LOW FREQUENCY WAVES IN THE BOW SHOCK ENVIRONMENT

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ABSTRACT

Using multi-point measurements of Cluster, we investigate low frequency wave characteristics in the terrestrial bow shock environment. The dispersion analysis along the s/c orbit suggests that the shock upstream waves represent the waves driven by the ion beam instability and the downstream waves exhibit the mirror mode properties. The statistical study provides complementary results to the dispersion analysis that the upstream and downstream waves exhibit the fast and slow magnetosonic wave properties, while these waves show propagation sense divergent at the shock and convergent toward the magnetopause. Based on these results a scenario about the shock upstream and downstream waves is proposed.

Key words: bow shock; wave modes; wave propagation.

1. INTRODUCTION

It is true that collisionless shocks, the shock waves without particle collision, are rare in our terrestrial world. In space physics and astrophysics, however, material is mostly ionized and the collisionless shocks are widespread phenomena, as Fig. 1 displays. Disturbance like shocks or waves in electrically conducting media like plasma is necessarily accompanied by magnetic field fluctuations, and *in situ* observations made by a number of spacecraft have been showing the existence of low frequency waves of the magnetic field both upstream and downstream of various planetary bow shocks and interplanetary shocks. The collisionless shock dissipates the flow energy into the wave energies, bringing its system toward an equilibrium state. Investigating wave properties is generally not easy in those regions, since the plasma flow sweeps waves toward downstream and spacecraft detect modulated frequencies, speeds, and directions of the waves. These properties should be investigated not in the spacecraft frame of reference but in the plasma rest frame in which the background plasma flow speed is zero. Only multi-spacecraft observations like the Cluster mission have a potential for detailed investigations of the upstream and the downstream waves of the terrestrial bow shock.

Early single and double spacecraft missions have in fact improved our knowledge about the upstream and the downstream waves very much, which also stimulated theoretical investigations. For example, it was understood that the ions that are reflected at the shock and backstreaming against the incoming ions in the upstream region (or *foreshock*) form an unstable distribution in velocity space which excites waves through the (right-hand) ion beam instability [1, 2, 3, 4]. Using double ISEE spacecraft it was shown that the foreshock waves propagated away from the shock toward upstream in the plasma rest frame [5, 6].

On the other hand, the physics of the downstream waves is a more complex subject, as there are multiple possible sources of waves in the magnetosheath: the solar wind fluctuations and the convected foreshock waves processed through the bow shock, waves generated by the bow shock or the magnetopause, and waves that grow in the magnetosheath. The downstream plasma is often characterized by large temperature perpendicular to the background magnetic field [7], and the temperature anisotropy is believed to provide free energy to excite waves through ion cyclotron instability or mirror instability. Indeed, many observations show mirror mode property in the magnetosheath, which is anti-correlated variations of the magnetic field strength and plasma density [8, 9, 10, 11].

We address two questions to understand the waves in the terrestrial bow shock environment: what wave modes they exhibit, and how their propagation characteristics are. Multi-point measurements made by Cluster offer unique wave analysis methods. Using the wave telescope technique (or k-filtering) wave vectors can be determined [12, 13, 14], which can further be applied to investigation of dispersion curves and statistical study. Fig. 2 displays an example of the wave vector determination in the magnetosheath. This paper presents dispersion curves and propagation directions taken from one Cluster orbit (see [15] for details) and a statistical study of wave phase ve-

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Figure 1. Image of bow shock around the very young star, LL Ori, in Orion nebula (M42) taken by Hubble Space Telescope. The surface between the two winds, fast wind from LL Ori colliding with slow-moving gas evaporating away from the center of the Orion Nebula, is the crescent-shaped bow shock (Courtesy of NASA and The Hubble Heritage Team of STScI/AURA).

