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WAVES IN THE PROTON CYCLOTRON FREQUENCY RANGE IN THE CME OBSERVED BY WIND ON AUGUST 7-8, 1996: THEORY AND DATA

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ABSTRACT

As first discussed by Farrugia et al. (*J. Geophys. Res., 103*, 6543, 1998), coronal mass ejections (CMEs) may support the excitation of electromagnetic ion cyclotron waves (EICWs). The proton plasma beta, and the electron temperature and anisotropy in the front region (~5 hours, translating to ~6x10^6 km) of the CME observed by WIND on August 7-8, 1996 favor this possible excitation. Supplementing these measured parameters by other data taken from a survey of CME properties observed by the ISEE 3 spacecraft (Gosling et al., *J. Geophys. Res., 92*, 8519, 1987), we solve the EICW dispersion relation numerically. We find short *e*-folding times of EICWs, of the order of 5 min, i.e., much less than the typical evolution time of these ejecta. We suggest that high resolution data will show enhanced power in the 0.5 Hz range.

INTRODUCTION

Coronal mass ejections (CMEs) are closed field line structures which are characterized by field and plasma properties differing substantially from those of the normal solar wind. Thus, for example, CMEs have low proton temperatures T_p (see e.g., Gosling, 1990; Richardson and Cane, 1995, and references therein), and frequently they present the following thermal properties: (1) negative thermal anisotropy of protons ($A_p \equiv T_{p,\perp}/T_{p,\|} - 1 < 0$), sometimes reaching values as high as $A_p \sim -0.9$ (Gosling *et al.*, 1987; Galvin *et al.*, 1987); (2) relative α particle-to-proton density ratio ($\eta_\alpha = n_\alpha/n_p$) which is highly variable and thus may differ from the typical 3-4 % observed in the solar wind; (3) electron temperatures (T_e) which are frequently $> T_p$ (Osherovich *et al.*, 1993; Richardson *et al.*, 1997); and (4) negative thermal anisotropy of electrons ($A_e \equiv T_{e,\perp}/T_{e,\|} - 1 < 0$; see Gosling *et al.* (1987)). The subset of CMEs called interplanetary magnetic clouds is distinguished by enhanced magnetic field strengths with respect to ambient values, a large rotation of the magnetic field vector, and low T_p (Burlaga *et al.*, 1981; Burlaga, 1995). Besides these well known properties, detailed proton distribution functions have not been published for CMEs.

In this paper, we shall model the protons by bi-Maxwellian distribution. The proton distribution function in the normal solar wind is known to be strongly non-Maxwellian. However, in view of the fact that CMEs represent a different sort of object, and in the absence of firm experimental evidence on the velocity distribution of protons in CMEs and magnetic clouds, it seems to us to be premature to extrapolate from the features of the distribution functions observed in the solar wind to CMEs. Rather we shall elaborate a simple model where we consider bi-Maxwellian functions and where we utilize a solid experimental datum, namely, the negative thermal anisotropy. This work examines the emission of electromagnetic ion cyclotron waves (EICWs) in the front region of the magnetic cloud that was observed by the Wind spacecraft on August 7-8, 1996, under the most plausible assumption at the present stage of our research. For this region, we predict e-folding times of the instability, which are much smaller than the typical evolution times of the CME, permitting these waves to grow before magnetic cloud parameters change sensibly. This is a clear prediction which may be refuted or confirmed by experiment.

PARAMETERS CHARACTERIZING THE MAGNETIC CLOUD ON AUGUST 7-8, 1996

According to the aforementioned criteria of Burlaga (1995) an interplanetary magnetic cloud arrived at Wind at 13 UT, August 7, 1996, and its passage lasted for 22 hours. Dotted vertical guidelines bracket the cloud interval (see Figure 1). From the measured bulk speed of protons and from the statistical relationship observed between the T_p and the bulk speed V_p for normal solar wind expansion (see Lopez, 1987; Richardson and Cane, 1995), an expected proton temperature (T_{ex}) is calculated. It is found that almost all the cloud contains cold protons, i.e., the measured proton temperature (T_p) is significantly lower than T_{ex}.

Figure 1 shows Wind plasma and magnetic field measurements for the event. From the top to the bottom the panels show the measured (solid line) and the expected (dot-dashed line) proton temperature (T_p and T_{ex}, respectively), the proton plasma beta (β_p), the magnetic field (B), and its latitude (θ_B) and Longitude (ϕ_B) in GSE coordinates.

