The Jovian Magnetopause Boundary Layer

There are plasma boundary layers at the magnetopause of Jupiter and the Earth (Eastman et al., 1979; Sonnerup et al., 1981; Scudder et al., 1981). It can be assumed that there is a boundary layer at Saturn's magnetopause as well. What are these boundary layers and how are they formed? Under what solar wind conditions? Figure 1 shows an example of the Earth's low latitude boundary layer using AMPTE/CHEM ion data (Gary and Eastman, 1979). Ions of solar wind origin (He^{++}, CNO) are found to have decreasing fluxes from the magnetosheath radially inward. Energetic singly ionized Oxygen and Helium ions (whose origins must ultimately be the ionosphere), have decreasing fluxes from the magnetosphere proper radially outward. Clearly, the magnetopause bounding layer must be a region where cross-field diffusion of plasma is occurring. Particles are diffusing from this layer in both directions.

The plasma boundary layers at Earth and Jupiter have ELF/VLF magnetic and electric waves present. These waves appear to be broadbanded when the data is viewed in spectrum channel format or as power spectra (Gurnett et al., 1979; Tsurutani et al., 1981; 1989; 1997; Rezeau et al., 1989, LaBelle and Treumann, 1988; Belmont et al., 1995). Gurnett et al. (1979) and Tsurutani et al. (1997) interpreted the magnetic waves as broadband whistler mode waves with a $f^{-2.6}$ power law spectrum. Because the wave magnetic to electric amplitude ratio (B_w/E_w) did not fit parallel propagating whistlers well, and there were electric signals at frequencies above f_{ce}, the above authors speculated that there must be additional electrostatic wave power present as well. Tsurutani et al. (1997) have determined the electric and magnetic wave spectrum at Jupiter and found that the magnetic waves similarly have a "broadband" spectral range with a superposition of broadband electric waves. Because plasma wave magnetic spectral shape at Jupiter ($f^{-2.4}$) is close to that at Earth, it is surmised that the generation mechanisms are most likely the same at the two planets.

Tsurutani and Thorne (1982) showed that through resonant wave-particle interactions between the waves and magnetosheath ions, the particles could diffuse at a ~0.1 D_B rate across the magnetic fields, forming the boundary layer for the Earth's case. D_B is the Bohm diffusion rate. The intensity of the waves at Jupiter were shown to be sufficient to diffuse the magnetosheath plasma across closed magnetic field lines to create the Jovian magnetopause boundary layer as well.

Why are these waves apparently "broadbanded", what are their sources of generation, and are they responsible for any coupling between the magnetosphere and the ionosphere? First, the waves are not really "broadbanded". Using very high time resolution data from the Earth-orbiting POLAR spacecraft, Tsurutani et al. (1998) have shown that the magnetic waves are indeed propagating in the electromagnetic whistler mode. However, the waves are not continuously present, but occur in millisecond packet bursts (Figure 2). There are presumably bursts at a variety of frequencies, leading to the "broadband magnetic spectra" when averaged over minutes. The superposed electric spectra is also not a "broadband" signal. This spectra is caused by electrostatic bipolar pulses (Franz et al., 1998; Tsurutani et al., 1998) similar to those detected at the ionospheric altitudes by instruments onboard the Freja (Mälkki et al., 1993) and FAST (Mozer et al., 1997; Ergun et al., 1998) satellites. High-time resolution data are available from the Galileo plasma wave detector for the Jovian case, but the nature of these plasma waves have not been reported yet.

The exact mechanisms for wave generation in the Earth's magnetopause boundary layer has not been identified. From resonance condition arguments, it has been speculated that the high frequency portion (3-5 kHz) of the electromagnetic whistler mode waves are locally generated by $E_{\parallel} < 1$ keV field-aligned beams of electrons. Low-frequency (~300 Hz) whistler mode waves may be first generated (by ions) as ion cyclotron waves near the ionosphere, with subsequent mode conversion to the whistler mode. The electric waves may first be generated as lower hybrid waves with field-aligned currents as a source of free energy (Lakhina and Tsurutani, 1999), with eventual evolution to bipolar pulses. Most workers in the field (Omura et al., 1996; Goldman et al., 1999), have explained the bipolar pulses as electron holes propagating along the ambient magnetic field lines.

There is a pitch angle scattering of particles and the concomitant loss to the terrestrial ionosphere, as noted by Tsurutani et al. (1981). If the electron energy is extrapolated to ~100 eV, the loss rate will be ~1 erg $cm^{-2}s^{-1}$, sufficient to form the dayside aurora. However, the loss rate of Jovian boundary layer plasma is several orders of magnitude too low to account for the Jovian high latitude aurora. Other processes such as ionospheric double layers may be the operative acceleration process. These double layers are speculated to be related to electrostatic bipolar pulses (electron holes), but the exact nature is unknown.