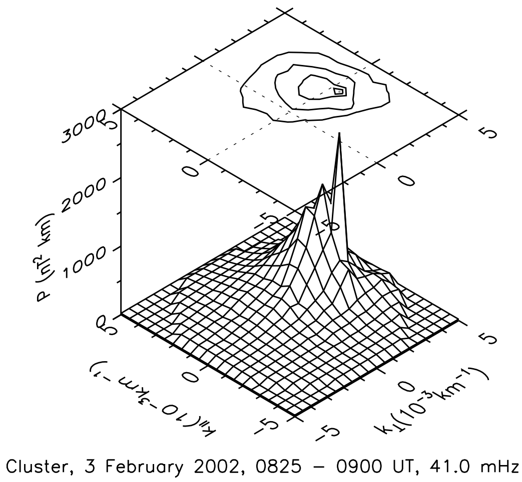

Figure 2. Example of wave telescope analysis showing wave power in the k-domain (parallel and perpendicular to the background magnetic field). A peak is found in the perpendicular direction.

locities and relations between plasma and magnetic field fluctuations (see [16] for details).

2. DISPERSION CURVES THROUGH BOW SHOCK

Dispersion curves in the plasma rest frame are determined for the upstream and downstream waves from the interval 0400-1000 UT on February 18, 2002, when the spacecraft separation was about 100 km. The detailed analysis method can be found in [17]. Cluster moved outbound from the magnetosphere into the solar wind, and we select four subintervals for the dispersion analysis: 0805-0840 UT for the upstream (foreshock) waves, 0700-0735 UT the outer sheath waves, 0600-0635 UT the middle sheath waves, and 0500-0535 UT the inner sheath waves. The shock angle determined by using the magnetic field coplanarity theorem is about 17°. In addition, transverse magnetic field polarization p is investigated. A value $p = +1$ indicates right-hand circular polarization with respect to the magnetic field direction, that is in the same sense as the gyro motion of an electron, $p = 0$ linear polarization, and $p = -1$ left-hand circular polarization, that is the same rotation sense as the ion gyro motion. p depends on frequency and the sign of polarization is changed when the rest frame frequency is negative (anomalous Doppler shift).

The results of the dispersion and polarization analysis are displayed in Fig. 3, where the rest frame frequency and the wave number are normalized to the proton cyclotron frequency and the inverse of the proton inertial length, respectively. We classify the polarization as right-handed (RH) if $p > 0.176$ (i.e. the polarization angle $\psi > 10°$, see [18]), left-handed (LH) if $p < -0.176$ (i.e. $\psi < -10°$), and linear (Lin) if $-0.176 \leq p \leq 0.176$. The upstream waves exhibit two branches (Fig. 3A). Branch 1 starts at $(\omega, k) \simeq (0, 0)$ and extends up to about $(\omega, k) \simeq (1.5, 1.5)$. Branch 2 reaches from $(\omega, k) \simeq (-1.0, 0.0)$ to about $(\omega, k) \simeq (0.5, 0.2 - 0.3)$, intersecting branch 1 at $(0.1, 0.1 - 0.2)$. Propagation is slightly off-angle at $20° - 30°$ for almost all wave numbers. Only for very small wave numbers it is perpendicular to the background magnetic field. In the outer magnetosheath (near the shock) frequencies are small (at most 0.4) at various wave numbers (Fig. 3B). Propagation is oblique to perpendicular with a few nearly parallel cases ($12° < \theta_{kB} < 20°$); the linear polarization is dominant. The nearly parallel propagating waves exhibit phase speeds about 0.1 - 0.2 as large as the Alfvén speed with left-hand polarization ($-0.2 < p < -0.6$), which may represent ion cyclotron waves. In the middle magnetosheath the dispersion appears as an almost horizontal line at about zero frequency, though the frequencies deviate a little from zero at wave numbers $0.4 - 0.6$ (Fig. 3C). Wave vectors are clearly perpendicular to the magnetic field and predominantly oriented in the direction from the sun to the Earth ($k_x < 0$ in the GSE coordinate system); the polarization is linear. The inner magnetosheath waves (near the magnetopause) exhibit scattered frequencies and propagation angles (Fig. 3D). Average propagation angles are $90° - 120°$; the polarization is still linear.

