New Plasma Physics Lab at Giacobini-Zinner

The ICE spacecraft found action aplenty when it passed through a comet last month; plasma physics has a windfall of new natural experiments

"The turbulence is wonderful! We see practically every space plasma instability there is," beamed one space plasma physicist after watching data flow in from the International Cometary Explorer (ICE) as it sped through Comet Giacobini-Zinner on 11 September. His enthusiasm is understandable. Plasma physicists want to understand how clouds of charged particles behave in everything from Earth's magnetic field, where they lead to aurora, to interplanetary space, solar flares, and the interior of stars. Their problem is that although 90 percent or more of the universe is in the form of plasma, nothing they do in the laboratory can properly simulate the phenomena of interest; lab experiments are simply too small and confining. But out in the real world, plasma physicists are limited to the uncontrolled experiments within reach of their instruments. The more experiments under different conditions, the more new knowledge.

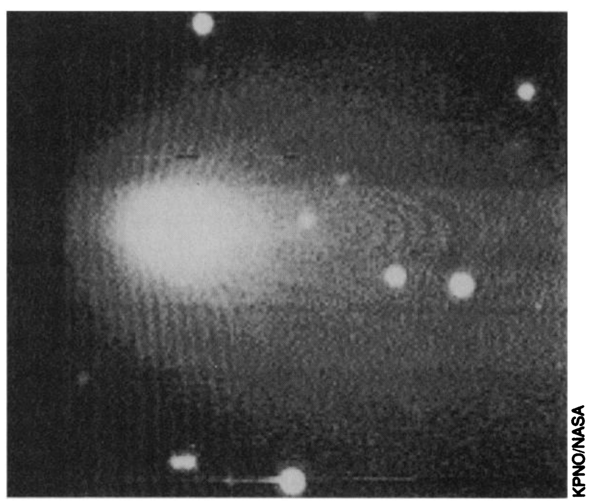
Within comets, it turned out, there is a new plasma physics laboratory that looks to be a busy, varied place. Plasma is being subjected to unique conditions and driven to an intensity of activity rarely encountered by spacecraft. Despite some fears that comets might be lackluster objects for study, Giacobini-Zinner heralded its presence millions of kilometers away with high-energy charged particles, plowed its way through the solar wind behind a unique plasma cushion, and treated researchers to a whole range of turbulent plasma behavior.

As ICE approached Giacobini-Zinner, some researchers, including a number of spacecraft experimenters, wondered whether ICE should be there. After all, it could have been left safely and profitably doing its original job of monitoring the solar wind blowing toward Earth. The 400-kilometer-per-second solar wind, which is primarily composed of protons and electrons embedded in the sun's magnetic field, shapes, energizes, and rejuvenates Earth's magnetosphere, the natural laboratory most prized by space plasma physicists.

Instead, controllers at the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, under the direction of Robert Farquhar nudged ICE, then called International Sun-Earth Explorer 3, off its perch on the thin line between the gravitational influence of Earth and the sun, and sent it down the long tail of the magnetosphere (*1*). Like a floating leaf caught in a whirlpool, the future ICE swirled and looped about the Earth-moon system, encountering the moon five times (the last encounter being a mere 120 kilometers from the moon's surface) before being spun out toward Giacobini-Zinner by the slingshot effect of the moon's gravity. Safety and guaranteed scientific return had been traded for the hazards of a distant comet encounter and a scientific mission of less than certain merit.

The first hints that the trip would not be for naught came more than a million kilometers out. Detectors on ICE began picking up some high-energy particles of possible cometary origin as far as 1.7 million kilometers from the center of the comet and by 0.8 million kilometers the influence of the comet was clear. That is quite a reach for an object whose heart is just a hunk of dirty ice a few kilometers across. Paradoxically, it is the tininess of a comet's icy nucleus that led to these early signs. The size of the nucleus makes getting anything away from its surface easy—a fast walk is enough speed to escape its feeble gravity. Gas sublimated from surface ice by the sun's heat, along with the ice's associated dust, expands into the vacuum of space at a speed of 1 kilometer per second to form the 70,000-kilometer coma or head of a comet. But at the same time the sun's ultraviolet light is ionizing the gas by knocking electrons off molecules to form ions. This slow-moving cometary plasma cannot travel far without encountering the solar wind, whose magnetic field can pick up charged particles but not neutral molecules. Any ion caught by the solar wind will be blown back to form an ion tail.

