OBSERVATIONS OF COMETARY PLASMA WAVE PHENOMENA

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ABSTRACT

The ICE plasma wave investigation utilized very long electric antennas (100 meters tip-to-tip) and a very high sensitivity magnetic search coil to obtain: (1) significant local information on plasma physics phenomena occurring in the distant pickup regions of Comet Giacobini-Zinner and Comet Halley, and (2) information on the processes that developed in the coma and tail of Giacobini-Zinner. Since ICE traversed cometary regions that complemented those sampled by VEGA and SAKIGAKE, it is important to compare observations from the three missions that carried wave instruments. Here we summarize ICE plasma wave measurements associated with both comet encounters and relate the very high sensitivity ICE observations to corresponding measurements from the other Halley spacecraft.

1. INTRODUCTION

During a six month period (September 1985 through March 1986) our understanding of comets changed drastically as six spacecraft made in situ measurements at Comet Giacobini-Zinner and Comet Halley. These encounters provided great scientific advances in essentially every area of cometary physics, and many of the noteworthy discoveries involved plasma phenomena. The spacecraft flybys clearly demonstrated that a variety of very strong and dynamically important wave-particle interactions develop in a vast region surrounding a comet. Plasma wave instruments were included in the payloads of ICE, VEGA 1 and 2, and SAKIGAKE, and the comet observations show that: (a) the distant ion pick-up region is characterized by the presence of significant levels of ion acoustic waves and whistler mode emissions, and (b) the closer-in region has extremely strong electromagnetic and electrostatic plasma turbulence associated with the large scale interaction of the mass-loaded solar wind and the cometary plasma. Localized wave enhancements are found during foreshock encounters, during traversals of boundaries with characteristics of collisionless bow shocks, and during entrance into the boundary of the critical ionization region.

In order to discuss the significance of the cometary wave measurements, we must take note of the differences in instrument capabilities and flyby trajectories for the various missions. Figure 1 contains a summary that covers both points for the natural comet encounters. As indicated here, short (VEGA), medium (VEGA and SAKIGAKE) and long (ICE) electric field antennas were flown across the tail of GZ (ICE) and on the sunward side of Halley (VEGA, SAKIGAKE and ICE); since the instrument sensitivity is essentially proportional to the antenna length, it can be seen that the various E-field systems had great differences in the ability to detect low level wave phenomena.

Magnetic wave sensors were only flown on ICE and SAKIGAKE; however, on SAKIGAKE the search coil was mounted directly on the spacecraft and the effective threshold was so high (H. Oya, private communication) that no significant cometary signals were detected. Thus, for all practical purposes, we can consider that the ICE search coil provided the only magnetic field plasma wave information during the comet encounters.

2. CLOSE-IN ICE OBSERVATIONS

ICE had the most sensitive wave instrument and the ICE tracking coverage was virtually continuous for an extended interval surrounding the GZ encounter; thus it is appropriate to use the ICE plasma wave observations (Scarf et al., 1986a) as a basis for discussing all of the cometary encounters. Figure 2 contains a summary of the ICE wave measurements for a ten hour period on September 11, 1985. During this interval (in which the spacecraft-to-comet distance varied from a maximum of 375,000 km to a minimum of 7,800 km) ICE traversed the inner part of the ion pick-up region, the comet foreshock, the bow shock-strong coupling region, and the comet tail. The bottom panels in Figure 2 show measurements from the magnetometer and the electron plasma probe, and the upper panels show the peak amplitudes measured in each of the bandpass channels of the ICE plasma wave instrument.

For each wave panel in Figure 2, the top-to-bottom amplitude range is approximately five orders of magnitude, and it can be seen that exceptionally intense plasma waves were detected in a vast region around Giacobini-Zinner. In fact, these plasma

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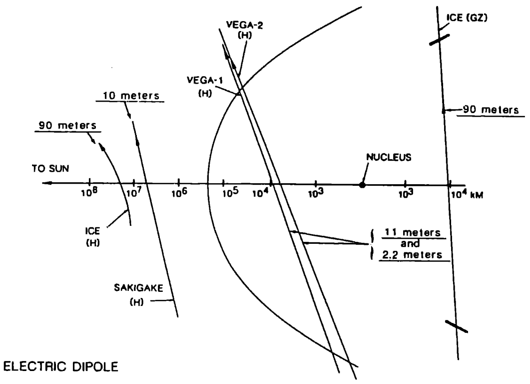

Figure 1. Projected flyby trajectories for the comet encounter spacecraft with on-board wave instruments. The nominal Halley bow shock curve is shown; for Giacobini-Zinner the heavy arcs on the ICE(GZ) plot depict the shock crossing distances. The underlined numbers give the tip-to-tip antenna lengths for the electric dipoles.