Two intersecting branches of the upstream waves have already been identified by [17] that they represent the whistler and the ion beam resonant mode, which indicate the (right-hand) ion beam instability. The dispersion analysis also shows that the upstream waves propagate nearly parallel to the background magnetic field. It is interesting to note that the upstream waves are not trans-

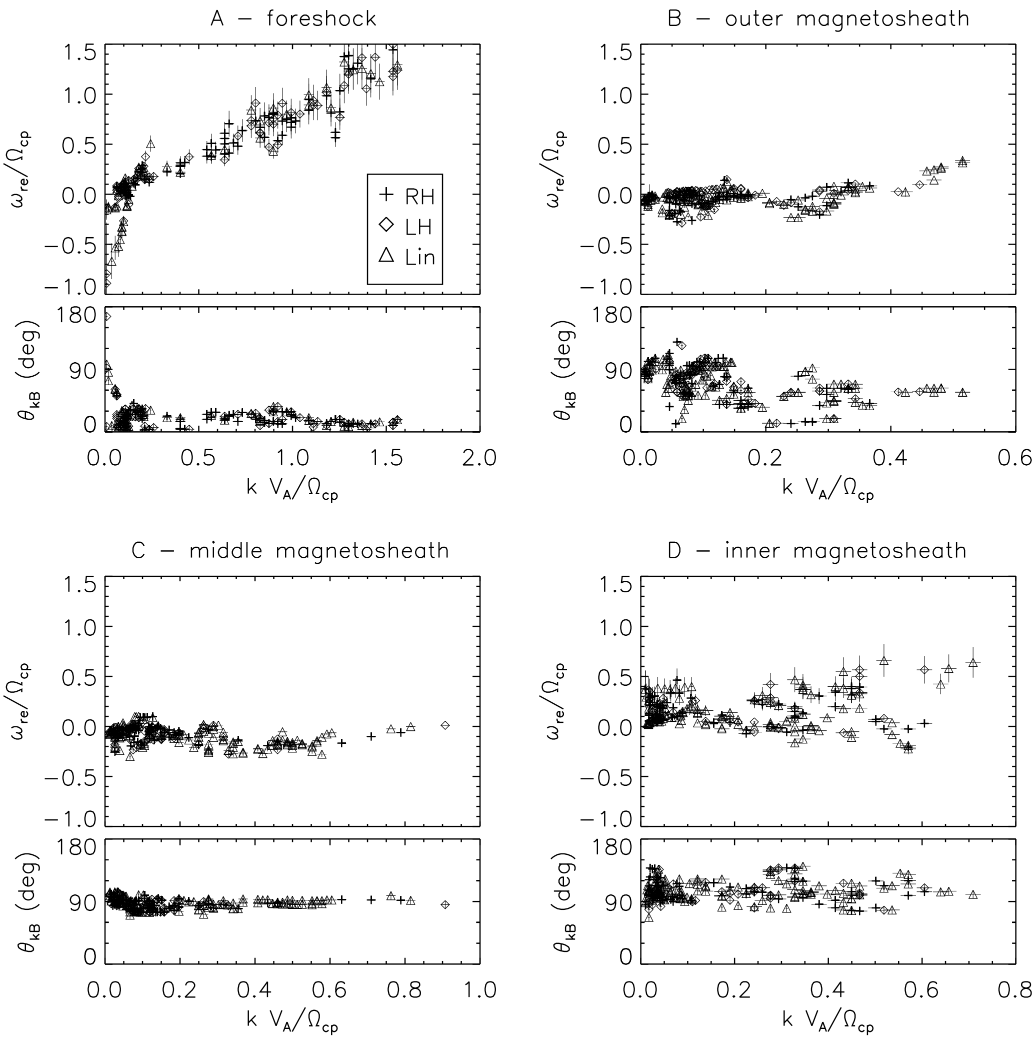

Figure 3. Dispersion curves (with error bars) and propagation angles for different regions.

mitted to the downstream region. Perhaps the waves lose their identity as they are convected downstream or as they hit against the shock.

In the downstream region the rest frame frequencies of the waves are close to zero and the wave vectors are nearly perpendicular, which is reminiscent of the mirror modes. This feature is clearest in the middle sheath, while it is distorted in the outer and inner sheath. The distortion may indicate that the ion cyclotron waves coexist or the mirror modes are coupled to the nonlinearity [19] or the background inhomogeneities [20, 21, 22].

3. STATISTICAL STUDY

Phase velocities in the plasma rest frame are investigated based on about 100 events for the upstream waves and about 400 events for the downstream waves for the interval February 3 to June 17, 2002, when the spacecraft separation was 100 km.

