RESONANCE ABSORPTION OF ALFVÉN WAVES AT COMET-SOLAR WIND INTERACTION REGIONS

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Abstract. The interaction of the low frequency (10^{-2} Hz) MHD waves, observed upstream of comets, with the structured plasma near the cometary bow wave is examined. It is suggested that the waves undergo resonant absorption due to either ambient density gradients or localized shear in the background magnetic field. The absorption process can give rise to rapid heating of the solar wind protons, in agreement with observations from comet Halley. Since the free energy for the generation of MHD waves came from deceleration (without accompanying heating) of the solar wind protons during the pick up of cometary ions, the subsequent reabsorption of the energy is equivalent to a nonlocal transformation of ordered to random energy and can be described as nonlocal viscosity.

Introduction

The recent spacecraft encounters with comets Giacobini-Zinner (G-Z) and Halley have provided a vast amount of data on the interaction of cometary magnetospheres with the solar wind [e.g. Galeev, 1987]. While it has been known for many years that the ionization of sublimating cometary ions decelerated (or mass loaded) the solar wind as it approached the comet [e.g. Mendis et al., 1985], the question of whether a bow shock is formed in the flow (as at the earth) has been a controversial issue for many years [Wallis, 1973]. The encounters not only provided data about the nature of the transition region (referred to also as the bow shock or bow wave), but also indicated strong plasma wave activity in it's vicinity. The transition structure is clearly complex and quite unlike anything seen at terrestrial or planetary bow shocks; it should be treated as an entity in it's own right [e.g. Omidi and Winske, 1987; Hizanidis et al., 1988].

Waves over the wide range of frequencies ($\sim 10^{-2} - 10^5$ Hz) are detected at both comets [Tsurutani and Smith, 1986a; Grard et al., 1986; Glassmeier, et al., 1987] corresponding to a wide range of plasma modes, from low-frequency magnetohydrodynamic (MHD) waves ($\sim 10^{-2}$ Hz) to high frequency electrostatic plasma waves ($\sim 10^5$ Hz). These waves are excited by the observed ring and beam distributions of the cometary ions picked-up by the solar wind [e.g. Brinca and Tsurutani, 1988] and are convected downstream

by the solar wind into regions of higher density and magnetic field closer to the comet. From a global perspective the density and magnetic field gradients are caused by the slowing of the solar wind due to mass loading. Furthermore localized gradients are caused by the fact that the pick up rate is unsteady. In the presence of global and local gradients the waves encounter resonances at the local upper and lower hybrid, electron and ion cyclotron, and Alfvén frequencies where they can be mode-converted into other modes with shorter wavelengths, resulting in resonance absorption and heating of the solar wind protons. For waves over such a wide range of frequencies, the resonances and the consequent plasma heating is expected to occur at different spatial points in the comet-solar wind interaction region. On a global scale such processes are equivalent to non-local viscosity. Namely, the streaming energy of the solar wind protons is first transfered to pick-up cometary ring distributions, subsequently transformed with a certain efficiency to the plasma waves, which are ultimately reabsorbed (again with certain efficiency) by the streaming protons near the transition region producing local proton heating. While such processes are undoubtedly occuring in the upstream and transition regions, it is important to determine to what extent they determine the dynamics of the transition region.

A particular class of waves studied by Tsurutani and Smith [1986a,b] are low-frequency, linearly polarized MHD waves with $\delta B/B = O(1)$ upstream from the G-Z bow wave. In the solar wind frame, these waves travel away (upstream) from the comet. As seen by the spacecraft, they are swept toward the comet by the solar wind, and ultimately impinge on the bow wave. Tsurutani and Smith [1986a,b] estimate the total wave energy at comet G-Z as 5×10^{22} ergs with an approximate energy density of 3×10^{-10} erg cm^{-3}. Analogous results from comet Halley [Glassmeier et al., 1987] indicate a wave energy content of 2×10^{24} ergs and similar energy density to G-Z. These energies represent a significant fraction of the total energy in the comet-solar wind interaction region.

In this paper we study the energetics, efficiency and observational consequences of reabsorption of the MHD part of the spectrum by the solar wind protons near the transition region. Absorption of MHD waves in the presence of density and magnetic field gradients has been studied in a variety of other settings [Tataronis and Grossmann, 1973; Chen and Hasegawa, 1974] and is known as resonance absorption. The absorption arises at the location where the frequency of the waves matches the Alfvénic frequency of the plasma and gives rise to strong local plasma heating.