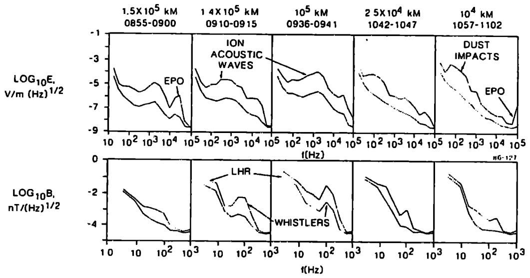

Figure 3. Characteristic peak and average E and B wave spectra measured as ICE moved inbound from the solar wind (0855-0900) to Giacobini-Zinner closest approach (1102).

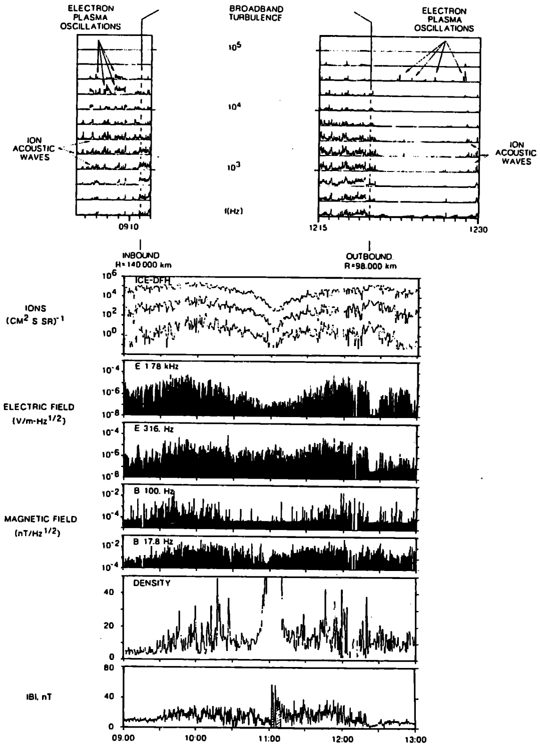

Figure 4. Bottom: Unaveraged wave profiles in four channels, along with plasma density, B-field magnitude and energetic particle fluxes. Top: Unaveraged profiles for all 16 E-field channels. The vertical dashed lines mark the events with collisionless bow shock wave characteristics.

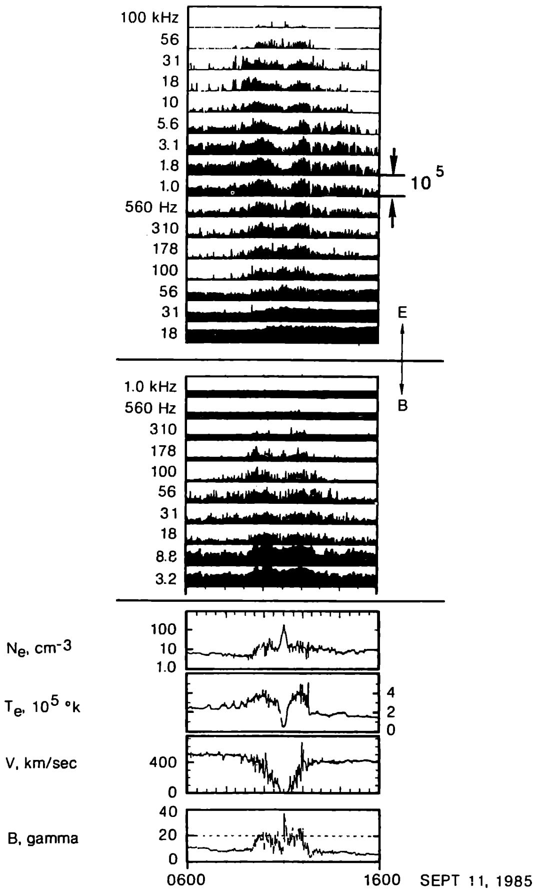

Figure 2. Summary of plasma wave amplitude data, plasma parameters and B-field profile for the ICE encounter with Comet Giacobini-Zinner.

turbulence levels are as large as any previously detected on ICE, and the low frequency B-field waves (near the lower hybrid frequency) were so intense that the instrument saturated. In the ion acoustic wave frequency range (several hundred to several thousand Hertz), the E-field channels were nearly saturated as ICE passed through the strong coupling region (R on the order of 70,000 to 100,000 km), and we conclude that the comet-solar wind interaction is characterized by the development of exceptionally strong wave-particle interactions.