The EICW instability depends on several properties of the plasma; however, one of the most sensitive parameters is β_p (Farrugia *et al.*, 1998; Dasso *et al.*, 1998; Dasso *et al.*, 1999; Dasso *et al.*, 2000). The β_p panel of the figure 1 shows that it is possible to classify several regions or layers of the ejecta according to their very different values of β_p. For instance, during the first twelve hours of the cloud (13 UT, August 7- 01 UT, August 8) $\beta_p \sim 0.3 - 0.4$. The average value of β_p in the entire cloud was 0.23±0.10; and the minimum and maximum values that β_p reached were 0.08 and 0.97, respectively. The β_p value was greater than 0.1 for more than 21 hours (i.e., almost 99 % of the time of duration for this event).

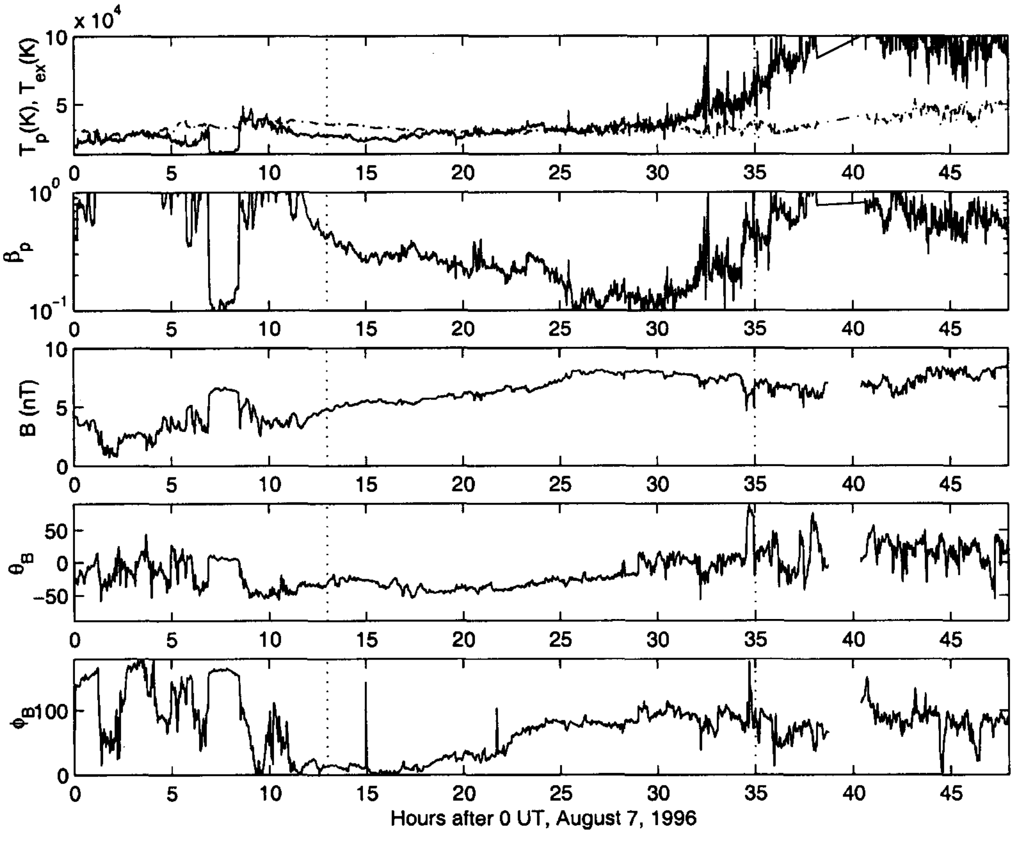

Figure 1: Proton and magnetic field data from Wind. From the top to the bottom the measured (solid line) and expected (dot-dashed line) proton temperature, the proton plasma beta (β_p), the magnetic field (B), the latitude (θ_B), and longitude (ϕ_B) of the magnetic field in GSE coordinates.

Figure 2 shows the electron thermal properties for the first twelve hours of the magnetic cloud. From top to bottom, the panels show the electron density (N_e), temperature (T_e), the ratio ($T_{e,\|}/T_{e,\perp}$), the parallel and perpendicular temperature of electrons (the dashed trace shows also T_p), and finally T_e/T_p. Quantity $T_e \geq 3T_p$ was sustained for more than the 85% of the time duration of all the cloud and during the first five hours of the cloud, the parallel temperature of electrons was $T_{e,\|} \geq 1.3T_{e,\perp}$. Hot electrons with $T_\| > T_\perp$ have a major effect on this instability (see Gratton *et al.*, 1998 and Dasso *et al.*, 2000), and thus the observed properties motivate a detailed study of the possibility of the EICW activity in this cloud.

