Cometary science

ICE encounters Giacobini–Zinner

from Stanley W. Cowley

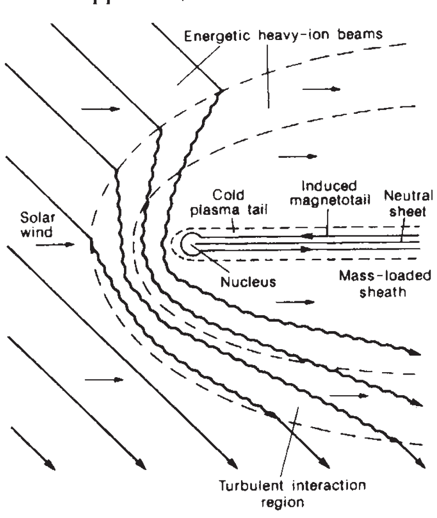
On 11 September 1985 the NASA International Cometary Explorer (ICE) spacecraft made the first ever close fly-by of a comet, passing through the tail of comet Giacobini–Zinner 7,800 km from its icy nucleus. Two days later, the first results presented at Godard Space Flight Center, Maryland, by the principal investigators of seven ICE experiments, revealed a rich and detailed data set.

The results have already ended more than thirty years of speculation on the nature of solar wind–comet interactions by showing how the comet's atmosphere interacts with the solar wind, the supersonic proton–electron plasma that blows continuously outward from the Sun into the Solar System at speeds of about 400 km s^{-1}. In particular, it has been verified that the interaction produces copious fluxes of energetic heavy ions in the region surrounding the comet, resulting from solar UV ionization of the extended cometary atmosphere followed by ion pick-up by the solar wind flow. The wind flow becomes mass-loaded and slowed in the process; the long, filamentary ion tails of comets are formed by the capture of magnetic flux from the solar wind resulting from this mass-loading, as first theorized by H. Alfvén (*Tellus* **9**, 92; 1957).

The ICE spacecraft was launched in August 1978 as ISEE-3 (International Sun-Earth Explorer-3). After a successful four-year programme to study particles and fields in the solar wind, it made the first detailed observations of the Earth's extended magnetic tail (see *Nature News and Views* **315**, 281; 1985). A final lunar swing-by on 22 December redirected ISEE-3 towards Giacobini–Zinner. On successful completion of this manoeuvre ISEE-3 was renamed ICE.

Giacobini–Zinner is a periodic comet, independently discovered by M. Giacobini in 1900 and E. Zinner in 1913. The elliptical orbit has a period of 6.5 years, and lies between the orbits of Earth and Jupiter. At the time of the ICE encounter the comet was six days past its closest approach to the Sun and was crossing the ecliptic plane at an angle of about 30°. Fortuitously, the component of the comet's speed in the plane of the ecliptic nearly matched that of ICE (30 km s^{-1}), so that Giacobini–Zinner made a simple north to south pass across the spacecraft at a sedate relative speed of 21 km s^{-1}. ICE was targeted so that the centre of the comet's tail should have passed across it, 10,000 km from the nucleus. But due to a hiccup in the comet's orbital parameters, the nucleus was only 7,800 km from the spacecraft, causing considerable concern that cometary dust would inactivate the spacecraft's solar cells. ICE survived the encounter with no measureable degradation in performance, although plasma bursts produced by the impact of micrometre-sized particles on the spacecraft body may account for the wave bursts detected at a rate of about one every second during the hour of closest approach, as reported by F.L. Scarf (TRW Systems, California).

Phenomena associated with the interaction of solar wind with the cometary atmosphere were observed over a much longer interval. The atmosphere results from sublimation of the icy surface material of the nucleus (itself about a kilometre in diameter), and is believed to expand outwards, essentially unrestrained by gravity, at about 1 km s^{-1}. As the gases (mainly water vapour) expand, they undergo complex photochemical reactions with sunlight, leading to breakup and ionization of the initial molecules. Time scales for the latter processes are of the order of 10^5–10^6 s, so that with about 1 km s^{-1} expansion speeds, these phenomena are expected to extend 10^5–10^6 km from the nucleus. Upon ionization the ions are picked up by the solar wind flow (~400 km s^{-1}) and accelerated to kinetic energies proportional to their mass, typically a few tens of keV for O^+ or OH^+. As reported by R.J.Hynds (Imperial College, London), pickup ions with these energies were detected by the energetic ion experiment run by Imperial College/SSD-ESA/Space Research Laboratory Utrecht more than one day before the spacecraft's closest approach, when it was still 2 million km from the comet. These observations constituted the first evidence of the approaching comet in the ICE data. Although bursty in nature, peak fluxes generally increased as the comet was approached, reaching values higher than any seen in the previous seven years of the experiment. Confirmation that these ions were low charge-state heavy ions was provided by the energetic ion experiment of the Max-Planck Institute, Garching and the University of Maryland, as reported by D. Hovestadt (MPI, Garching).



Giacobini–Zinner's interaction with the solar wind. The cold plasma tail is about 25,000 km across. The solid icy nucleus (not to scale) is probably only a few km across. Short arrows indicate the direction of plasma flow away from the Sun. Solid lines indicate magnetic field lines lying approximately in the ecliptic plane.

Although the production of copious fluxes of heavy ions by solar wind pick-up is confirmed to be a unique feature of the solar wind–comet interaction, the energy and momentum input to energetic ions close to the comet may be expected to become so large that substantial slowing of the flow occurs (the flow becomes 'mass loaded'). The magnetic field which is frozen into the highly conducting plasma should then become distorted and 'draped' around the cometary obstacle (see figure). This was broadly confirmed by the ICE thermal-electron and magnetic-field experiments, described by S.J. Bame (Los Alamos National Laboratory) and E.J. Smith (Jet Propulsion Laboratory), respectively.

An overview based largely on these results is shown in the figure. No clear shock was observed in the magnetometer data in the outer part of the mass-loaded region, but a broad, turbulent interaction region was found 70,000 –120,000 km from the comet's nucleus. Intense plasma waves were detected in this region. Inside this broad turbulent layer a less disturbed 'sheath' region of slowed flows was detected before ICE crossed the cold plasma tail of the comet for a 20 min interval centred on closest approach. Thus, the tail is 25,000 km across, and is characterized by draped magnetic fields and cold electron densities of about 100 cm^{-3}. Within this region is an induced bipolar magnetotail with embedded neutral sheet, which presumably results from cometary capture of solar wind magnetic flux by mass-loading. Electron densities in the heart of this tail, deduced from measurements made by the radio-wave experiment, were reported by J.-L. Steinberg (Paris Observatory, Meudon) to exceed 600 cm^{-3} in a ~1,000-km thick layer, with energies ~3 eV. The predominant ion in this region is from the 'water group' though some CO^+ may also be present, according to K.W. Ogilivie (Goddard Space Flight Center).

Many more months of study will be required before the full implications are realized. But it is already clear that a quantum leap has taken place in knowledge and understanding of the atmospheres of comets and their interactions with the solar wind. □

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