet/Solar Wind Interaction

Before discussing in detail ICE's instruments and the science goals they will address, it is worth examining the basic properties of the regions of a comet which ICE will traverse. Figure 1 is a schematic diagram which shows 7 regions and features to keep in mind. The *nucleus* is a several kilometers wide chunk of frozen ices with embedded dust grains, a kind of "dirty iceberg." Under the action of solar heating, the surface layers of the nucleus go directly into the gas phase, a process known as "sublimation." The gases and dust grains they carry out with them expand with a speed of about 1 kilometer per second (0.6 mile per second) with respect to the nucleus. The gas molecules, such as H_2O, CO, and CO_2, are initially neutral, but as they flow outward they gradually become ionized; that is, they lose an electron and acquire a net positive charge. Some neutrals are ionized very close to the nucleus, say within 100 seconds after leaving it; others may survive for 10^6 seconds before being ionized at large distances from the nucleus. As Figure 1 shows, these ions are created in the *ionosphere* and *foreshock* regions, respectively. Both kinds of ions have special roles in the interaction of a comet with the solar wind, as explained below.

The most effective (though not only) ionization mechanism is probably photoionization, which occurs when an energetic particle of sunlight, or photon, interacts with the neutral molecule to produce an ion and a free electron. For example:

$$CO + \text{photon} \blacktriangleright CO^+ + \text{electron}$$

Other ions which have been observed in past comets include H_2O^+, CO_2^+, and C^+.

The solar wind consists mostly of protons, electrons, and a "frozen in" interplanetary magnetic field, which is an extension into interplanetary space of the Sun's magnetic field. The "frozen in" property referred to above is a general feature of magnetic fields in many plasmas, both in the laboratory and in space, and is a difficult concept to grasp; the basic idea is that the magnetic field is part of the plasma and moves with it. The point to be made about cometary ions in the foreshock region is that they cannot freely penetrate the interplanetary magnetic field, despite their speed of about 400 kilometers per second relative to it. A magnetic force is exerted on the ion perpendicular to its motion and the magnitude of this force depends on the component of the ion's motion perpendicular to the magnetic field. If the ion moves parallel to the field, *i.e.*, has a zero perpendicular component, there is no force, whereas the force achieves a maximum value if the ion's velocity is exactly perpendicular to the magnetic field. As a result, the ion spirals around the magnetic field line (see Figure 1) and is in effect "captured" onto it. Since the ions have appreciable mass (*e.g.*, CO^+ equals the mass of 28 protons), they provide a "drag" force on the solar wind and slow it down. The solar wind is decelerated continually as it moves toward the nucleus and captures more and more cometary ions.

At some critical distance from the nucleus of a comet, the solar wind will have been contaminated by cometary ions to the extent that a bow shock will probably form. For Comet Giacobini-Zinner, the "nose" of the shock will probably lie somewhere between 50,000 and 100,000 kilometers (about 30,000 to 60,000 miles) toward the Sun from the nucleus. In a sense, the shock will be qualitatively similar to the wake of a ship because it will separate smooth or "quiet" solar wind in the foreshock region from a turbulent and heavily contaminated solar wind in the *magnetosheath* region (see Figure 1). Owing to the limitations of traditional observations from the ground, a bow shock has never been observed in any comet. The detection of Comet Giacobini-Zinner's bow shock is a major objective of the ICE mission.

The shocked plasma in the magnetosheath of a comet is greatly compressed and slowed down from the initial density and speed of the undisturbed solar wind. In addition, the strength of the frozen-in magnetic field is substantially increased over the interplanetary field, perhaps by a factor of five to ten. If enough ions are created close to the nucleus in the cometary *ionosphere*, then the outward pressure exerted by these ions may be sufficient to withstand the inward pressure of the solar wind plasma. At the point of pressure balance, a *contact surface* forms, separating the magnetosheath plasma and magnetic fields from the ionosphere. Note that the interplanetary magnetic fields become "hung up" on the contact surface and fold around behind the comet to form a magnetic tail structure which channels ions created in the head region. Because some of these ions fluoresce in sunlight, the magnetic tail is visible in photographs and has a name: *plasma tail*. Comet Giacobini-Zinner's plasma tail, as it appeared in October, 1959, is shown on the accompanying International Cometary Explorer poster.

