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MHD WAVES DETECTED BY ICE AT DISTANCES > 28 x 10^6 KM FROM COMET HALLEY: COMETARY OR SOLAR WIND ORIGIN?

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ABSTRACT

Spectral analyses of the high resolution magnetic field data are employed to determine if there is evidence of cometary heavy ion pickup when ICE was closest to Halley, ~ 28 x 10^6 km. No evidence is found for the presence of heavy ion cyclotron waves. However, from this search, two new wave modes are discovered in the solar wind: electromagnetic ion cyclotron waves and drift mirror mode waves. Both modes have scales of 10 - 60 s (1 - 6 T_p) in the spacecraft frame. The possibility of wave generation by cometary hydrogen pickup is explored. Theoretical arguments and further experimental evidence indicates that cometary origin is improbable. The most likely source is plasma instabilities associated with solar wind stream-stream interactions. VLF electrostatic emissions are found to occur in field minima or at gradients of the drift mirror structures. Possible generation mechanisms of drift mirror mode waves, cyclotron waves and electrostatic waves are discussed.

Keywords: MHD waves, Halley, ICE, electrostatic emissions, generation mechanisms

1. INTRODUCTION

It has recently been suggested by ICE investigators that cometary pickup ion effects may have been detected at distances beyond 28 x 10^6 km from comet Halley. Wenzel et al. (ref. 1) have reported enhanced fluxes of energetic ions and MHD wave power at 10^{-2} Hz (the H_2O group ion cylcotron frequency) coincident with enhanced ELF/VLF plasma wave turbulence that have many characteristics similar to Giacobini-Zinner cometary waves (refs. 2, 3).

The above articles state that for cometary neutrals to reach such large distances, they would have to have velocities of 2 - 3 km s^{-1} or ionization time scales of ~ 5 x 10^6 s, or both, giving effective ionization scale lengths of 10 - 20 x 10^6 km. Both sets of authors cautiously note that their observations occurred during high-speed solar wind streams and that the observations could instead, simply be due to physical processes associated with stream-stream interactions. Because of these difficulties in the interpretation of the ICE results, the above authors have encouraged further analyses to determine the source of the plasma and MHD waves and energetic particles.

In an attempt to resolve this issue, we undertake a careful examination of the ICE magnetic field data to determine if there are any distinguishing MHD wave features that could be of cometary origin. The purpose is to help resolve part of the question of the source of the enhanced MHD turbulence, energetic particles, and ELF/VLF plasma waves.

2. OBSERVATIONS

Figure 1 is taken from Wenzel et al. (ref. 1) and is repeated here to illustrate the relationship between energetic ion fluxes, solar wind velocity and density and transverse wave peak power at 10^{-2} Hz. Enhanced transverse wave power above "intermediate" solar wind conditions (ref. 4) and enhanced energetic ion fluxes are detected on days 82-83 and 86-87, 1986. These are illustrated in the bottom and top panels, respectively. However, these intervals occur during high-speed solar wind streams, shown in the second panel. It is thus uncertain whether the enhanced wave power is simply a result of the stream-stream interaction or of cometary ion pickup.

Daily averaged power spectra of the transverse fluctuations for the interval of interest are plotted in Figure 2. The number of degrees of freedom are indicated in each panel. Because these latter values are large, the uncertainty is quite small. The spectra have general ~ $f^{-5/3}$ dependences consistent with Kolmogorov turbulence. The power level increases and decreases with solar wind velocity (see Figure 1), but there is little or no indication of any pronounced wave power spectral peaks. There are no particularly remarkable features at frequencies corresponding to the water ion gyrofrequency (10^{-2} Hz) or the proton gyrofrequency (~ 10^{-1} Hz). The power spectra of the field magnitude was also computed for the same days, with similar results. No obvious peaks were detected.

A careful scan of the high resolution data (1-1/2 vectors s^{-1}) was made to determine if there is a possibility that H_2O^+ group (or any other ion group) waves occurred with low amplitudes or on a sporadic basis (which would not show up in a power spectral analysis). Within the limit of the natural noise present in the data, no evidence was found for such waves.

However, from the scan of the high resolution data, two other distinct modes were discovered. They are identified as nonoscillatory drift mirror mode "waves" and electromagnetic cyclotron waves. The wave amplitudes for both modes are relatively small, and the occurrence sporadic. The drift mirror waves are most apparent in the data set, while only a few definite cases of the cyclotron waves are detected.