The Cassini mission to Saturn will address many of the above issues. Does Saturn's magnetopause have a boundary layer and how is it maintained? What is the nature of ELF/VLF plasma waves in this region of space and what roles do they play? Are there electromagnetic ion cyclotron waves or whistler mode waves responsible for cross-field ion diffusion, leading to the formation of the boundary layer? Do the electromagnetic whistler mode waves cause significant electron pitch angle diffusion such that the polar aurora can be explained? Are there bipolar electric pulses or double-layers that are responsible direct particle acceleration and discrete auroral arcs? These are some of the pertinent Saturnian boundary layer questions.

REFERENCES

Belmont, G., F. Reberac, and L. Rezeau, Resonant amplification of magnetosheath MHD fluctuations at the magnetopause, *Geophys. Res. Lett., 22*, 295, 1995.

Eastman, T.E., E.A. Greene, S.P. Christian, G. Gloeckler, D.C. Hamilton and F.M. Ipavich, *Geophys. Res. Lett., 17*, 7378, 1979.

Ergun, R.E., C.W. Carlson, J.P. McFadden, et al., FAST satellite observations of large amplitude structures, *Geophys. Res. Lett., 25*, 1998.

Franz, J.R., P.M. Kintner and J.S. Pickett, POLAR observations of coherent electric field structures, *Geophys. Res. Lett., 25*, 1277, 1998.

Gary, S.P. and T. E. Eastman, The lower hybrid drift instability at the magnetopause, *J. Geophys. Res., 84*, 7378, 1977.

Goldman, M. V., M.M. Oppenheim, and D.L. Newman, Theory of localized bipolar wave structures and northward particle distribution in the auroral ionosphere, *Nonlinear Proc. in Geophys.*, in press, 1999.

Gurnett, D.A., R.R. Anderson, B.T. Tsurutani, E.J. Smith, G. Paschmann, G. Haerendel, S.J. Bame and C.T. Russell, Plasma wave instabilities at the magnetopause: Observations from ISEE 1 and 2, *J. Geophys. Res., 84*, 7043, 1979.

LaBelle, J. and R.A. Treumann, Plasma waves at the dayside magnetopause, *Space Sci. Rev., 47*, 175, 1988.

Lakhina, G.S. and B.T. Tsurutani, A generation mechanism for the polar cap boundary layer broadband plasma waves, *J. Geophys. Res., 104*, 279, 1999.

Mälkki, A., A.I. Eriksson, P.-O. Dovner, R. Böstrom, B. Holbeck, G. Holmgren, and H.E.J. Koskinen, A statistical study of auroral solitary waves and weak double-layers 1. Occurrence and net voltage, *J. Geophys. Res., 98,* 15521, 1993.

Mozer, F., R. Ergun, M. Temerin, New features of time domain electric-field structures in the auroral acceleration regions, *Phys. Rev. Lett., 79,* 1281, 1997.

Omura, Y., H. Matsumoto, T. Miyaki and H. Kojima, Electron beam instabilities as generation mechanism of electrostatic solitary waves in the magnetotail, *J. Geophys. Res., 101*, 2685, 1996.

Rezeau, L., A. Morane, S. Perraut, A. Roux, and R. Schmidt, Characterization of Alfvénic fluctuations in the magnetopause boundary layer, *J. Geophys. Res., 94*, 101, 1989.

Scudder, J.D., E.C. Sittler, and H.S. Bridge, A survey of the plasma electron environment of Jupiter: A review from Voyager, *J. Geophys. Res., 86,* 8157, 1981.