The concept of interplanetary magnetic field capture and resultant plasma tail formation by a comet is not an easy one but an analogy perhaps makes the process clearer. Suppose you were to throw a baseball at a spider web whose strands were strong enough to stretch without breaking. Web strands would stick on the front side of the ball (analogous to the comet head): away from and behind the ball, the strands would form a tube or tail structure. The captured interplanetary magnetic field lines threading the plasma tail of a comet are analogous to the hypothetical spider web strands stuck to the baseball.

If our intuitive picture of a plasma tail is correct, then the tail should be divided into two magnetic lobes of opposed magnetic field direction (Figure 1). The reason for this is that the tail forms from field lines folding from opposite directions. It is a known fact in electromagnetism and plasma physics that when oppositely directed magnetic fields come in close contact, they drive electric currents of charged particles (mostly electrons). These currents are themselves often unstable and break down, generating radio and plasma waves. Plasma waves may be thought of as electric and/or magnetic vibrations or disturbances in the plasma (ionized gas). Their properties (such as wavelength and amplitude) reveal the type of instability and the character of the plasma itself. Because of its double-polarity structure, the cometary plasma tail is expected to possess a current sheet near the middle of the tail (Figure 1), and this sheet will probably be the site of plasma and radio wave activity that may be detected by ICE.

Strategy and Objectives of the Mission

ICE has been targeted to pass on the anti-solar side of Comet Giacobini-Zinner, with intersection of the tail and embedded current sheet as the prime objective (ICE will also fly through the foreshock, bow shock, and magnetosheath regions). Because the Comet Halley probes will fly through the *solar* side of Halley and hence miss the tail, the ICE tail data will be unique even after the flybys of the Halley probes in March 1986. The approximate location at which ICE will cross the tail is at 10,000 kilometers (about 6000 miles) from the nucleus. There, ICE will be far enough from the nucleus that there will be little risk of damaging impacts of dust particles on the spacecraft, yet close enough that intersection of the plasma tail (which wiggles in the solar wind) is a near certainty.

Of the thirteen experiments or instruments carried by ICE, six are considered to have an especially good chance to obtain valuable cometary data (recall that ICE was originally the third International Sun Earth Explorer and was not designed to observe comets). They are listed below, with short summaries of the comet-related capabilities and objectives.

1. Plasma Electron Experiment. Will measure electron density, energy, velocity, and temperature as the ICE flys through the comet. The energies of the electrons may tell us a great deal about ionization processes, and in particular, about the importance of photo-ionization. This experiment will be crucial in the detection and measurement of the bow shock and plasma tail.

2. Plasma Ion Experiment. Will measure the velocities, energies, and composition of cometary ions. This experiment will provide very important data about the number of different species of ions and their characteristic flow patterns outside the bow shock, and in the magnetosheath and plasma tail.

3. Energetic Protons Experiment. Will measure very rapid or energetic protons. As the solar wind crosses the bow shock, heating of the plasma is expected to occur. The degree of heating and the energy range of the heated protons will provide one indication of the strength of the bow shock.

4. Magnetic Fields Experiment. Will provide data on the strength and orientation of the magnetic fields in the magnetosheath and plasma tail. According to our expected model, the tail should be double-lobed, with reversed direction in each lobe. However much acceptance this picture has today, it must be tested with ICE data.

5. Plasma Wave Experiment. Will provide data on the plasma turbulence level in the various regions of the

The principal features and regions of the interaction of a comet with the particles, plasma and magnetic fields of the solar wind. Note that other features of comets, not explicitly relevant to this chapter, are omitted.

