JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. A11, PAGES 24,863–24,867, NOVEMBER 1, 1999

Intermediate electromagnetic turbulence at comets

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Abstract. Low-frequency electromagnetic turbulence observed in cometary environments mostly peaks at the gyrofrequency of the water-group ions of cometary origin, because of cyclotron resonance fueled by relative drifts parallel to the interplanetary magnetic field. Nevertheless, some of the observations point to pickup proton cyclotron turbulence, to single-cycle magnetic pulses or solitary waves at the proton gyrofrequency, and also to intermediate frequencies between the water-group and the proton gyrofrequencies. The generation of turbulence at such frequencies has been attributed to cascade via wave-wave interactions, but here an alternative and direct mechanism for the generation of these waves is suggested in an unstable wavelength band when the solar wind is sufficiently mass-loaded by cometary material. It is shown, for average parameters near comet 1P/Halley, that unstable modes of the intermediate frequency kind can indeed occur up to several million kilometers from the cometary nucleus and are easier to excite in higher-velocity solar wind flows.

1. Introduction

Low-frequency electromagnetic instabilities have been shown to explain the observed levels of magnetic field turbulence in cometary environments [*Neubauer et al.*, 1986; *Riedler et al.*, 1986; *Smith et al.*, 1986], as these instabilities thermalize the streaming cometary ion distributions [*Sagdeev et al.*, 1986, 1987] and hence lead to the pickup of cometary ions by the solar wind plasma [*Gary et al.*, 1984, 1985; *Winske et al.*, 1985; *Gary et al.*, 1986; *Winske and Gary*, 1986]. In contrast, higher-frequency instabilities saturate at much lower levels of turbulence.

At the comets observed so far, 21P/Giacobini–Zinner, 1P/Halley, and 26P/Grigg–Skjellerup, most of the turbulence is characterized by a spectral peak at the gyrofrequency of the water-group ions of cometary origin, and the preferred mechanism is cyclotron resonance between these pickup ions and the waves, fueled by relative drifts between the solar wind and cometary ions along the external magnetic field $\mathbf{B}_0$. Such resonant modes prevail far from the cometary nucleus, in the distant plasma environment, and they are the first ones to become unstable [see, for example, *Lee*, 1989; *Tsurutani*, 1991]. Closer to the cometary nucleus, nonresonant modes might become dominant [*Lakhina*, 1987; *Lakhina and Verheest*, 1988], but their long wavelengths are not measurable yet in single-spacecraft missions.

The identification of the water-group ions has been facilitated by their mass difference with the protons which dominate the solar wind. However, some of the observations at comet 1P/Halley also point to pickup proton cyclotron turbulence [*Neugebauer et al.*, 1990; *Mazelle and Neubauer*, 1993; *Lakhina and Verheest*, 1995]. In addition, single-cycle magnetic pulses or solitary waves at the proton gyrofrequency have been reported at 21P/Giacobini–Zinner by *Tsurutani et al.* [1989], although they are related more to bursts than to fully developed waves.

In the present paper, we will look at an intermediate situation, where wave frequencies have been observed, although not very frequently, that are between the water-group and the proton gyrofrequencies [*Johnstone et al.*, 1987; *Glassmeier et al.*, 1989; *Tsurutani et al.*, 1997]. It has been suggested that the occurrence of frequencies higher than the water-group gyrofrequency could be due to turbulent cascade via wave-wave interactions [*Tsurutani and Smith*, 1986; *Glassmeier et al.*, 1989; *Tsurutani et al.*, 1997]. However, since upward cascading in frequency is not evident, we offer an al-

Paper number 1999JA900331.
0148–0227/99/1999JA900331$09.00

ternative and direct interpretation for the generation of waves in the domain between the gyrofrequencies of the cometary water-group ions and the solar wind protons. This interesting new regime is partly inspired by recent work on the possible influence of cometary dust on the pickup process [*Verheest and Meuris*, 1998].