Fig. 4 top shows the distribution (occurrence frequency) of the wave propagation angle. The upstream waves propagate nearly parallel to the background magnetic field, while the downstream waves propagate nearly perpendicular. The magnitudes of the phase velocities are compared to the fast, intermediate, and slow mode speeds defined in magnetohydrodynamics with respective propagation directions taken into account. The comparison gives the result that the upstream waves are closest to the fast mode speed, whereas the downstream waves are closest to the slow mode speed (Fig. 4 middle). The relation between the plasma and the magnetic field variations are investigated additionally, as the three MHD waves exhibit different properties: correlated plasma velocity and magnetic field fluctuations for the intermediate mode; correlated and anti-correlated density and magnetic field fluctuations for the fast and slow mode, respectively. Fig. 4 bottom displays the distributions of the phase angle between the density and the magnetic field

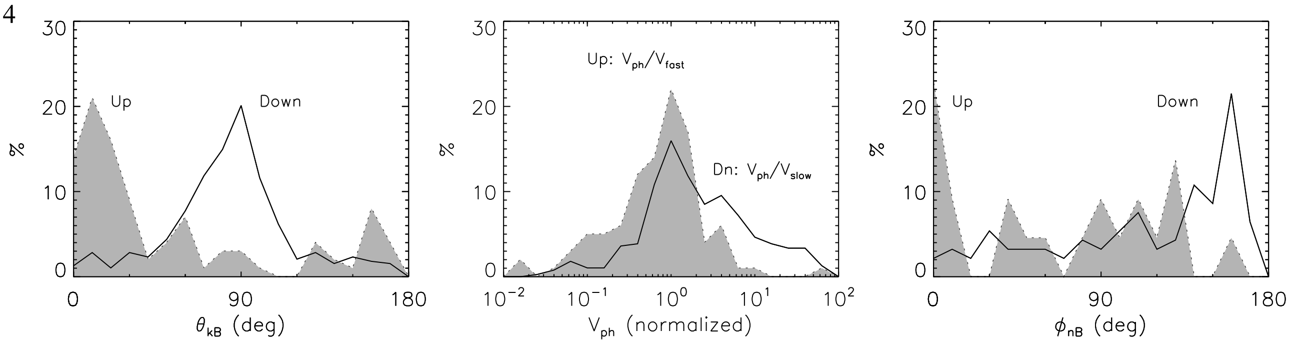

Figure 4. Distribution (occurrence frequency) of propagation angle, phase velocities, and phase angle between the density and the magnetic field variations for the upstream waves (filled in gray) and the downstream waves (black line). The phase velocities are divided by the fast mode speed for the upstream waves, and by the slow mode speed for the downstream waves, taking propagation angles into account.

fluctuations (ϕ_{nB}). The upstream waves exhibit in-phase variations ($\phi_{nB} \simeq 0°$) and the downstream waves exhibit out-of-phase variations ($\phi_{nB} \simeq 180°$). Hence the statistical study suggests that the upstream and downstream waves are most likely the fast mode wave nearly parallel to the background magnetic field and the slow mode wave nearly perpendicular, respectively.

The spatial distribution of the phase velocity vectors (normalized to the Alfvén velocity) are displayed in Fig. 5. To aid the eyes, the vectors are averaged over segments. Propagation sense is outward divergent in the upstream region, toward the magnetosheath flank near the nose of the magnetopause, and convergent toward the magnetopause in the magnetosheath flank. The waves propagate away from the shock both on the upstream and downstream side.

The statistical study confirms the propagation angle derived by the dispersion analysis and indicates that the upstream and downstream waves are the fast and slow mode, respectively. These waves show a interesting propagation pattern that they are divergent at the bow shock and convergent toward the magnetopause.

4. CONCLUSIONS

To conclude, we propose the following scenario about the waves in the terrestrial bow shock environment, a part of which is schematically sketched in Fig. 6. The ion reflection at the shock results in excitation of the fast mode waves through the ion beam instability. The waves propagate nearly parallel to the background magnetic field and toward upstream, but they are convected by the solar wind and the identity of the upstream waves is lost possibly at the shock. In the downstream region, temperature anisotropy created by the shock excites the mirror modes with frequencies and propagation angles distorted. One of the possibilities is that the ion cyclotron waves may coexist in the outer sheath and the nonlinearity or the background inhomogeneities are coupled to the mirror modes in the inner sheath. On a statistical basis, however, they can be interpreted as the slow mode waves nearly perpendicular to the background magnetic field. Of course, this scenario needs to be verified in various ways. For example, the dispersion curves will be determined for each event used for the statistical study. The possibility of the ion cyclotron waves, the soliton models, and the background inhomogeneities need to be discussed in detail, too.