Wave Propagation Near the Cometary Bow Wave

The properties of MHD waves upstream from comet G-Z have been summarized by Tsurutani and Smith [1986a] and Tsurutani et al. [1987]. They found $\delta B/B = O(1)$, linear polarization, a strong compressional component ($\delta \rho/\rho = O(1)$) and an angle of propagation (θ) with respect to the magnetic field of between 6° and 40° depending on the location of the observations. Similar properties have been found at the Halley encounter [Johnstone et al., 1987] although no explicit angle of propagation appears to have been determined. A variety of possible instabilities involving both cometary ring and beam ion distributions have been invoked to explain these wave properties [e.g. Gary and Winske, 1986; Brinca and Tsurutani, 1988]. Glassmeier et al. [1987] note that at comet Halley, both compressional and transverse magnetic field fluctuations are seen, so it is appropriate to discuss how both kinds of waves interact with the structured medium in the vicinity of a cometary bow shock.

The Alfven resonance absorption concept was originally developed for arbitrary plasma β (where $\beta = 8\pi p/B^2$), though it has been widely applied to the low β laboratory plasmas such as tokamáks [Chen and Hasegawa, 1974]. The question of the validity of the process in the turbulent cometary plasma is an important one and cannot be readily answered. We shall comment on this issue later in this letter. A compressional (magnetosonic) wave moving inward will be subjected to resonant absorption when $\omega^2 \approx k_{\|}^2 v_A^2$ [Chen and Hasegawa 1974] where $k_{\|} = (\underline{k} \cdot \underline{B}_o)/|\underline{B}_o|$ and V_A is the local Alfvén speed. Assuming that the upstream waves behave as $\omega \approx k \, V_{AO}$, where V_{AO} is the upstream Alfvén speed, the condition for resonant absorption is then: $\cos \theta = V_{AO}/V_A = (B_o/B)(n/n_o)^{1/2}$ where θ is defined earlier. The location of the absorption layer thus depends on both the propagation angle and the ambient plasma structure. For example, if the magnetic field is roughly perpendicular to the comet-sun line, then $B \sim n$ and $\cos \theta \sim (n_o/n)^{1/2}$; for $\theta \approx 30^o$, the density must increase by roughly 20% before resonance absorption can occur. Absorption of more obliquely propagating waves occurs closer to the comet. In the perpendicular case of comet Halley [Neugebauer et al., 1987] the density increases gradually ($\sim 30\%$ between 19.00 and 20.00 SCET) as the comet is approached, so that the resonance condition will be satisfied. However, if B increases more slowly than $\sqrt{n}$, the resonance condition is not satisfied for a straight field.

In the case of a magnetic field with no gradient the resonance condition can be satisfied with a shear. The data of Neugebauer et al. [1987] suggest that regions of extremely rapid magnetic shear exist. Figure 1a shows the magnetic field data given by Neugebauer et al. [1987: their Figure 2], viz. the field magnitude, solar ecliptic longitude and latitude angles, and the root mean square of the field fluctuations. Clearly there are strong shear layers at $t = 19.23$, 19.33 and 19.38 SCET, with a characteristic length scale of 1000 - 2000 km. In each case, the magnetic field is skewed

START OF PLOT : 19:10:00 UNIVERSAL TIME (SCET)
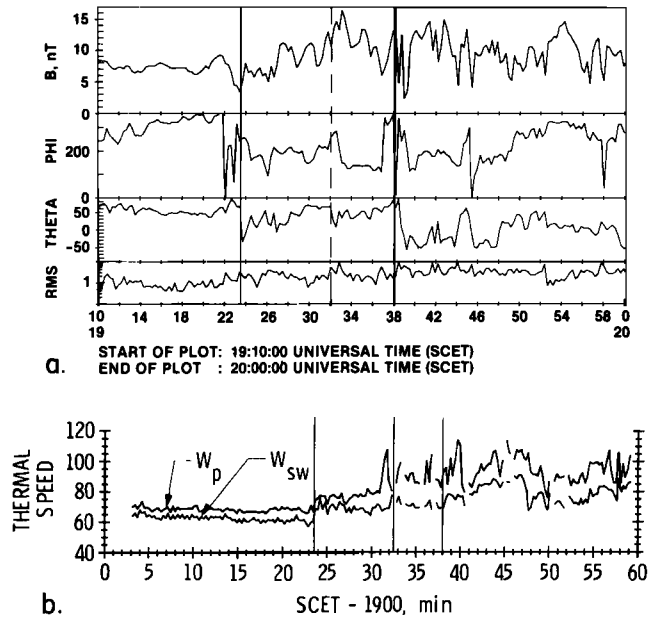END OF PLOT : 20:00:00 UNIVERSAL TIME (SCET)