NUMERICAL PROCEDURE AND RESULTS

We solve exactly the kinetic dispersion relation (Stix, 1992) for a plasma composed of protons, α-particles and electrons. In this preliminary study we model each species by bi-Maxwellians. This is a model simplification. However, we note that analyses of ISEE 3 and WIND solar wind proton data make a similar assumption (R. Zwickl, D. Larson, private communications, 2001). In future work we intend to model with more sophisiticated distribution functions. An in-house numerical code to evaluate the plasma *Z*eta function, and non-linear optimization methods to compute the roots, as explained in Dasso *et al.*, (2000), are used. From the roots of the dispersion relation, the complex dimensionless frequency x, as a function of the wavenumber y, is obtained. Here x is the dimensionless frequency of the wave ($x = x_r + ig = \omega/\Omega_p$), and y is the dimensionaless wave number, $y = kV_a/\Omega_p$, where $V_a = B_0/\sqrt{4\pi n_p m_p}$ is the proton Alfvén velocity. Wave quantities vary as $\exp[i(kz - \omega t)]$, where the z axis is aligned along the magnetic field, thus $g > 0$ corresponds to the unstable case (growth).

The dispersion relation is solved for a set of fixed parameters, which represent the physical conditions of the first five hours in the studied magnetic cloud. Where available, the parameters are taken from the measured values; where not available, they are obtained from average values in the statistical survey of CMEs (Gosling *et al.*, 1987; Richardson *et al.*, 1997) and cases studied (e.g. Galvin *et al.*, 1987; Osherovich *et al.*, 1993). The thermal anisotropy of α-particles is chosen equal to the proton anisotropy, which is equivalent to assuming that the physical mechanism producing the anisotropy of both kind of ions is the same, i.e., the conservation of magnetic moment during the expansion of the cloud. We define a reference case choosing β_p, T_e/T_p, and $T_{e,\|}/T_{e,\perp}$ according to the observed values, a moderate thermal anisotropy for protons, a low abundance of alpha particles, and the same thermal velocity for protons and alphas. Thus the reference case is represented by: $\beta_p = 0.35$, $A_p = -2/3(= A_\alpha)$, $\eta_\alpha = 0.04$, $T_\alpha/T_p = 4$, $T_e/T_p = 5.5$, and $A_e = -0.286$.

The top panel of Figure 3 shows the wavenumber y plotted versus the real frequency x_r. The ratio x_r/y (inverse gradient in panel 1) gives the phase velocity of the wave. The bottom panel shows the growth rate, g, versus x_r. To bring out the effect of η_α, the reference case (thick lines) is compared with results obtained for $\eta_\alpha = 0, 0.08$, and 0.12, respectively. The first panel shows that η_α influences the wave speed: when η_α is increased, the phase velocity decreases permitting more ions to travel with the wave and resonate. The value of the maximum growth rate for the reference case ($\eta_\alpha = 0.04$) is $\gamma \sim 0.5\text{x}10^{-3}$ Hz at the frequency $\omega \sim \Omega_p \sim 1/2$ Hz, which translates to a growth rate of $\tau \sim 5$ minutes (i.e., the amplitude of a small perturbation takes 5 minutes to increase by a factor of ~ 3). If the abundance of α particles is 12%, the maximum growth rate corresponds to $\tau \sim 1$ min at $\omega = 0.36$ Hz. In this last case, the wide frequency range 0.1 Hz $< \omega <$ 0.75 Hz corresponds to growth rates $\gamma > 0.5\text{x}10^{-3}$ Hz. Even for the case when α-particles are absent, the instability is still significant with a growth time of about 14 minutes. An absorption band, with values of the damping rates similar to the growth rates, appears after the unstable band in all the analyzed cases [not shown].

Figure 4 is similar to figure 3 but for variations (with respect to the reference case) of the proton thermal anisotropy. The cases shown correspond to computer runs with $T_{p,\|}/T_{p,\perp} = 1$, 2, 3, and 5. The case with $T_{p,\|}/T_{p,\perp} = 5$ corresponds to an instability growth time of $\sim$45 s at $\omega = 0.53$ Hz. The case with low proton anisotropy ($T_{p,\|}/T_{p,\perp} = 2$) has only marginal instability with a growth time of 12 hours. Note that cases with stronger anisotropies than those considered here have been observed. For example $T_{p,\|}/T_{p,\perp} = 10$ was reported in Galvin *et al.*, (1987), and thus it is possible to expect growth rates greater (growth times shorter) than the results presented here. For a case with isotropic electrons and the rest of the parameters equal to the reference case, the instability is marginal [not shown]. Thus the presence of hot electrons with parallel greater than the perpendicular temperatures is essential to excite EICWs in the cloud studied.