Figure 3 gives an example of what we believe to be drift mirror mode structures. They are characterized by pronounced changes in field magnitude with little or no changes in field direction. This identification is based on observations of these waves in the earth's magnetosheath (refs. 5, 6). Unfortunately, because of the low data rate mode, the plasma and energetic ion data had insufficient time resolution to provide additional support for this identification.

The second panel of the figure illustrates the sine of the angle between the interplanetary magnetic field and solar wind velocity, α. For the event at 1637-1658 UT, sin α is ~ 0.7. However, for the previous event occurring at 1615-1625 UT, sin α was considerably smaller (~0.5).

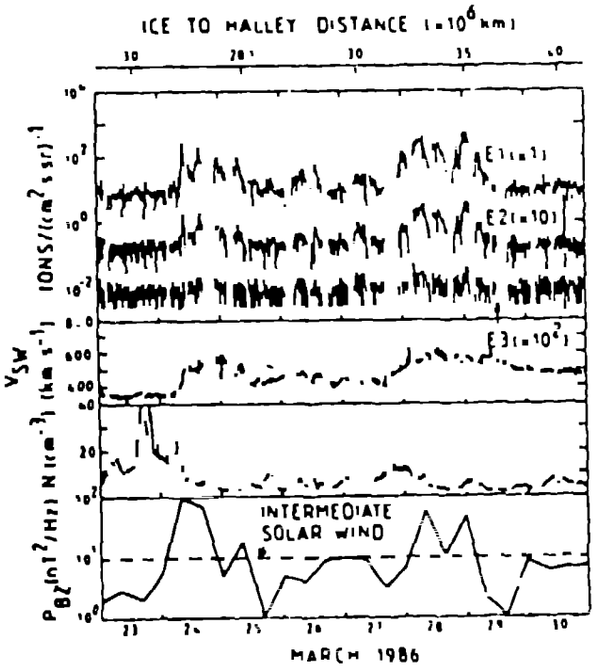

Figure 1. From Wenzel et al. (1986). Energetic ions, plasma velocities and densities, and peak magnetic field power at 10^{-2} Hz during the ICE encounter with comet Halley.