2. Low-Frequency Electromagnetic Modes

We will start from parallel modes since these are the easiest to excite, have the highest growth rates for ion-ion beam instabilities, and do not directly involve ring distribution effects [*Gary et al.*, 1984; *Gary and Madland*, 1988]. The dispersion law for parallel electromagnetic modes in a multispecies ion-ion beam plasma model, as used, for example, for the discussion of resonant water-group ion modes at comet 26P/Grigg-Skjellerup [*Verheest and Lakhina*, 1993], is in standard notation

$$\omega^2 = c^2k^2 + \sum_\alpha \frac{\omega_{p\alpha}^2(\omega - k_\parallel U_\alpha)}{\omega - k_\parallel U_\alpha \pm \Omega_\alpha}. \qquad (1)$$

Here $\omega_{p\alpha} = (N_\alpha e_\alpha^2/\varepsilon_0 m_\alpha)^{1/2}$ and $\Omega_\alpha = e_\alpha B_0/m_\alpha$ are the plasma and the cyclotron frequencies, respectively, of the species denoted by the subscript α, and N_α, m_α, and e_α stand for the number densities, masses, and charges of the α species. Furthermore, U_α are the beam velocities when projected on the direction of the interplanetary magnetic field.

This dispersion law can be rewritten, with the help of charge and current neutrality in equilibrium and in a low-frequency approximation (compared to the plasma frequencies), as

$$\sum_\alpha \sigma_\alpha \frac{(\omega - k_\parallel U_\alpha)^2 \Omega_\alpha}{\omega - k_\parallel U_\alpha \pm \Omega_\alpha} \mp k_\parallel^2 V_A^2 = 0. \qquad (2)$$

Here σ_α refers to the equilibrium mass densities of the different plasma species, normalized to the total mass density of the combined plasma, and V_A refers to the global Alfvén speed for the combined plasma.

We label the terms connected with the solar wind protons *sw* and those with the cometary water-group ions *ci*, viewed in a frame moving with the comet. The electrons maintain the equilibrium charge and current neutrality but contribute little to the mass averages. Hence (2) becomes

$$\sigma_{ci}\frac{\omega^2\Omega_{ci}}{\omega \pm \Omega_{ci}} + \sigma_{sw}\frac{(\omega - k_\parallel U)^2\Omega_{sw}}{\omega - k_\parallel U \pm \Omega_{sw}} \mp \sigma_{sw}k_\parallel^2 V_{Asw}^2 = 0, \qquad (3)$$

where $\sigma_{ci} + \sigma_{sw} = 1$, $U_{sw} = U$, $U_{ci} \simeq 0$, and V_{Asw} is the reference Alfvén velocity of the undisturbed solar wind.

The frequency regime of interest is that where $|\Omega_{ci}| \ll \omega$ and $|\omega - k_\parallel U| \ll |\Omega_{sw}|$. In this approximation the dispersion law (equation (3)) is rewritten as

$$\sigma_{ci}\omega\Omega_{ci} \mp \sigma_{ci}\Omega_{ci}^2 \pm \sigma_{sw}(\omega - k_\parallel U)^2 \mp \sigma_{sw}k_\parallel^2 V_{Asw}^2 = 0 \qquad (4)$$

and can be transformed into

$$\left(\omega - k_\parallel U \pm \frac{\sigma\Omega_{ci}}{2}\right)^2 = k_\parallel^2 V_{Asw}^2 \mp \sigma k_\parallel U\Omega_{ci} + \sigma\Omega_{ci}^2 + \tfrac{1}{4}\sigma^2\Omega_{ci}^2, \qquad (5)$$