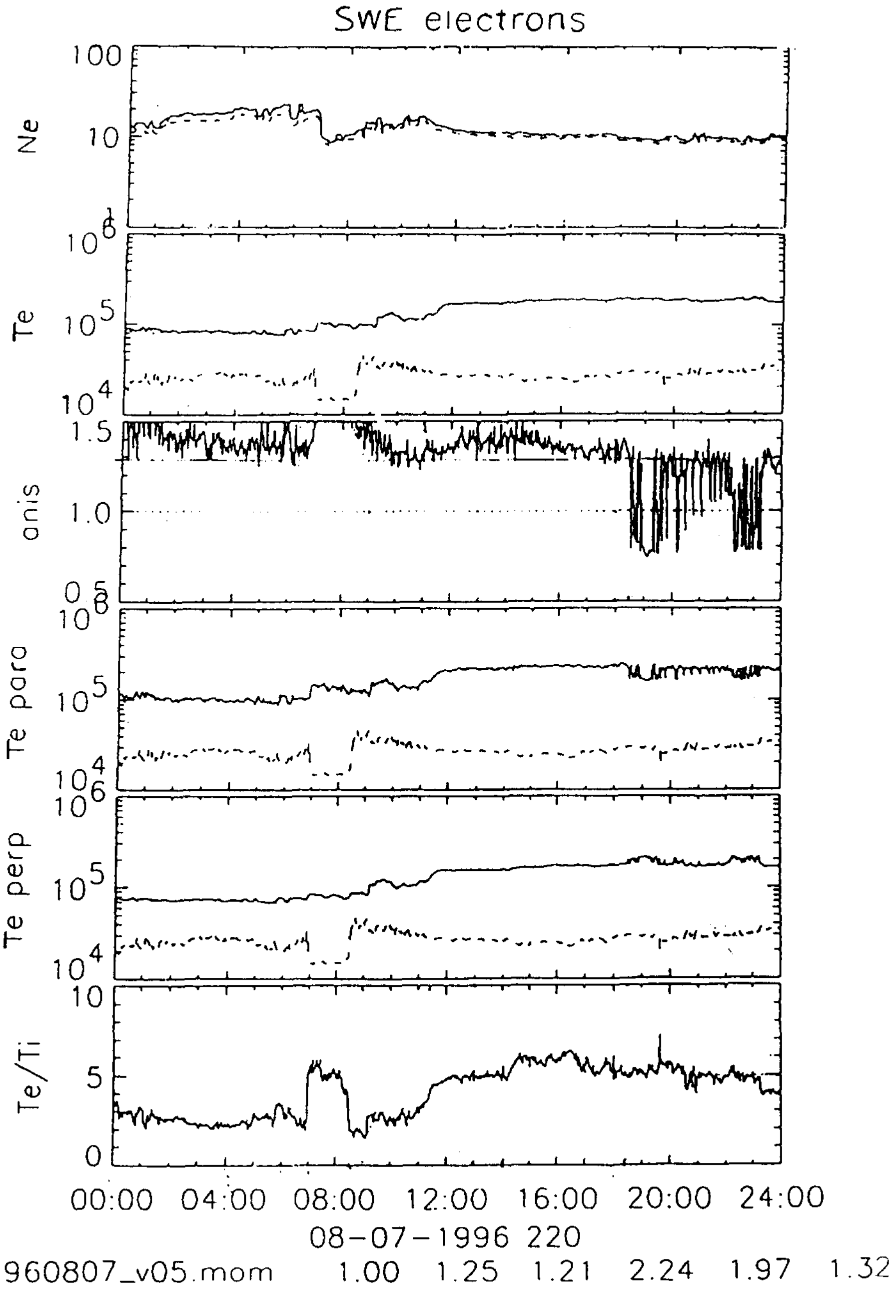

Figure 2: Electron thermal properties observed by Wind on August 7, 1997. From the top to the bottom, the first panel shows (continuous line) the electron density *Ne* (cm^{-3}), the dashed line corresponds to the proton density; the continuous line of the second panel shows the temperature *Te* (K), the dashed line corresponds to the protons; the third panel shows the parallel to perpendicular electron temperature ratio (*anis*); the next two panels indicate respectively the parallel and the perpendicular electron temperature (*Te para* and *Te perp*); finally the electron to proton temperature ratio (T_e/T_i) is given.