Another important aspect of the Giacobini-Zinner wave observations involves the large number of wave modes that are excited in the interaction region. Figure 3 shows calibrated peak and average E and B spectra from different regions on the inbound pass. As noted on the drawing, we were clearly able to identify lower hybrid resonance and ion acoustic waves, whistlers, and electron plasma oscillations. The B-field panels show a sharp jump in LHR and whistler mode amplitudes in the region near the 0911 UT discontinuity that Scarf et al. (1986a) identified as having characteristics similar to that of the bow shock, and this region was also associated with an increase in ion acoustic wave level. However, Figure 3 clearly shows even higher intensities for all of these waves near 0930 to 1000. The latter region is generally interpreted as the "strong coupling region" (Coroniti et al., 1986), and Kennel et al. (1986) showed that here the E and B wave spectra were very similar to those measured at quasiparallel shock transitions. In this strong coupling region it can be demonstrated that the wave-particle interactions were quite significant. Straightforward calculations based on use of the measured wave amplitudes and plasma parameters suggest that this level of electrostatic turbulence will produce significant electron heating over time scales of minutes, while the whistlers will strongly pitch-angle electrons on comparable time scales. Thus, the Giacobini-Zinner plasma wave data in the bow shock-strong coupling region clearly indicate that many wave modes are simultaneously excited by plasma instabilities, and that most of them have such large amplitudes that the associated wave-particle interactions are certain to be of great dynamical significance.

The actual identification of the Giacobini-Zinner bow shock is somewhat controversial. The lower panels in Figure 4 show data from the energetic ion instrument, the electron plasma probe and the magnetometer, along with unaveraged amplitude profiles from two E-field and two B-field filter channels. It can be seen that the wave activity was extremely impulsive, with huge amplitude excursions from one measurement to the next, one second later. In these plots the existence of a broad strong coupling region with enhanced wave amplitudes is clearly evident (at 0930 to 1000 and at 1140 to 1220), and for the outbound case, the end of this region has a sudden shock-like transition to relatively quiet plasma conditions. The upper right panel, taken from the initial paper by Scarf et al. (1986a) shows all of E-field wave levels from this outbound boundary region, and it is clear why several of the ICE plasma wave investigators called this a bow shock.

The inbound case is more complex. The lower drawing shows that at 0911, where the wave instrument detected an abrupt onset of broadband turbulence (see upper left panel), the magnetometer and electron plasma probe measured relatively smooth variations in N and B. However at this same time, it is evident that the DFH ion instrument detected large and sudden increases in the fluxes of energetic heavy ions. This suggests that the 0911 plasma wave discontinuity was associated with spacecraft penetration into the outer boundary of a region with enhanced fluxes of gyrating energetic heavy ions.

3. THE COMET TAIL TRAVERSAL

The ICE encounter with Comet Giacobini-Zinner provided the only traversal of a comet tail, and thus it is of great interest to analyze the plasma physics phenomena in this region. The summary plot in Figure 2 shows that in many of the plasma wave filter channels (f > 1 kHz for E; f > 18 Hz for B), the peak wave levels were relatively low near closest approach. However, for the lower frequency E and B channels, the near-comet observations included some very large amplitude readings. Indeed, the closest-approach spectra in Figure 3 (1057-1102) show that for f < 10 Hz, the B-field waves were almost as intense as the peak values detected in the strong coupling region (0936-0941). Moreover, for the lower frequency E-field waves (f near 56 to 100 Hz), it turns out that the strongest signals were actually detected near closest approach.

Some of these tail waves can be identified readily, but in other cases, more discussion is required. It is natural to relate the low frequency magnetic field peak to the lower hybrid resonance, and the high frequency E-field enhancement to electron plasma oscillations. However, detailed analysis of the in-tail wave measurements suggests that the 56-100 Hz E-field spectral peak in Figure 3 is actually associated with dust impacts (see Gurnett et al., 1986), and that the real E-field plasma waves had moderate amplitudes in this region.