with $\sigma = \sigma_{ci}/\sigma_{sw} = \rho_{ci}/\rho_{sw}$ defined as the mass fraction of the cometary material in terms of the original solar wind composition. We assume for the expanding solar wind $U > 0$ and take $k_\parallel$ positive. For instability we need $\mp\sigma k_\parallel U\Omega_{ci}$ from the structure of the right-hand side of (5) to be negative, and it will all depend on the relative orientation of the interplanetary magnetic field (IMF) with respect to the solar wind flow, because the sign of $B_0 = \mathbf{B}_0 \cdot \mathbf{e}_z$ is implicit in Ω_{ci} (see *Williams and Zank* [1994] for a thorough discussion of different orientations between the solar wind flow, the IMF, and other relevant directions). If the angle between the IMF orientation and the solar wind flow is acute, then B_0 and Ω_{ci} are both positive, and the upper signs in all equations respectively refer to the right-hand circularly polarized (RHCP) mode, and similarly the lower signs refer to the left-hand circularly polarized (LHCP) mode. Thus it is the RHCP mode which becomes unstable. Conversely, when the angle between the IMF orientation and the solar wind flow is obtuse, B_0 and Ω_{ci} are both negative, and the whole sign discussion has to be reversed. However, the definitions of RHCP and LHCP modes have also to be inverted, so that again it is the RHCP mode which becomes unstable.

If we write for all quantities henceforth the absolute values, in order to lighten the notation question, the right-hand side of (5) can become negative for the RHCP mode between the two roots

$$k_{\parallel 1} = \frac{\sigma U\Omega_{ci}}{2V_{Asw}^2}\left(1 - \sqrt{1 - \frac{V_{Asw}^2}{U^2} - \frac{4V_{Asw}^2}{\sigma U^2}}\right),$$

$$k_{\parallel 2} = \frac{\sigma U\Omega_{ci}}{2V_{Asw}^2}\left(1 + \sqrt{1 - \frac{V_{Asw}^2}{U^2} - \frac{4V_{Asw}^2}{\sigma U^2}}\right), \qquad (6)$$

in other words, when $k_{\parallel 1} < k_\parallel < k_{\parallel 2}$, provided the cometary mass loading exceeds a critical value

$$\sigma > \sigma_{cr} = \frac{4V_{Asw}^2}{U^2 - V_{Asw}^2}. \qquad (7)$$

In that case, the real part of the frequency and the growth rate are given by

$$\operatorname{Re}\omega = k_\parallel U - \frac{\sigma\Omega_{ci}}{2},$$

$$\operatorname{Im}\omega = \sqrt{\sigma k_\parallel U\Omega_{ci} - k_\parallel^2 V_{Asw}^2 - \sigma\Omega_{ci}^2 - \tfrac{1}{4}\sigma^2\Omega_{ci}^2}. \qquad (8)$$

Maximum growth occurs for

$$k_{\parallel m} = \frac{k_{\parallel 1} + k_{\parallel 2}}{2} = \frac{\sigma U\Omega_{ci}}{2V_{Asw}^2} \qquad (9)$$