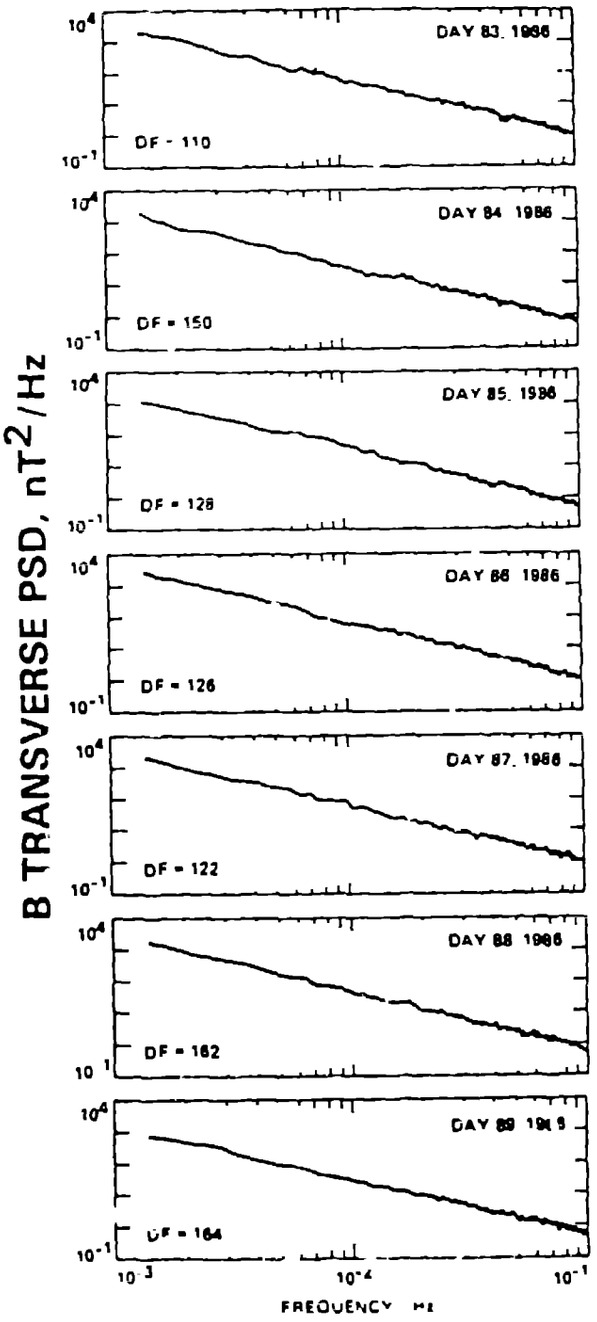

Figure 2. Power spectral densities of the magnetic field from Days 83 to 88, 1986. The statistical uncertainties are small, indicated by the large number of degrees of freedom.

The ICE plasma wave data were examined to determine if (ELF) electromagnetic ion roars were generated in the low field (high β) regions as discussed in refs. 5, 7-10, and if (VLF) electrostatic ion acoustic waves are present in the high field (low β) regions (ref. 11). Neither wave modes were found with the same correlation with drift mirror mode waves as in the Earth's magnetosheath. However, broad-band electrostatic emissions were detected during the same time interval. This is illustrated in Figure 4. Only the 1.78 kHz channel is illustrated, for brevity. Vertical shading has been applied to each of the electrostatic bursts. It can be seen from the figure that each of the bursts is associated with either dips in the magnetic field (high β regions) or magnetic field gradients.

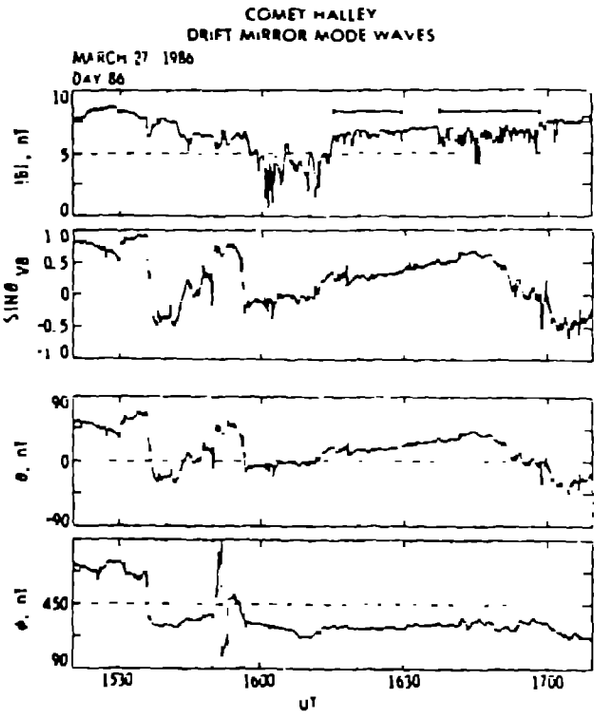

Figure 3. Examples of events of magnetic field decreases with little changes in direction horizontal (bars). These are presumed to be drift mirror mode waves. The sine of the angle between the solar wind velocity vector and field direction is given in the second panel. The magnetic field GSE θ and φ components are given in the bottom two panels.

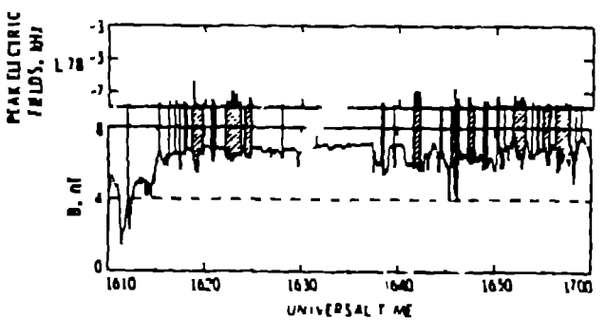

Figure 4. The relationship between VLF electrostatic waves and drift mirror mode waves.