The high-energy ions that ICE detected so far from the comet must have been neutral gas molecules that survived a 10-day, million-kilometer trip only to be ionized, immediately energized by acceleration to the speed of the solar wind, and shot back downwind past ICE. For investigators uncertain that their instruments would ever have anything to detect, these early signs were welcome. "I had doubts about going to the comet," said Robert Hynds of Imperial College, "but I'm glad we did."



Comet Giacobini-Zinner

The ICE spacecraft was embedded in the bright coma 8000 kilometers tailward of the invisibly small central nucleus when this image was made through the 210-centimeter telescope of the Kitt Peak National Observatory near Tucson. The striations are artifacts of image acquisition.

The next surprise came when an expected phenomenon failed to appear, at least in its familiar garb. Many plasma physicists had likened a comet immersed in the solar wind to an aircraft moving at supersonic speeds—both should be moving fast enough relative to their surroundings to create a bow shock in front of them where air or solar wind piles up and compresses. A plane's bow shock can be heard as a sonic boom. A comet's bow shock, like that of Earth and other obstacles in the solar wind, should have made itself dramatically evident in the ICE observations.

Giacobini-Zinner's bow shock did not

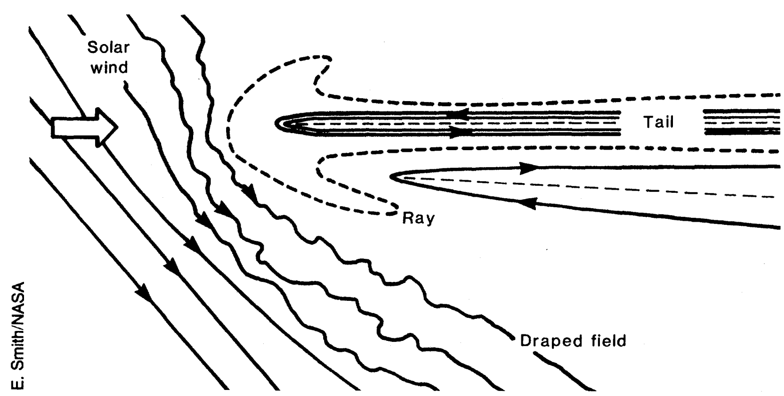
show up as expected, if the comet can be said to have one at all. Frederick Scarf of TRW in Redondo Beach did report at the time of the encounter that he was confident his group's plasma wave instrument, which measures fluctuating electric and magnetic fields associated with waves in the plasma, had recorded strong bow shock phenomena 188,000 kilometers before ICE crossed the tail downwind of the nucleus. A mathematical model of the comet run the day before had indeed predicted that distance for the position of the bow shock. Surprisingly, that was the only instrument to find the expected sudden transition. "There is usually an abrupt jump in the intensity of the magnetic field," said experimenter Edward Smith of the Jet Propulsion Laboratory, "but instead we see a lot of noise and a gradual rise."

Researchers' first reaction to the absence of a classic bow shock was that it is another manifestation of a comet's ability to spread itself thinly through space. They had expected a comet's plasma cloud to act enough like a solid obstacle in the solar wind to slow the solar wind abruptly and create a bow shock. Instead, it seems, the comet plasma may act as a soft cushion that gradually slows the solar wind without a bow shock. The cushion would form as the unionized gas molecules capable of ignoring the solar wind move outward, are eventually ionized, and are accelerated to high energies, draining energy and speed from the solar wind at the same time. As it encounters gradually increasing plasma densities nearer the nucleus, the solar wind would gradually slow, eventually colliding with such high plasma densities that it would be deflected around the comet. Some researchers have also suggested that there may be a bow shock but an intermittent or unsteady one, due perhaps to varying gas production by the nucleus.