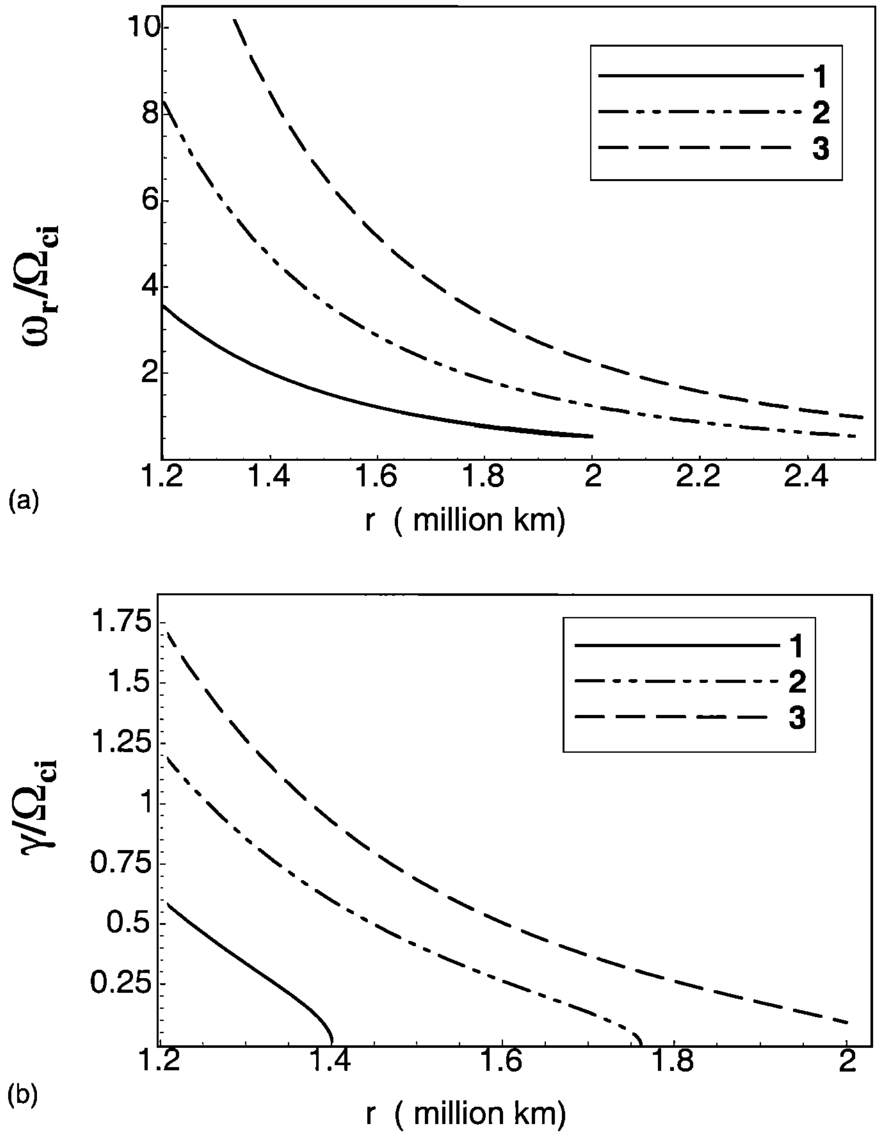

Figure 1. Variation of normalized real frequency ω_r/Ω_{ci} and maximum growth rate γ/Ω_{ci} versus r, the distance from the comet nucleus for $N_{sw} = 6.5 \times 10^{-6}$ m^{-3}, for $B_0 = 6$ nT, and for $M = 4$, 6, and 8 for curves 1, 2, and 3, respectively. For all the curves we have taken the cometary water-group ion density $N_{ci} = 0.2 \times 10^{-6}$ m^{-3} just before the bow shock and then extrapolated its value to larger distances, assuming a falloff with distance as $r^{-3.7}$.

and yields

$$\omega_r = \mathrm{Re}\,\omega_m = \frac{\sigma U^2 \Omega_{ci}}{2V_{Asw}^2}\left(1 - \frac{V_{Asw}^2}{U^2}\right),$$

$$\gamma = \mathrm{Im}\,\omega_m = \tfrac{1}{2}(k_{\|2} - k_{\|1})V_{Asw}. \qquad (10)$$

We find waves which propagate downstream, with frequencies which are close to the Doppler shift induced by the solar wind flow. In the solar wind frame the frequency becomes negative, although with very small values, so that the state of polarization of the mode gets inverted; that is, the mode would become left-hand circularly polarized (LHCP), and the waves would propagate upstream. Another way of looking at this is that since the phase velocity of the RHCP modes in the comet frame is smaller than the solar wind velocity, they are overtaken by the fast moving solar wind and hence seen as being LHCP in that frame.