Two easily identifiable cases of electromagnetic cyclotron waves occurred on March 25 (Day 84) and March 28 (Day 87). Figure 5 illustrates the example on Day 84. The waves are almost purely transverse (little field magnitude variation). The wave period is ~ 8 seconds. The amplitude is quite small, ~1 nT peak-to-peak with a <0.2 nT compressional component. The magnetic field is illustrated in the principal axis system where the φ variations correspond to the field rotation from B_1 to B_2 (standard notation, as in ref. 12). The directions of the principal axis and the magnetic field are given in the figure. The waves have a left-hand sense of rotation about the ambient magnetic field (in the spacecraft frame) and are propagating nearly along the field with an average angle of 4°. The waves are elliptically polarized, with λ_1/λ_2 = 4.4.

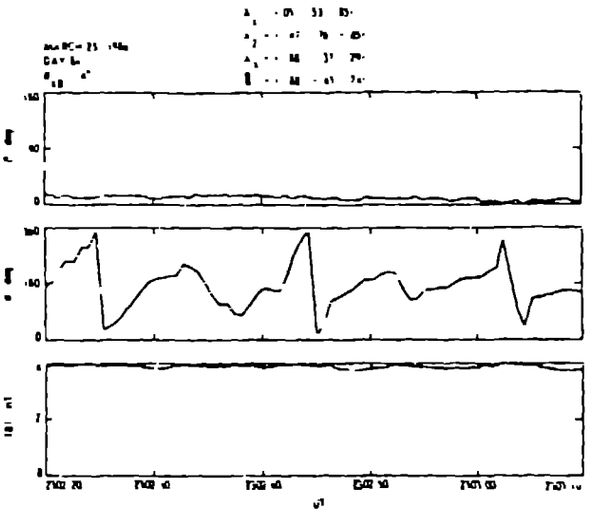

Figure 5. An example of an electromagnetic cyclotron wave in the solar wind.

The cyclotron waves at 1408-1409 UT, Day 87 (not shown) have periods of ~ 15 s. The wave amplitudes are large, ~ 6.0 nT peak-to-peak. The magnetic field magnitude variation is ~ 3.5 nT peak-to-peak. The waves are elliptically polarized (λ_1/λ_2 = 2.7) and are propagating at relatively large angles to the ambient magnetic field ~ 40°. The waves are left-hand polarized in the spacecraft frame.

During both of the above cyclotron wave events, the direction of the interplanetary magnetic field is more or less along the spacecraft-sun line. $\cos^{-1}(\hat{B} \cdot \hat{X}_{SE})$ = 28° for the event on Day 84 and $\cos^{-1}(\hat{B} \cdot \hat{X}_{SE})$ = 27° for the Day 87 event.

The detection of two new modes of waves in the solar wind, possibly associated with the pickup of cometary protons, is quite exciting. Because of the high neutral hydrogen velocities of 8 km/s and 20 km/s relative to the nucleus (for the dissociation of OH and H_2O, respectively), and H ionization time scales of ~ 10^6 s, ionization scale lengths of 8 - 20 x 10^6 km are obtained, in agreement with the values suggested as being necessary by Scarf et al. (ref. 3) and Wenzel et al. (ref. 1)

To determine if these two wave modes are indeed caused by MHD instabilities associated with the pickup of comet Halley ions, we discuss below theoretical growth rates for both modes. We will also examine a prior passage of one of the corotating solar wind streams, to determine if similar waves are detected. During this prior high-speed stream passage, the ICE spacecraft was considerably farther from comet Halley, ~ 0.75 AU versus ~ 0.2 AU (Farquhar, private communication)

3. GENERATION MECHANISMS

3.1 Drift Mirror Waves

Mirror-mode instability requires an anisotropic pressure distribution with $\beta_\perp/\beta_\parallel > 1 + 1/\beta_\perp$ where $\beta_\perp$ and $\beta_\parallel$ are the perpendicular and parallel plasma beta ($8\pi NkT/B^2$) values (refs. 13, 14). The plasma will be unstable to the drift mirror mode if the pressure anisotropy, $\beta_\perp/\beta_\parallel > 1.6$ for $\beta = O(1)$ or for smaller anisotropies if $\beta >> 1$. We will calculate the effect of the addition of cometary pickup protons on the total $\beta_\perp$ at a distance of ~ 30 x 10^6 km to determine if the pickup ions can be responsible for instability.