However it manages it, the solar wind does eventually accomplish the heating and compression of plasma seen around other obstacles in its path. Plasma electrons increased in density from about 10 per cubic centimeter in the solar wind to 20 or 30 per cubic centimeter across the "bow shock" or interaction region, as plasma electron experimenter Samuel Bame of Los Alamos National Laboratory prefers to call it. Electron temperatures rose from 150,000 K, cold by space plasma standards, to 500,000 K, a bit higher than inside Earth's typical bow shock.

Most striking was the amount of turbulence found in the interaction region. The intense plasma disturbances there nearly drove some instruments off scale and prompted some observers to dub this comet the source of the most turbulent known plasma in the solar system. It might claim that title because of the amount of plasma the solar wind picks up. One moment a neutral molecule is ambling along at 1 kilometer per second and the next it is an ion doing 400 kilometers per second. But the abrupt acceleration involved has a preferred direction, whereas plasma tends to adjust toward an equilibrium in which there is no preferred direction. Thus, loading the solar wind with cometary ions leads to a plethora of the instabilities that move plasma toward an equilibrium and it is plasma instabilities that plasma physicists so love to study.

ICE investigators had fewer surprises when the spacecraft reached Giacobini-Zinner's tail, where the sun blows gas, dust, and plasma away in a narrow stream. As had been long predicted by theoretical models, and as happens at other obstacles like Venus that lack their own magnetic field, the magnetic field of the solar wind drapes over the comet's plasma cloud like limp spaghetti hanging from a fork. With some luck and considerable targeting precision, ICE confirmed models of comet tails by passing through both lobes of this magnetic field and the 100-kilometer-thick neutral sheet between them, the only part of the comet that exhibits no magnetic field whatsoever.



The solar wind's magnetic field draped over a comet

The solar wind's magnetic field lines (left) were compressing, draping tightly downwind of the nucleus to form the ion tail, and sloughing off again (right, below tail).

The 10,000- to 15,000-kilometer width of the tail was considerably greater than predicted and the 50-nanotesla strength of its magnetic field, although 1000 times weaker than the one at Earth's surface, was five times higher than generally predicted. The first in situ analyses of the composition of comets, made in the tail by the ion composition instrument of Keith Ogilvie of GSFC and his group, confirmed that at least this comet nucleus is predominantly water ice with a small portion of carbon monoxide ice.

ICE also confirmed earlier estimates that a passage 8000 kilometers tailward of the nucleus of Giacobini-Zinner would probably be a safe one. No one was sure of that. At a relative speed of 21 kilometers per second, even a rare millimeter-sized dust grain could cripple the spacecraft, a smaller particle might shear off an antenna, or a storm of micron-sized particles might degrade the solar cells and cut off the power. None of that happened, confirming in a crude way model estimates of impact rates based on observations during prior appearances of the comet.

More quantitatively, Scarf inspected his plasma wave data and found that his antenna had detected the ionized vapor from about one particle per second hitting the spacecraft. The method was serendipitously discovered when a similar instrument on Voyager 2 passed through the fringe of Saturn's G ring. There, hundreds of particles hit per second, still causing no damage.

Scarf's impact rate is in rough agreement with the predicted one, giving some comfort to those sending spacecraft into Comet Halley. The dust hazard at Halley will be thousands of times greater because of that comet's greater activity and the spacecraft's closer approaches (*2*). Despite this greater chance-taking, the Halley probes cannot duplicate ICE's accomplishments. It passed through a comet's tail; the fleet of Halley probes must pass ahead of the comet to avoid blinding their cameras in the solar glare. And ICE visited a comet other than Halley, a distinction that is liable to stand for some years to come.

—RICHARD A. KERR

References

1. R. A. Kerr, *Science* **226**, 1298 (1984).
2. ______, *ibid.* **229**, 541 (1985).