In Figure 1 we have plotted the real and imaginary parts of ω at maximum growth, given by (10), using some average values for the different parameters occurring in (9) and (10). The solar wind proton number density is taken as 6×10^6 m^{-3}, with an IMF strength of 6 nT, giving $V_{Asw} \simeq 55$ km/s. Alfvénic Mach numbers $M = U/V_{Asw}$ of 4, 6, and 8 have been used, giving the curves labeled by 1, 2, and 3, respectively. While there is little discussion about the average cometary water-group ion mass, of the order of 16.8 proton masses, the cometary mass loading of the solar wind has been less easy to infer. Observations of comet 1P/Halley by the

Giotto spacecraft would indicate that $N_{ci} = 27 \times 10^6$ m^{-3} at $r = 1.5 \times 10^5$ km [*Balsiger et al.*, 1986] and that N_{ci} decreases as r^{-2} outside the contact surface (at 10^4 km). On the other hand, *Mukai et al.* [1986] seem to find $N_{ci} = 10 \times 10^6$ m^{-3} at the same reference distance of $r = 1.5 \times 10^5$ km. More recent observations of cometary water-group ions indicate $N_{ci} = 0.2 \times 10^6$ m^{-3} just upstream of the bow shock at about $r = 1.15 \times 10^6$ km, with a falloff with distance as $r^{-3.7}$ [*Neugebauer et al.*, 1990; *Coates et al.*, 1990]. Evidently, the value of N_{ci} can vary over a considerable range, as seen in the data from different spacecraft that also observed in different regions, and our computations can only yield indicative values. We use the observations of water-group ions by *Neugebauer et al.* [1990] and *Coates et al.* [1990] to compute N_{ci} as a function of distance r from the cometary nucleus [*Lakhina and Verheest*, 1995]. Then, from Figure 1 we can conclude that unstable modes of the intermediate frequency kind discussed in our paper can occur up to several million kilometers from the cometary nucleus, and, of course, are easier to excite in higher-velocity solar wind flows.

From Figure 1 it is noticed that typical real frequencies and growth rates associated with the excited modes lie in the ranges of $\omega_r \simeq (2 - 10)\,\Omega_{ci} \simeq (10 - 55)$ mHz and $\gamma \simeq (0.25 - 1.75)\,\Omega_{ci} \simeq (1.5 - 10)$ mHz, respectively. The wavenumbers corresponding to the maximum growth rates typically fall in the range of $k_{\parallel m} V_{Asw}/\Omega_{ci} \simeq (0.2 - 1.75)$ for the parameters of Figure 1 (not shown). Therefore the excited modes would have wavelengths $\lambda \simeq (0.5 - 5.0) \times 10^4$ km.

3. Conclusions

Although low-frequency electromagnetic turbulence observed in cometary environments mostly peaks at the gyrofrequency of the water-group ions of cometary origin, because of cyclotron resonance fueled by relative drifts parallel to the interplanetary magnetic field, some of the observations also point to pickup proton cyclotron turbulence and to single-cycle magnetic pulses or solitary waves at the proton gyrofrequency. In addition, some intermediate frequencies between the water-group ions and the proton gyrofrequencies have been observed [*Tsurutani et al.*, 1997]. The occurrence of such frequencies has been explained by turbulent upward cascading in frequency via wave-wave interactions, which is, however, not evident at all. Hence we have offered in this paper an alternative and direct interpretation for the generation of these waves in the domain between the cometary water-group ion and the proton gyrofrequencies. This interesting new regime, partly inspired by the possible influence of charged cometary dust on the pickup process, can occur in an unstable wavelength band, and some maximum growth rates have been computed for representative solar wind and cometary ion conditions, showing indeed that unstable modes of this kind are possible up to several million kilometers from the cometary nucleus. It should be noted that the real frequencies of these modes in the cometary frame of reference are, for some typical parameters, of the order of 10 – 55 mHz, with typical wavelengths of the order of 5000 – 50,000 km. These modes would be Doppler-shifted in the spacecraft frame to somewhat higher frequencies. As usual, they are easier to excite in higher-velocity solar wind flows.