This point is illustrated in Figure 5, which shows wave profiles for 13 of the filter channels (again, five orders of magnitude for each panel) along with a B-field plot labeled with the magnetopause locations defined by Slavin et al. (1986). The data in the wave panels clearly have a few isolated noise spikes (dust impacts) superimposed on a low level mid-frequency spectrum that does not show any relation with the local electron cyclotron frequency. We conclude that strong whistler turbulence was not present in the comet tail and we identify these plasma waves as electrostatic. Since acoustic waves for protons and heavy ions would have (rest frame) frequencies below a few kiloHertz, these are logical candidates, and the sporadic broadband noise bursts (e.g., at 15,000 km from the tail axis) would seem to resemble the broadband electrostatic bursts detected on the boundaries of the earth's plasma sheet (Scarf, 1986c). Thus, although the tail plasma waves only had moderate amplitudes, it is likely that they were dynamically significant.

4. WAVES IN THE DISTANT PICK-UP REGION

The discovery of very high intensities for cometary plasma waves was quite surprising, and another unexpected result from the *in situ* measurements is related to the huge size of the interaction region. Although it was found that Giacobini-Zinner had an extensive conventional foreshock (see, for example, Fuselier et al., 1986), Scarf et al. (1986a,b)

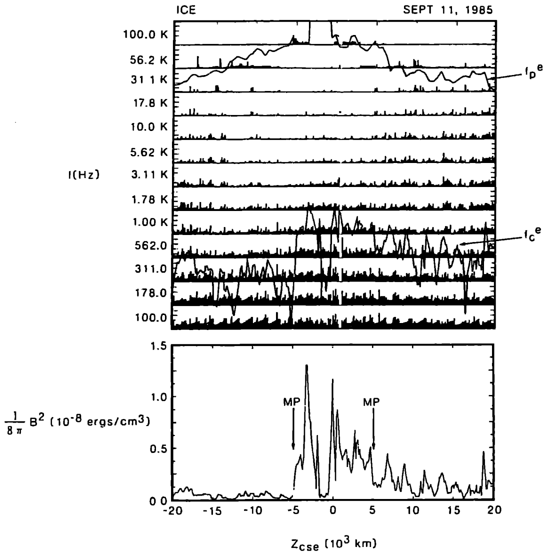

Figure 5. B-field magnitude and 13 channel E-field wave amplitudes for the ICE crossing of the Giacobini-Zinner plasma tail.

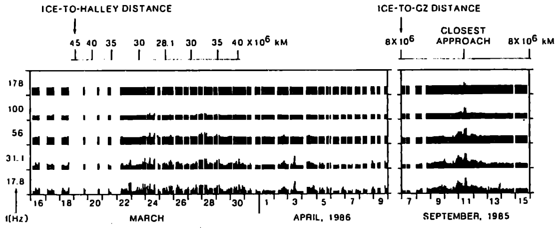

Figure 6. Low frequency B-field waves observed during closest approach to comets Halley and Giacobini-Zinner.

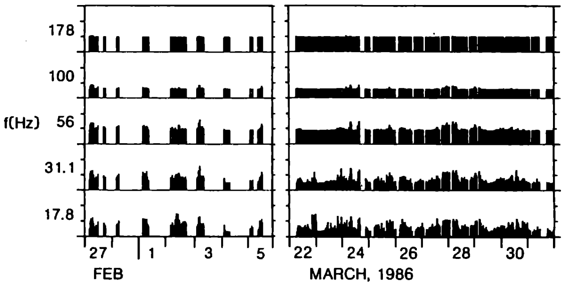

Figure 7. B-field wave activity detected during the Halley closest approach and during the previous passage of the recurrent high-speed stream.

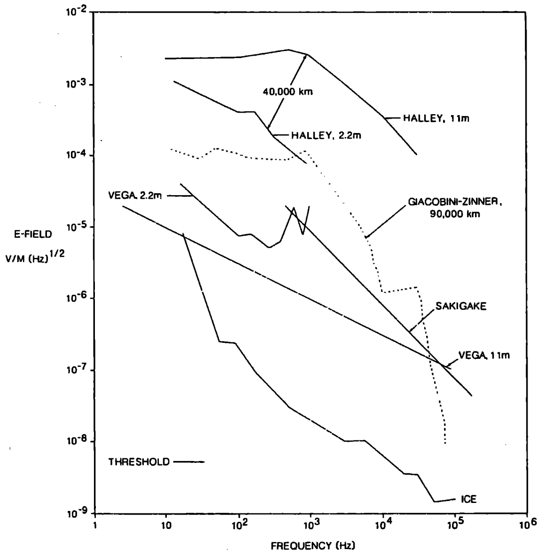

Figure 8. Plasma wave spectra from Halley (VEGA 1 and 2) and Giacobini-Zinner (ICE), together with E-field threshold curves for the comet plasma wave instruments.

noted that ICE measured effects of pick-up ions out to at least four million kilometers from the nucleus of Giacobini-Zinner. The full set of very remote measurements from ICE also involved direct detection of energized pick-up ions (Sanderson et al., 1986) and Scarf et al. (1986b) showed that these particle observations were correlated with simultaneous measurements of electrostatic ion acoustic waves and electromagnetic whistlers. Thus, it was concluded that these waves detected at great distances were associated with the pick-up of Giacobini-Zinner ions by the magnetized solar wind.