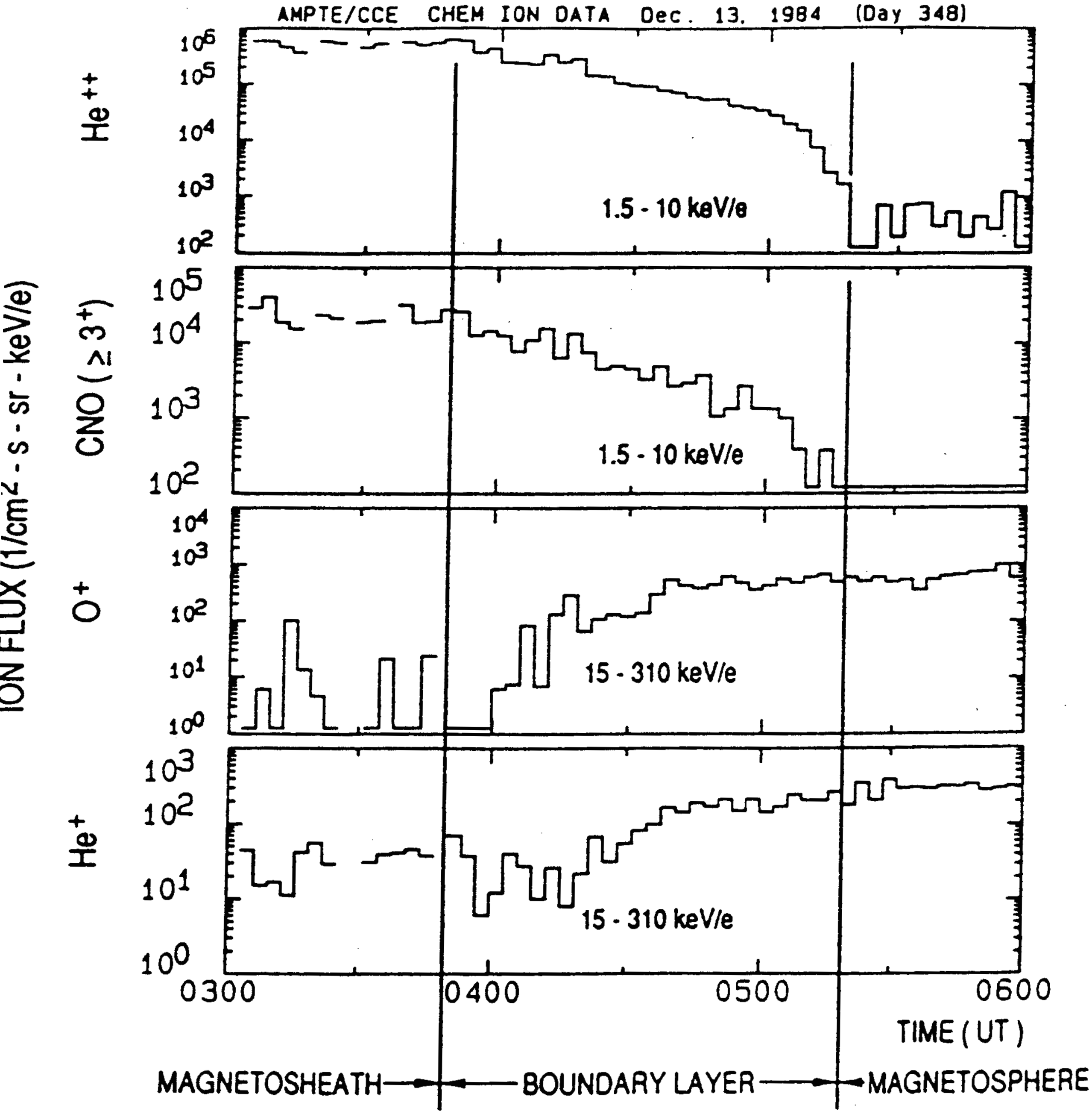
Sonnerup, B.U.O., G. Paschmann, I. Papamastorakis, N. Schopke, G. Haerendel, S. Bame, J. Asbridge, J. Gosling and C. Russell, *J. Geophys. Res., 86*, 10049, 1981.