We would like to point out that our model is based on a multifluid approach and does not consider the possibility of generation of frequencies from different parts of the pickup shell as discussed by *Huddleston and Johnstone* [1992] and *Johnstone* [1995]. Furthermore, there is a possibility that the pickup protons can also contribute to the generation of intermediate frequencies via some proton-beam-driven instability. Equations (1) and (2) are quite general, and the effect of pickup protons on the generation of intermediate frequencies can be studied by the approach outlined here.

Acknowledgments. F.V. thanks the Fund for Scientific Research (Flanders, Belgium) for a travel grant and the Jet Propulsion Laboratory for its kind hospitality during his stay in which part of this work was carried out. Portions of this research were performed at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, under contract with the National Aeronautics and Space Agency, Washington, D. C.

Michel Blanc thanks Padma K. Shukla and Andrew Coates for their assistance in evaluating this paper.

References

Balsiger, H., et al., Ion composition and dynamics at comet Halley, *Nature, 321*, 330–334, 1986.

Coates, A.J., B. Wilken, A.D. Johnstone, K. Jockers, K.-H. Glassmeier, and D.E. Huddleston, Bulk properties and velocity distributions of water group ions at comet Halley: Giotto measurements, *J. Geophys. Res., 95*, 10,249–10,260, 1990.

Gary, S.P., and C.D. Madland, Electromagnetic ion instabilities in a cometary environment, *J. Geophys. Res., 93*, 235–241, 1988.

Gary, S.P., C.W. Smith, M.A. Lee, M.L. Goldstein, and D.W. Forslund, Electromagnetic ion beam instabilities, *Phys. Fluids, 27*, 1852–1862, 1984 (Erratum, *Phys. Fluids, 28*, 438, 1985).

Gary, S.P., C.D. Madland, and B.T. Tsurutani, Electromagnetic ion beam instabilities, II, *Phys. Fluids, 28*, 3691–3695, 1985.

Gary, S.P., C.D. Madland, D. Schriver, and D. Winske, Computer simulation of electromagnetic cool ion beam instabilities, *J. Geophys. Res., 91*, 4188–4200, 1986.

Glassmeier, K.-H., A.J. Coates, M.H. Acuna, M.L. Goldstein, A.D. Johnstone, F.M. Neubauer, and H. Rème, Spectral characteristics of low-frequency plasma turbulence upstream of comet P/Halley, *J. Geophys. Res., 94*, 37–48, 1989.

Huddleston, D.E., and A.D. Johnstone, Relationship between wave energy and free energy from pickup ions in the comet Halley environment, *J. Geophys. Res., 97*, 12,217–12,230, 1992.

Johnstone, A.D., Cometary ion pickup processes: Halley and Grigg-Skjellerup compared, *Adv. Space Res., 16(4)*, 11–18, 1995.

Johnstone, A., et al., Waves in the magnetic field and solar wind flow outside the bow shock at comet Halley, *Astron. Astrophys.*, *187*, 47-54, 1987.

Lakhina, G.S., Low-frequency plasma turbulence during solar wind-comet interaction, *Astrophys. Space Sci.*, *133*, 203-218, 1987.

Lakhina, G.S., and F. Verheest, Alfvén wave instabilities and ring current during solar wind-comet interaction, *Astrophys. Space Sci.*, *143*, 329–338, 1988.

Lakhina, G.S., and F. Verheest, Pickup proton cyclotron turbulence at comet P/Halley, *J. Geophys. Res.*, *100*, 3449–3454, 1995.

Lee, M.A., Ultra-low frequency waves at comets, in *Plasma Waves and Instabilities at Comets and in Magnetospheres*, *Geophys. Monogr. Ser.*, vol. 53, edited by B.T. Tsurutani and H. Oya, pp. 13–29, AGU, Washington, D. C., 1989.

Mazelle, C., and F.M. Neubauer, Discrete wave packets at the proton cyclotron frequency at comet P/Halley, *Geophys. Res. Lett.*, *20*, 153–156, 1993.