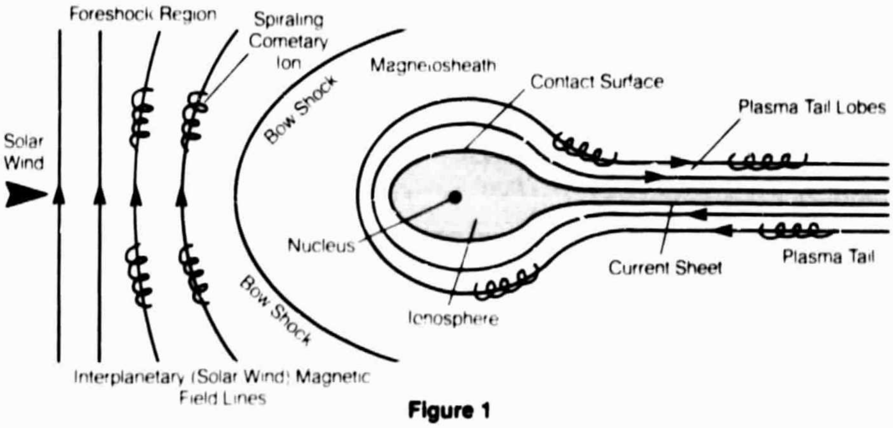

Figure 1

comet. The regions of major interest are the magnetosheath and the current sheet separating the two magnetic tail lobes. Plasma wave data are a major diagnostic tool in assessing the character of non-equilibrium plasmas, such as the contaminated solar-wind/comet plasma.

6. Radio Wave Experiment. Will provide data similar in nature to that returned by the Plasma Wave Experiment, the major difference being that higher frequency wave patterns will be sampled by the Radio Wave Experiment. The goal of the instrument is to assess the character of the tail plasma, which is likely to be turbulent at times.

A Low Energy Cosmic Ray Experiment may also gather useful cometary data. The six remaining experiments on ICE, which may or may not provide useful cometary data, were designed to measure: X-rays, medium energy and high energy cosmic rays, cosmic ray electrons, and gamma ray bursts. To ration electric power aboard the spacecraft, some of these instruments may be turned off during the encounter with Comet Giacobini-Zinner.

When ICE flys past the comet, the distance between bow shock crossings will probably be in the range 200,000 to 400,000 kilometers (about 125,000 to 250,000 miles). Since the speed of the spacecraft relative to the comet will be 21 kilometers per second (13 miles per second), the time between bow shock crossings will be 2.5 to 5.0 hours (one recent estimate, however, places this interval at just 90 minutes). This can be thought of as essentially the duration of the cometary encounter, although measurements will certainly be made well outside the bow shock, as the spacecraft approaches and recedes from the comet. In contrast, the very thin plasma tail (whose thickness may only be 5000 kilometers or about 3000 miles) will be traversed in less than about five minutes.

Despite the very fast nature of the flyby (contrast this with the total telescope time devoted to the observation of comets with telescopes during the present century!), the data obtained by ICE will be unique and may answer many long-standing questions about comets. ICE will certainly inaugurate a new age of cometary exploration.

Beyond Comet Giacobini-Zinner

Robert W. Farquhar

ICE and Halley's Comet

After ICE passes through the tail of Comet Giacobini-Zinner on September 11, 1985, its trajectory will make it pass between the Sun and Comet Halley on two occasions. On October 31, 1985, the spacecraft will pass between the Sun and the comet at a distance of about 140,000,000 kilometers (about 86 million miles) from Comet Halley. A closer pass will occur on March 28, 1986; then the distance from the comet will be about 31,000,000 kilometers (about 20 million miles).

In each case, since the spacecraft will pass on the sunward side of Comet Halley, ICE will be upstream of the comet in the solar wind. Measurements of solar wind conditions by ICE will be compared with observations made shortly thereafter with groundbased telescopes. The telescopes will photograph the plasma tail of Comet Halley, which responds to disturbances in the solar wind. Thus, just as ISEE-3 originally provided solar wind data for comparison with measurements of disturbances by the solar wind of the Earth's magnetosphere, ICE will provide the input data for studies of the effects of the solar wind on the plasma tail of Comet Halley.

ICE in the Twenty-First Century

Since departing the Earth-Moon system on its voyage to Comet Giacobini-Zinner, ICE has been on a heliocentric orbit that takes it around the Sun once approximately every 353 days, about 12 days less than the period of the Earth's orbit around the Sun. ICE will return to the vicinity of the Earth for the first time in the year 2013. Will the aging spacecraft, which by then will have been in space for 35 years, be operable and commandable? Planners at the Goddard Space Flight Center are hoping that the answer is yes! They would like to retarget ICE in an August, 2013 lunar swingby, so that it can enter an orbit around the Earth. From that proposed Earth orbit, it might be possible to capture the spacecraft, using a lunar shuttle vehicle of the type that may be in use in the next century. If this too were to occur, the International Cometary Explorer could be returned to the ground for study and exhibition, perhaps in a place of honor at the National Air and Space Museum in Washington, DC. Or do your students have a better suggestion for the future disposition of this historic spacecraft?

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