Fig. 1. Selected magnetic field and plasma data from Neugebauer et al. (1987). Figure 1a shows 16s averages of the magnetic field magnitude, solar ecliptic longitude and latitude angles, and the rms value of the magnetic field fluctuations, respectively. Figure 1b shows the thermal speed of the solar wind protons in km/s (curve labelled W_{sw}). Data is from the IMS spectrometer and magnetometer. The time axes in Figures 1a and 1b have different scales.

by 50° - 100° both in the ecliptic plane and normal to it. Such large shears will easily satisfy the resonance conditions, given the ambient plasma parameters. These regions of magnetic shear are also well correlated with localized heating of the solar wind protons as shown in Figure 1b [Figure 1 of Neugebauer, et al., 1987], the temperature rising some 30-50%. The origin of these shear layers is unclear. They could be associated with the steepening of magnetosonic waves (Omidi and Winske, 1987), but the single spacecraft data makes a determination of their motion impossible. Also they could be quasi-stationary structures standing in the solar wind flow. As the transverse (shear Alfvén) waves move toward the comet in a sheared field, the direction of wave propagation with respect to the ambient magnetic field changes. For waves initially propagating roughly parallel to the field, $k_{\|}$ becomes small as the magnetic field is sheared, and $k_{\perp}$ component becomes important.

In both cases, the resultant waves will be the kinetic Alfvén waves (KAW). Hasegawa and Chen [1976] noted that magnetosonic waves propagating into a magnetic field gradient undergo mode conversion to a KAW in the resonance layer. Similarly in a sheared field, as the Alfven wave develops a larger $k_{\perp}$, the quantity $k_{\perp} \rho_i$ becomes finite and damping becomes significant. The energy dissipated by both classes of cometary MHD waves is thus due to the damping of the KAW for a finite β plasma.

Alfvén Wave Heating

We now discuss the applications of this heating process to the localized solar wind proton heating observed by Neugebauer et al. [1987: see previous Section]. The heating rate due to Landau damping of the KAW is [Hasegawa and Chen, 1976]:

$$ n \frac{dT_i}{dt} = \omega_o \frac{\delta_i}{2} \beta_i \left(\frac{T_e}{T_i}\right)^2 f(\lambda_i) \frac{\delta B^2}{8\pi} , \qquad (1) $$

where $\delta_i = 2\sqrt{\pi} \, \beta_i^{-3/2} \exp(-1/\beta_i)$, $\lambda_i = k_\perp \rho_i$, $\rho_i = v_i/\Omega_i$, $v_i^2 = 2T_i/m_i$ and the function $f(\lambda_i)$ describes the damping due to the finite Larmor radius effect. Note that following Hasegawa and Chen [1976] we have ignored coupling to the fast (magnetosonic) wave. If this coupling is included the contribution from the fast mode damping would increase the above heating rate. In Eq. (1) the product $\delta_i f(\lambda_i)$ is a weak function of the thermal energy. For $T_e \sim T_i$, we can define a heating time scale τ_H due to the wave heating:

$$ \frac{1}{\tau_H} \approx \frac{1}{2} \omega_o \delta_i \, f(\lambda_i) \left(\frac{\delta B}{B}\right)^2 \qquad (2) $$