Late in March, 1986, ICE passed very far in front of Halley and the plasma wave search coil again detected enhanced whistler mode turbulence with characteristics very similar to those measured in the distant ion pick-up region of Comet Giacobini-Zinner (electrostatic waves were also detected here but it is likely that some of these were simply associated with the solar wind). Figure 6 compares the search coil wave profiles from Halley and Giacobini-Zinner; Scarf et al., (1986b) analyzed these observations and concluded that the March 1986 measurements of whistler mode activity were associated with the Halley ion pick-up process. Wenzel et al. (1986) reported that Halley-associated ions were also detected on ICE at this time, and a comparison of ion and wave profiles for an eight-day period in March, 1986, when ICE was near its closest approach to Halley suggested a close (but not one-to-one) correlation. Since the wave enhancements were generally detected during periods when energetic ion flux enhancements were observed, this could mean that: (a) the pick-up ion distribution was unstable with respect to production of plasma turbulence, and (b) wave-particle interactions associated with the pick-up process could have produced significant changes in the distribution function.

However, on the basis of particle observations from ICE, the identification of the energetic particles as heavy ions from the comet is not certain, and it is worth noting that the ICE approach to Halley occurred when the spacecraft was in the midst of a recurrent high speed solar wind stream. High solar wind velocities do make it easier to detect pick-up ions on ICE (Sanderson et al., 1986; Wenzel et al., 1986), but it also possible that the flux enhancements represented ions of solar origin. Because of these uncertainties, we examined the ICE wave data during the previous passage of the stream. Figure 7 compares the search coil amplitudes for seven days centered around March 2 with corresponding measurements from the Halley closest approach interval. It can be seen that some low frequency electromagnetic turbulence was detected during the initial stream passage, but the near-Halley levels seem significantly higher, for longer intervals. This again suggests that ICE measured Halley-associated plasma turbulence late in March; however, the conclusion is clearly speculative and a firm decision about the size of the Halley ion pick-up region will probably have to await more definitive measurements in 2062.

5. COMET COMPARISONS

As noted in Figure 1, the plasma wave instruments on SAKIGAKE and VEGA used shorter dipoles, and thus they were less sensitive. The four lower plots in Figure 8 contain threshold data for SAKIGAKE (Oya et al., 1986), VEGA (Klimov et al., 1986 and Grard, private communication) and ICE; it can be seen that the long E-field antennas on ICE allowed detection of very low level waves, since the ICE threshold was as much as two orders of magnitude below those from the other spacecraft.

This difference in sensitivity did not prove to be a problem because the VEGA investigators actually detected considerably stronger signals at Halley than the very intense ones previously obtained by ICE at Giacobini-Zinner. Klimov et al. (1986) and Grard et al. (1986) found wave spectra with peak intensities more than a factor of ten higher than the peaks reported during the Giacobini-Zinner encounter. The upper curves in Figure 8 show the most intense Hally spectra reported by the VEGA teams (Grard et al., 1986; Klimov et al., 1986), and the dashed curve is the 0910-0915 peak ICE spectrum from Figure 3, above. The VEGA wave investigators also found that the inbound Halley bow shock was more clearly defined than the Giacobini-Zinner shock (Galeev et al., 1986a), and that enhancements in lower hybrid resonance emissions appeared to be associated with critical ionization phenomena closer to the nucleus (Galeev et al., 1986b).

6. SUMMARY

The _in situ_ observations from the Halley and Giacobini-Zinner encounters conclusively demonstrate that plasma wave investigations provide first order information on the physics of the comet-solar wind interaction, the characteristics of the comet tail, mass loading and cometary pick-up processes, and phenomena associated with ionization and particle acceleration. The measured wave levels appear to produce strong wave-particle interactions over enormous distances, and the wave observations also yield significant diagnostic information on the cometary plasma environment.

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