The cometary neutral density at a distance r from the nucleus is $N_n = Qe^{-r/V_g t}/4\pi V_g r^2$, where Q is the molecular production rate, V_g the hydrogen atom velocity relative to the nucleus, and τ the ionization time. A reasonable value of Q for Halley is 4 x 10^{29} s^{-1} (ref. 15, and references therein). Assuming 80% of all cometary molecules are H_2O, and using the higher value V_g = 20 km s^{-1}, we get an upper limit of 3 x 10^{-4} H cm^{-3} at r = 30 x 10^6 km. By assuming all of the ions gain the maximum possible kinetic energy during pickup, $1/2\ m_i V_{sw}^2$ (where V_{sw} = 425 km/s at the time of drift mirror mode detection) and the ion ring formation time is long, say 10^4 s, then the beta associated with the pickup ions is $\beta_\perp = (N_i \times E_i)/(B^2/8\pi)$ or $\beta_\perp \sim 10^{-4}$ (with a measured 5 nT magnetic field). Thus, it is clear that cometary ions make a negligible contribution to the total plasma pressure anisotropy in a the solar wind plasma where β is typically of order ~ 1.

3.2 Electromagnetic Ion Cyclotron Waves

The electromagnetic cyclotron waves were detected when the IMF was nearly parallel to the solar wind velocity direction. Thus, an ion beam (ref. 16) or ring distribution (refs. 17, 18) is the most likely source of instability. By using the previously derived number for the hydrogen atom density of 3 x 10^{-4} cm^{-3} at r = 30 x 10^6 km, an ionization time scale of 10^6 s, and a beam formation time of 10^4 s, the ion beam density can be calculated from $N_i = N_n\ t/\tau_i$. Substituting, we get $N_i = 10^{-6}$ cm^{-3}. For a solar wind density of ~ 5 cm^{-3}, the relative ion beam density would be $N_i/N_{sw} = 2 \times 10^{-7}$.

Assuming wave generation by streaming cometary proton beams, the maximum linear growth rate determined from the kinetic dispersion relation is $\gamma_{max} = 7.2 \times 10^{-7}\ n_p$ This low value excludes the possibility that the cyclotron waves are generated by beams of cometary protons.

3.3 Previous Passage of the Corotating Event

A careful scan of days 56 - 64, 1986 was made for the previous appearance of the corotating stream. Similar drift mirror waves were detected. An example is shown in Figure 6. The temporal scale of the structures is ~ 60 s. This value is somewhat larger than in the previous example, but is still comparable. Maximum amplitudes of the field decreases are ~ 3 nT, comparable in scale to the former event. The ambient magnetic field lies at an angle of ~ 40° relative to the solar wind velocity.

As stated previously, the distance of ICE from Halley at this time was ~ 0.75 AU, 3.75 times further away. Halley protons will thus be ~ 6 x

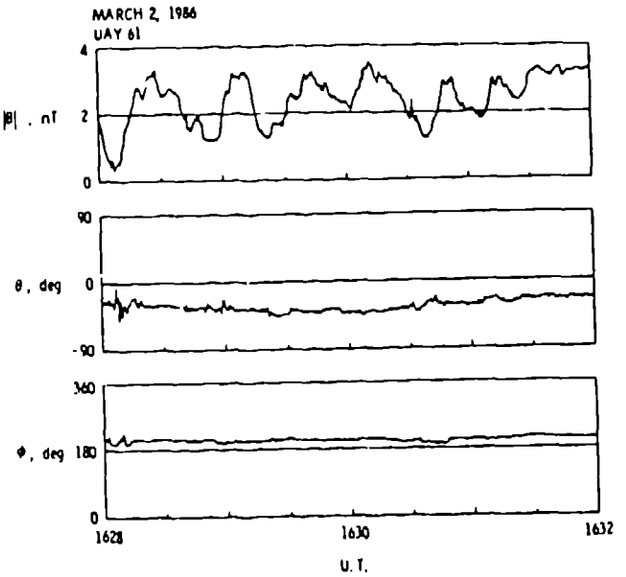

Figure 6. Nonoscillatory drift mirror mode waves on Day 61, at a distance of 110 x 10^6 km from Halley.

10^3 less dense. It is even more unlikely that these waves have any association with Halley pickup ions.

4. DISCUSSION

A search for waves near the cyclotron frequencies of heavy cometary ions was conducted during the interval of closest approach to comet Halley by both power spectral analyses and visual inspection. No obvious signatures were found.