In a time interval δt the increment in T_i is $\delta T_i = T_i \delta t/\tau_H$. Typical parameters are $\omega_o \approx 6 \times 10^{-2} s^{-1}$ and $T_e/T_i \approx 1$. Using the expression for $f(\lambda_i)$ given by Hasegawa and Chen [1976] with a modification for finite β_e, we find that for $\beta_i = 0.5$, $f(\lambda_i)$ has values between .26 and .38 for λ_i between .1 and .5, with the maximum at $\lambda_i = .4$. Though the fluctuations have $\delta B/B \sim 0(1)$ on the whole, the observations show that it changes locally in the range 0.5 - 1. For $\beta_i = 0.5$ and $\delta B/B \sim .5$-1, we find $\tau_H \approx 60$-350s. Let us now examine the localized heating events observed by Neugebauer, et al. [1987], as shown in Figure 1. Between 1938 - 1939 SCET, the solar wind proton thermal velocity increases from 70 km/s to 80 km/s. This implies $\delta T_i/T_i = 0.3$ so, with $\delta B/B = 0.7$, the heating time calculated from Eq. (2) is $\sim$ 40s and this corresponds to a heating length of 2000 km. The velocity of the absorption region relative to the bow wave is $[v_n - v_A \cos \alpha]$ where v_n is the normal component of the solar wind velocity, and α is the angle between the wave propagation and the bow wave normal (chosen as $\pi/4$). We note that the waves are observed to move back into the solar wind; away from the comet in the solar wind reference frame. In the short event between 1932 - 1932.5 SCET the solar wind proton thermal velocity increases from 70 km/s to 75 km/s. The computed heating length in this case is $\sim$ 1000 km. Lastly between 1923.5 - 1924 SCET the velocity increases from 60 km/s - 70 km/s and the computed heating length is $\sim$ 4000 km. Thus the observed heating lengths are 1400-2000 km [Neugebauer et al., 1987] in each case compare quite well and it seems that these events could be attributed to the resonance absorption of the MHD waves generated upstream.

We note that there are locations of density compression without magnetic shear [e.g. 19.26

SCET: Figure 1 of Neugebauer, et al. 1987] where there is no proton heating, whereas at 19.38 SCET there is shear and proton heating before a density compression. Hence a predictive result of this paper is a connection between magnetic shear and proton heating. This heating mechanism will initially give bulk heating in the parallel direction, but anisotropy driven instabilities may subsequently transfer the energy to the perpendicular direction. Also, the observed turbulence will deflect the particles during the interaction with the parallel electric field. However the interaction times, as seen above, are short compared to the gyroperiod and hence the turbulence will not have a strong effect on this heating process. The Alfven waves will also lead to alpha particle heating, though at a rate slower than the protons. The observed alpha particle heating [Neugebauer, et al. 1987] shows strong correlation with gradients in the magnetic field. However, the alpha particle heating is more complex than that of the protons and various processes such as heating by parametric coupling to the ion-ion hybrid resonance, transit time magnetic pumping, etc. will play an important role. It may be noted that the proton heating events cannot be due to adiabatic heating (Omidi and Winske, 1987) as they correspond to density rarefactions, rather than the expected compressions in an adiabatic process. The Alfven wave heating will lead to a depletion in the power spectrum of the low frequency waves. However the continual mass loading will rapidly replenish the power (within $\sim$ 120 secs), so that this decay may not be observable.

We also suggest that the proton heating is not a steady state process occurring at one point in space but moves around in a quasi-random fashion, depending upon where the resonance condition is satisfied. This would produce a series of localized ˆhot spotsˆ as, indeed, is observed by Neugebauer et al. [1987]. An analysis of the global proton heating due to a series of localized absorption regions is beyond the scope of the present letter, but could be amenable to a statistical treatment.

Discussion

The conversion of solar wind kinetic energy to plasma thermal energy, the principal net process in any planetary bow shock or transition region can hence proceed in a comet by a sequence of different mechanisms. For example, in the present paper, we have discussed a 3-step non-local process to describe how solar wind protons are heated. First, ion beams or rings interact with the solar wind, low frequency MHD waves are generated which subsequently mode convert to kinetic Alfvén waves and then damp on the protons. A similar example was discussed by [Hizanidis et al. 1988] involving lower hybrid waves damping their energy to heat the cometary pick-up ions. We stress that the energy transfer process goes through many non-local paths as the plasma goes from pick-up to heating. These arguments serve to emphasize the inappropriatness of using the word shock. In a

shock the free energy which drives the processes that dissipate the upstream directed energy into random energy downstream is self-generated. In supercritical quasi-perpendicular shocks, reflection of a fraction of the upstream ions and their eventual thermalization downstream keeps the required pressure balance as given by the Hugoniot conditions [Leroy, et al., 1982]. Similarly in resistive subcritical shocks, the free energy source, which in this case is the current associated with the magnetic field gradient at the front [Mellot and Greenstadt, 1984] is driven by the steepening process without interference by extraneous sources. In the cometary case the free energy available for the thermalization is not generated by the steepening process but by the presence of a source external to the solar wind, the cometary ions. If we view the presence of the comet and its associated gas outflow as the piston which drives a shock ahead of it, analogous to the earth's magnetosphere driving the bow shock, then one can conclude that the piston contamination of the "shock" region is the main cause that creates the free energy available for thermalization downstream. It cannot, therefore, be properly called a shock, since the free energy is not self-consistently created by the steepening of the non-linear wave pulse driven by the piston, but by what is essentially piston leakage.