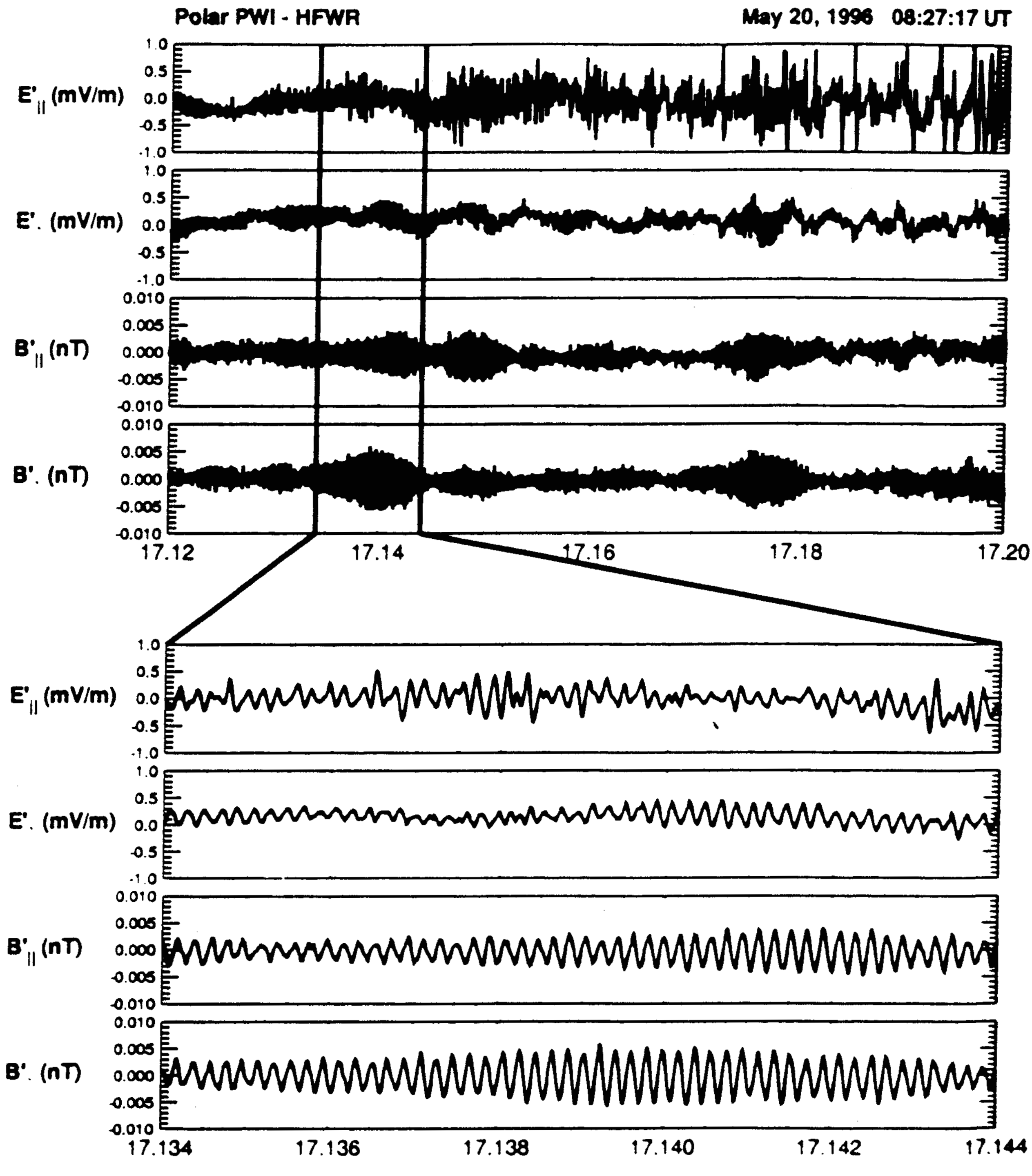
Tsurutani, B.T., E.J. Smith, R.M. Thorne, R.R. Anderson, D.A. Gurnett, G.K. Parks, C.S. Lin and C.T. Russell, Wave-particle interactions at the magnetopause. Contributions to the dayside aurora, *Geophys. Res. Lett., 8*, 183, 1981.

Tsurutani, B.T., A.L. Brinca, E.J. Smith, R.T. Okada, R.R. Anderson, and T.E. Eastman, A statistical study of ELF-VLF plasma waves at the magnetopause, *J. Geophys. Res., 94*, 1270, 1989.

Tsurutani, B.T., J.K. Arballo, B.E. Goldstein, C.M. Ho, G.S. Lakhina, E.J. Smith, N. Cornilleau-Wehrlin, R. Prange, N. Lin, P. Kellogg, J.L. Phillips, A. Balogh, N. Krupp and M. Kane, Plasma wave characteristics of the Jovian magnetopause boundary layer: Relationship to the Jovian Aurora?. *J. Geophys. Res., 102*, 4751, 1997.

Tsurutani, B.T., J.K. Arballo, G.S. Lakhina, C.M. Ho, B. Buti, J.S. Pickett and D.A. Gurnett, Plasma waves in the dayside polar cap boundary layer: Bipolar and monopolar electric pulses and whistler mode waves, *Geophys. Res. Lett., 25*, 4117, 1998.


AMPTE/CCE CHEM ION DATA Dec. 13, 1984 (Day 348)
ION FLUX (1/cm² - s - sr - keV/e)
He++
1.5 - 10 keV/e
CNO (≥ 3+)
1.5 - 10 keV/e
O+
15 - 310 keV/e
He+
15 - 310 keV/e
0300
0400
0500
0600
TIME (UT)
MAGNETOSHEATH
BOUNDARY LAYER
MAGNETOSPHERE


Polar PWI - HFWR
May 20, 1996 08:27:17 UT
E'|| (mV/m)
E'⊥ (mV/m)
B'|| (nT)
B'⊥ (nT)
1.0
0.5
0.0
-0.5
-1.0
0.010
0.005
0.000
-0.005
-0.010
17.12
17.14
17.16
17.18
17.20
17.134
17.136
17.138
17.140
17.142
17.144