Two types of electromagnetic waves have been detected for the first time in solar wind stream-stream interaction regions: drift mirror mode non-oscillatory, "waves" and elliptically polarized electromagnetic cyclotron waves with periods of ~ 10 - 60 s in the spacecraft frame. Both waves have scales near the proton gyroradius. The detection of drift mirror mode waves in a more distant solar wind stream indicates a lack of uniqueness of the Halley encounter interval. Theoretical arguments rule out the possibility of generation of either wave mode by cometary protons.

The amplitude of the waves are generally small (although some large amplitude cases were shown) and their occurrence infrequent. Their contribution to the power in solar wind fluctuations is negligible, as was indicated by the lack of any significant peaks appearing in power spectral analyses of an entire days' worth of data.

The formation of mirror mode waves at ICE must therefore be due to an anisotropic plasma pressure present in the bulk of the solar wind proton distribution. It was speculated by Tsurutani et al. (ref. 5) that such conditions for instability could be created by the heating of solar wind plasma as it passes through an interplanetary quasiperpendicular shock. Ion and electron heating (refs. 19-20) can lead to a downstream β of > 3. This plus the preferential ion heating in the perpendicular direction (refs. 19, 21) presumably leads to the

growth of drift mirror waves in the planetary magnetosheaths of Earth, Jupiter and Saturn (ref. 5).

The VLF electric noise at frequencies well above the electron cyclotron (170 Hz) but below the electron plasma (27 kHz) frequencies and the lack of any magnetic signatures, indicate that these emissions are probably electrostatic waves. The occurrence of the emissions on the gradients of the magnetic field also gives an important clue to possible generation mechanisms. Ashour-Abdallah and Okuda (ref. 22) have suggested that cold counter-streaming ion beams, where $T_p << T_i \sim T_e$ and $V_{Te} > V_{ib} > C_s$, could lead to growth of electrostatic waves. Whether such beams exist in solar wind stream-stream interaction regions is presently unknown. However, adiabatic decompression of solar wind protons in the mirror waves will be expected to lead to the formation of anisotropic field-aligned streaming and could possibly support such a mechanism.

The possibility that the emissions are Doppler shifted lower hybrid drift waves associated with the density gradients in the drift mirror waves (we assume magnetic plus plasma pressure is constant, or pressure isotropy) is another possible generation mechanism. Using the formulation of Huba et al. (ref. 23) for the threshold of instability $L_n/\rho_i < (m_i/m_e)^{1/4}$ we estimate L_n by $1/2(\beta_e + \beta_i)$ $L_B \sim L_p$ where $L_B = (1/B_o\ \delta B/\delta s)^{-1}$. L_n has a minimum value of 2×10^3 km at a sharp field gradient at 1658 UT Day 86. We find that the threshold for instability is not met, unless higher magnetic field and plasma variations are present but escape measurement because of the temporal resolution of the instrumentation.

It is also possible to understand why lion roars are not generated in the high β regions, in contrast to the case of earth's magnetosheath. From refs. 5, 7. it is shown that lion roars are generated when $E_m \leq E_{th}$, where $E_m = B^2/8\pi N$ and E_{th} is the electron thermal energy. For the case illustrated here, $B = 7n\Gamma$, $n \sim 3\ cm^{-3}$ and thus, $E_m = 6.5 \times 10^{-11}$ erg. For the electromagnetic cyclotron instability, this requires an electron temperature of at least 4.7×10^5 K. The actual measured electron temperature is only 1.5×10^5 K. Thus, independent of the temperature anisotropy necessary for instability, the solar wind electron temperature is too low to lead to the generation of lion roars.

From the above, it can be concluded that lion roars should be only rarely detected in conjunction with drift mirror waves in the interplanetary medium. Electrons have temperatures $\geq 3.2 \times 10^5$ only 1-2% of the time (ref. 24), thus E_m is typically $\geq E_{th}$, leaving the solar wind electrons stable to the growth of lion roars.

5. CONCLUSION

We have not found any evidence of heavy ion cyclotron waves at distances $\geq 28 \times 10^6$ km. We have, however, detected two new solar wind electromagnetic wave modes due to this search: drift mirror mode waves and electromagnetic cyclotron waves with periods 10 - 60 s in the spacecraft frame. From theoretical considerations, it is most probable that these waves are generated by processes associated with solar wind stream-stream interactions

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