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REFERENCES

1. Barnes, A., Theory of generation of bow-shock-associated hydromagnetic waves in the upstream interplanetary medium, *Cosmic Electrodyn.*, *1*, 90-114, 1970.

2. Paschmann, G., N. Sckopke, I. Papamastorakis, J. R. Asbridge, S. J. Bame, and J. T. Gosling, Characteristics of reflected and diffuse ions upstream from the Earth's bow shock, *J. Geophys. Res.*, *86*, 4355-4364, 1981.

3. Gary, S. P., Electromagnetic ion/ion instabilities and their consequences in space plasma: A review, *Space Sci. Rev.*, *56*, 373, 1991.

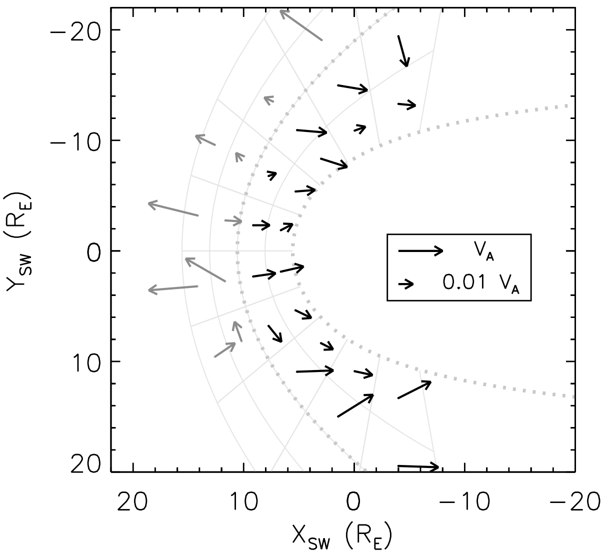

Figure 5. Distribution of phase velocity vectors of the upstream waves (in gray) and the downstream waves (in black) averaged over segments in gray. The x axis is oriented anti-parallel to the solar wind direction and the xy plane is spanned by the solar wind and the interplanetary magnetic field directions. The phase velocities are normalized to the Alfvén velocity. The outer and inner dotted curved lines represent the bow shock and the magnetopause, respectively.

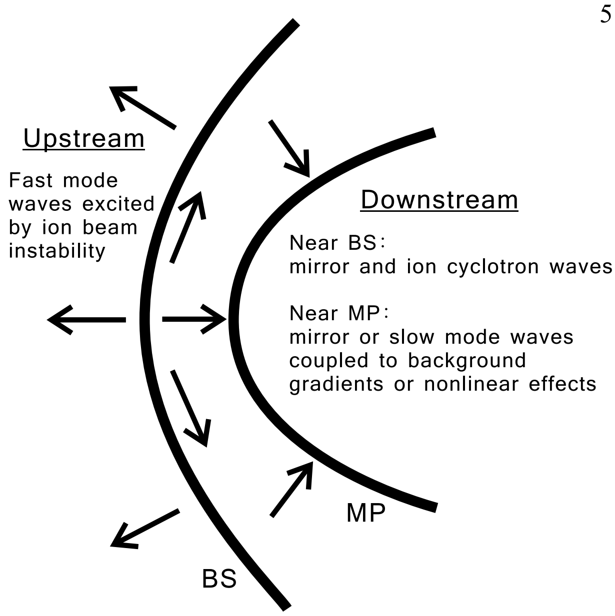

Figure 6. Propagation sense of low frequency waves in the plasma rest frame and the wave habitats in the bow shock environment.

4. Treumann, R. A., and W. Baumjohann, *Advanced Space Plasma Physics*, pp. 341-352, Imperial College Press, London, 1997.

5. Hoppe, M. M., C. T. Russell, L. A. Frank, T. E. Eastman, and E. W. Greenstadt, Upstream hydromagnetic waves and their association with backstreaming ion populations - ISEE 1 and 2 observations, *J. Geophys. Res., 86*, 4471-4492, 1981.