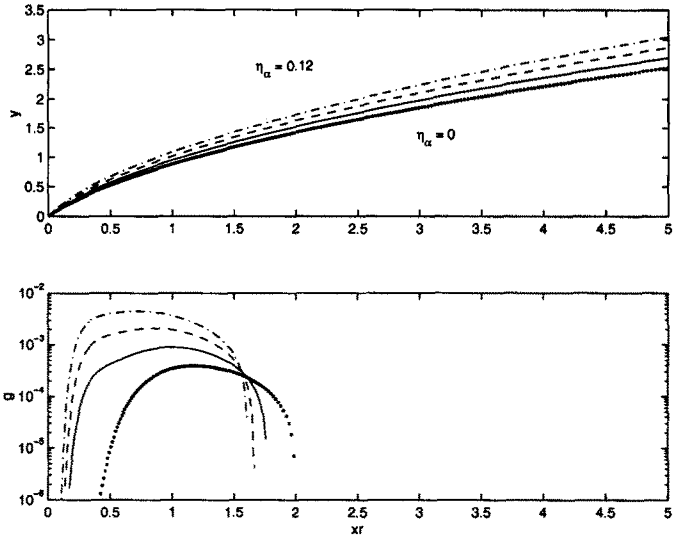

Figure 3: From the top to the bottom, the wave number (y) and the growth (g) rate are given versus the frequency (x_r). Variations of η_α for β_p=0.35, A_p=A_α=-2/3, T_α/T_p=4, A_e=-0.286, T_e/T_p=5.5, fixed. Dot, solid, dash, and dash-dot lines correspond to the cases with η_α=0, 0.04, 0.08, and 0.12, respectively.

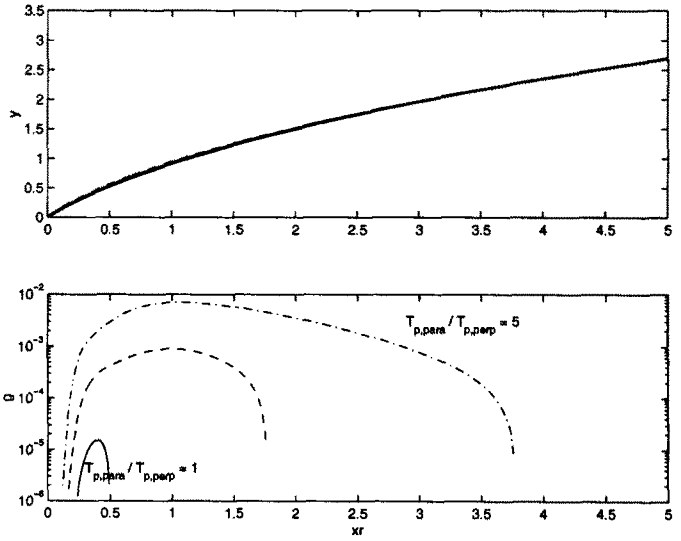

Figure 4: Idem Figure 3, but showing variations of A_p for β_p=0.35, η_α=0.04, A_α=A_p, T_α/T_p=4, A_e=-0.286, T_e/T_p=5.5, fixed. Dot, solid, dash, and dash-dot lines correspond to the cases with, A_p=0, -0.5, -0.67, and -0.8, respectively.

DISCUSSION AND CONCLUSIONS

This study has explored the possibility of the excitation of right-hand polarized EICWs in the magnetic cloud of August 7-8, 1996. We have solved the exact dispersion relation using measured values (β_p, T_e/T_p, and $T_{e,\|}/T_{e,\perp}$) for a region of this event and using statistical surveys to obtain the other properties. We have found times (of several minutes) for the growth of the instability of EICWs that are significantly lower than the evolution time of a CME (~ many hours). The presence of hot electrons with negative anisotropy is essential to the development of this instability in cases with low proton anisotropy, such as illustrated by the case studied here.

Plasma parameters vary considerably inside a given ejecta. Since β_p is a key parameter in the excitation of EICWs in ejecta, we thus expect that only some regions of a given ejecta might have EICW emission, i.e., only those regions where β_p is not too low.

The excitation of EICWs we have discussed in a case example might be important to understand the unusually high levels of magnetic field fluctuations observed in ejecta in the last 4 years by Wind (e.g., Janoo *et al.*, 1998).

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