Mukai, T., W. Miyake, T. Terasawa, M. Kitayama, and K. Hirao, Plasma observation by Suisei of solar-wind interaction with comet Halley, *Nature*, *321*, 299–303, 1986.

Neubauer, F.M., et al., First results from the Giotto magnetometer experiment at comet Halley, *Nature*, *321*, 352–355, 1986.

Neugebauer, M., A.J. Coates, and F.M. Neubauer, Comparison of picked-up protons and water group ions upstream of comet Halley's bow shock, *J. Geophys. Res.*, *95*, 18,745–18,753, 1990.

Riedler, W., K. Schwingenschuh, Ye.G. Yeroshenko, V.A. Styashkin, and C.T. Russell, Magnetic field observations in comet Halley's coma, *Nature*, *321*, 288–289, 1986.

Sagdeev, R.Z., V.D. Shapiro, V.I. Shevchenko, and K. Szegő, MHD turbulence in the solar wind–interaction region, *Geophys. Res. Lett*, *13*, 85–88, 1986.

Sagdeev, R.Z., V.D. Shapiro, V.I. Shevchenko, and K. Szegő, The effect of mass loading outside cometary bow shock for the plasma and wave measurements in the coming cometary missions, *J. Geophys. Res.*, *92*, 1131–1137, 1987.

Smith, E.J., B.T. Tsurutani, J.A. Slavin, D.E. Jones, G.L. Siscoe, and D.A. Mendis, International Cometary Explorer encounter with P/Giacobini-Zinner: Magnetic field observations, *Science*, *232*, 382–385, 1986.

Tsurutani, B.T., Comets: A laboratory for plasma waves and instabilities, in *Cometary Plasma Processes*, *Geophys. Monogr. Ser.*, vol. 61, edited by A.D. Johnstone, pp. 189–209, AGU, Washington, D. C., 1991.

Tsurutani, B.T., and E.J. Smith, Strong hydromagnetic turbulence associated with Comet Giacobini-Zinner, *Geophys. Res. Lett.*, *13*, 259–262, 1986.

Tsurutani, B.T., A.L. Brinca, B. Buti, E.J. Smith, R.M. Thorne, and H. Matsumoto, Magnetic pulses with durations near the local proton cyclotron period: Comet Giacobini-Zinner, *J. Geophys. Res.*, *94*, 29–35, 1989.

Tsurutani, B.T., K.H. Glassmeier, and F.M. Neubauer, A review of nonlinear low frequency (LF) wave observations in space plasmas: On the development of plasma turbulence, in *Nonlinear Waves and Chaos in Space Plasmas*, edited by T. Hada and H. Matsumoto, pp. 1–44, Terra Sci., Tokyo, 1997.

Verheest, F., and G.S. Lakhina, Resonant electromagnetic ion-ion turbulence at comet P/Grigg-Skjellerup, *J. Geophys. Res.*, *98*, 21,017–21,021, 1993.

Verheest, F., and P. Meuris, Interaction of the solar wind with dusty cometary plasmas, *Phys. Scr.* *T75*, 84–87, 1998.

Williams, L.L., and G.P. Zank, Effect of magnetic field geometry on the wave signature of the pickup of interstellar neutrals, *J. Geophys. Res.*, *99*, 19,229–19,244, 1994.

Winske, D., and S.P. Gary, Electromagnetic instabilities driven by cool heavy ion beams, *J. Geophys. Res.*, *91*, 6825–6832, 1986.

Winske, D., C.S. Wu, Y.Y. Li, Z.Z. Mou, and S.Y. Guo, Coupling of newborn ions to the solar wind by electromagnetic instabilities and their interaction with the bow shock, *J. Geophys. Res.*, *90*, 2713–2726, 1985.

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(Received April 8, 1999; revised June 18, 1999; accepted July 10, 1999.)