In summary, we have outlined how the observed low-frequency hydromagnetic waves seen upstream of comets can be damped by resonant absorption at the cometary bow wave. This could explain the localized heating of the solar wind protons seen by Neugebauer et al. [1987], and represents an important example of the non-local dissipative phenomenon present at comets. We also suggest that the proton heating may occur in a non-steady fashion depending upon the location of the resonance regions. A comprehensive picture of the interaction including the role of the lower hybrid waves as well as other modes is in progress and will be published elsewhere.

References

Brinca, A.L., and B.T. Tsurutani, Survey of low-frequency electromagnetic waves stimulated by two coexisting newborn ion species, J. Geophys. Res., 93, 48-58, 1988.

Chen, L., and A. Hasegawa, Plasma heating by spatial resonance of Alfvén wave, Phys. Fluids, 17, 1399-1403., 1974.

Galeev, A.A., Encounters with comets: discoveries and puzzles in cometary plasma physics, Astron. Astrophys., 187, 12-20, 1987.

Gary, S.P., and D. Winske, Linearly polarized magnetic fluctuations at comet Giacobini-Zinner, J. Geophys. Res., 91, 13099-13709, 1986.

Glassmeier, K.H., et al., Low-frequency magnetic field fluctuations in comet P/Halley's magnetosheath: Giotto observations, Astron. Astrophys., 187, 65-68, 1987.

Grard, R., et al., Observations of waves and plasma in the environment of comet Halley, Nature, 321, 290-291, 1986.

Hasegawa, A., and L. Chen, Kinetic processes in plasma heating by resonant mode conversion of Alfvén wave, Phys. Fluids, 19, 1924-1934, 1976.

Hizanidis, K., P.J. Cargill, and K. Papadopoulos, Lower hybrid waves upstream of comets and their implications for the comet Halley bow wave, J. Geophys. Res., in press, 1988.

Johnstone, A.D., et al., Alfvénic turbulence in the solar wind flow during the approach to comet P/Halley, Astron. Astrophys., 187, 25-32, 1987.

Leroy, M.M., et al., The structure of perpendicular bow shocks, J. Geophys. Res., 87, 5081-5094, 1982.

Mellott, M.M., and E.W. Greenstadt, The structure of oblique subcritical bow shocks, J. Geophys. Res., 89, 2151-2161, 1984.

Mendis, D.A., H.L.F. Houpis, and M.L. Marconi, The physics of comets, Fund. Cosmic Phys., 10, 1-380, 1985.

Neugebauer, M., F.M. Neubauer, H. Balsinger, S. Fuselier, B.E. Goldstein, R. Goldstein, F. Mariani, H. Rosenbauer, R. Schwenn, and E.G. Shelley, The variation of protons, alpha particles, and the magnetic field across the bow shock of comet Halley, Geophys. Res. Lett., 14, 995-998, 1987.

Omidi, N., and D. Winske, A kinetic study of solar wind mass loading and cometary bow shocks, J. Geophys. Res., 92, 13409-13425, 1987.

Tataronis, J., and W. Grossmann, Decay of MHD waves by phase mixing, Z. Phys., 261, 203-216, 1973.

Tsurutani, B.T., and E.J. Smith, Strong hydromagnetic turbulence associated with comet Giacobinni-Zinner, Geophys. Res. Lett., 13, 259-262, 1986a.

Tsurutani, B.T., and E.J. Smith, Hydromagnetic waves and instabilities associated with cometary ion pickup: ICE observations, Geophys. Res. Lett., 13, 263-266, 1986b.

Tsurutani, B.T., et al., Steepened magnetosonic waves at comet Gracobini-Zinner, J. Geophys. Res., 92, 11074-11082, 1987.

Wallis, M.K., Weakly shocked flows of the solar plasma through atmospheres of comets and planets, Plan. Space Sci., 21, 1647-1660, 1973.

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