6. Hoppe, M. M., and C. T. Russell, Plasma rest frame frequencies and polarizations of the low-frequency upstream waves - ISEE 1 and 2 observations, *J. Geophys. Res., 88,* 2021-2027, 1983.

7. Sckopke, N., G. Paschmann, A. L. Brinca, C. W. Carlson, and H. Lühr, Ion thermalization in quasi-perpendicular shocks involving reflected ions, *J. Geophys. Res., 95,* 6337-6352, 1990.

8. Tsurutani, B. T., E. J. Smith, R. R. Anderson, K. W. Ogilvie, J. D. Scudder, D. N. Baker, and S. J. Bame, Lion roars and nonoscillatory drift mirror waves in the magnetosheath, *J. Geophys. Res., 87*, 6060-6072, 1982.

9. Hubert, D., C. C. Harvey, and C. T. Russell, Observations of magnetohydrodynamic modes in the earth's magnetosheath at 0600 LT, *J. Geophys. Res., 94*, 17,305-309, 1989.

10. Fazakerley, A. N., and D. J. Southwood, Theory and observation of magnetosheath waves, in *Solar Wind Sources of Magnetospheric Ultra-Low Frequency Waves*, pp 147-158, American Geophysical Union, 1994.

11. Denton, R. E., M. R. Lessard, J. W. Labelle, and S. P. Gary, Identification of low-frequency magnetosheath waves, *J. Geophys. Res., 103*, 23,661-676, 1998.

12. Pinçon, J.L., and Lefeuvre, F., Local characterization of homogeneous turbulence in a space plasma from simultaneous measurement of field components at several points in space, *J. Geophys. Res., 96*, 1789-1802, 1991.

13. Motschmann, U., Woodward, T.I., Glassmeier, K.H., Southwood, D.J., and J.L. Pinçon, Wavelength and direction filtering by magnetic measurements at satellite arrays: Generalized minimum variance analysis, *J. Geophys. Res., 101*, 4961-4965, 1996.

14. Glassmeier, K.-H., U. Motschmann, M. Dunlop, A. Balogh, M. H. Acuña, C. Carr, G. Musmann, K.-H. Fornaçon, K. Schweda, J. Vogt, E. Georgescu, and S. Buchert, Cluster as a wave telescope - first results from the fluxgate magnetometer, *Ann. Geophysicae, 19*, 1439-1447, 2001. (Correction, *21*, 1071, 2003).

15. Narita, Y., and K.-H. Glassmeier, Dispersion analysis of low-frequency waves through the terrestrial bow shock, *J. Geophys. Res., submitted,* 2005a.

16. Narita, Y., K.-H. Glassmeier, K.-H. Fornaçon, I. Richter, S. Schäfer, U. Motschmann, I. Dandouras, H. Rème, and E. Georgescu, Low frequency wave characteristics in the upstream and downstream regime of

the terrestrial bow shock, *J. Geophys. Res., submitted*, 2005b.

17. Narita, Y., K.-H. Glassmeier, S. Schäfer, U. Motschmann, K. Sauer, I. Dandouras, K.-H. Fornaçon, E. Georgescu, and H. Rème, Dispersion analysis of ULF waves in the foreshock using cluster data and the wave telescope technique, *Geophys. Res. Lett*, *30*, SSC 43-1, 2003.

18. Fowler, R. A., Kotick, B. J., and R. D. Elliott, Polarization analysis of natural and artificially induced geomagnetic micropulsations, *J. Geophys. Res.*, *72*, 2871-2883, 1967.

19. Stasiewicz, K., Reinterpretation of mirror modes as trains of slow magnetosonic solitons, *Geophys. Res. Lett.*, *31*, L21804, doi: 10.1029/2004GL021282, 2004.

20. Hasegawa, A., Drift mirror instability in the magnetosphere, *Phys. Fluids*, *12*, 2642, 1969.

21. Johnson, J. R., and C. Z. Cheng, Global structure of mirror modes in the magnetosheath, *J. Geophys. Res.*, *102*, 7179-7189, 1997.

22. Pokhotelov, O. A., M. A. Balikhin, R. A. Treumann, and V. P. Pavlenko, Drift mirror instability revisited: 1. Cold electron temperature limit, *J. Geophys. Res.*, *106*, 8455-8464, 2001.