Possible evidence of damped cavity mode oscillations stimulated by the January, 1997 magnetic cloud event

J. Goldstein, M. K. Hudson, and W. Lotko
Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755, U.S.A.

Abstract. A sudden drastic change in the solar wind dynamic pressure is one proposed mechanism for the excitation of cavity mode resonances in the plasmasphere. To study the possibility of cavity mode occurrence following a 180 cm$^{-3}$ solar wind density pulse on January 11, 1997, a numerical MHD simulation was run on a dipole grid. The simulated spectra recorded by a virtual satellite are compared with those produced from the Polar magnetic time signals during the interval 0228 – 0304 UT. In both sets of spectra, power is concentrated between 2 and 5 mHz; observed FLR-like spectral peaks in the range 6 – 20 mHz are in rough agreement with simulated plasmaspheric FLRs between 7 – 21 mHz. In the simulation, the fundamental plasmaspheric cavity mode is at 3.5 mHz; phase analysis of observed 3.5 mHz electric and magnetic field signals from the interval 0230 – 0237 UT supports the possibility of a heavily damped standing wave at this frequency.

1. Introduction

It is believed that the magnetosphere can act as a resonant cavity for ultra-low-frequency (ULF) magnetosonic waves. Developed by numerous theoretical and numerical efforts (e.g. Allan et al. [1986]; Zhu and Kivelson [1989], Lee and Lysak [1989]), the cavity mode hypothesis proposes that MHD fast-mode (or compressional) waves get trapped between Alfvén gradients at the magnetopause, plasmapause, and equatorial ionosphere. The trapped waves resonate at normal frequencies of the system, and in the process (unless the wave fields are completely axisymmetric) couple to toroidal mode field line resonances (FLRs) where local toroidal eigenfrequencies match those of the cavity modes.

Despite its conceptual simplicity and intuitive appeal, in situ evidence [Kivelson et al., 1984, 1997] for the cavity mode hypothesis is relatively scarce. One suggested mechanism for exciting cavity modes is a strong pressure pulse in the solar wind [Yamamoto et al., 1992]. A 180 cm$^{-3}$ density pulse was observed around 0159 UT on January 11, 1997 by the Wind spacecraft at the tail end of the preceding magnetic cloud [Burlaga et al., 1998]. The pulse’s impact propagated to the plasmasphere and was recorded by the Polar satellite as a large magnetic disturbance that peaked at about 0222 UT.

To study this event, we used a numerical MHD simulation consistent with previous models by Lee and Lysak [1989] and Allan et al. [1986], but which incorporates measurements made by the Polar Plasma Wave Instrument (PWI) [Gurnett et al., 1995], the Hydra plasma experiment [Scudder et al., 1995], and the Electric Field Instrument (EFI) [Harvey et al., 1995] to specify a zero-order plasma density. This letter presents a comparison between the model results and field data from two Polar instruments, the EFI and the Magnetic Field Experiment (MFE) [Russell et al., 1995]. The frequency and phase of the observed fields are suggestive of a 3.5 mHz cavity resonance triggered by the 0222 UT magnetic disturbance, and lasting less than two wave cycles.

2. The Model

We use a modification of the numerical model of Goldstein et al. [1999] (P1). The linearized, cold ideal MHD equations are advanced in time via a finite-difference scheme. A nonuniform 2D dipole grid is used to discretize a meridional cut of the magnetosphere. The three coordinates are $\mu$ (field-aligned), $\phi$ (azimuthal) and $\nu$ ($\phi = \phi \times \hat{\mu}$). The model wave fields have azimuthal harmonic wave number $m = 3$, which most effectively couples fast and toroidal modes [Allan et al., 1986]. The simulation region is filled with a cold, perfectly conducting plasma with background density $\rho_0$, and dipole background magnetic field. The boundaries are rigid conductors at the magnetopause ($L_{MP} = 10$) and ionosphere (equatorial ionosphere at $L = 1$, N. and S. ionospheres at average radius $r \approx 2R_E$). Similar models have been used, most notably by Lee and Lysak [1989]. Our model only differs in one significant respect: $\rho_0$ is specified by incorporating the combined observations of the Polar PWI, Hydra, and EFI instruments during 0218 – 0400 UT on January 11. This permits a more direct and reliable quantitative comparison with the observations.

Fig. 1 shows equatorial electron number density $n_e(L)$; a symbol indicates the source of each measurement. Two density values $N_{UHR}$ (denoted by squares) were obtained from PWI measurements of the upper hy-
brid resonance (UHR) [Persoon and Menietti, private communication, 1990] in a fashion similar to P1. The densities \(N_{SC}\) (circles) were obtained from an empirical correlation between spacecraft potential and density, deduced from the 01/11/97 observations of the EFI, PWI and Hydra instruments [Scudder, private communication, 1990] as done by Scudder et al. [1999]. Uncertainties in \(N_{SC}\) are discussed later. At \(L = 1\) (not covered by Polar) density \(N_{mol}\) (filled circle) was estimated with the model of Carpenter and Anderson [1992].

The densities \(N_{UHR}\) and \(N_{SC}\) shown in Fig. 1 include a latitude correction which maps observations down to the equator, using an \(R^{-\alpha}\) dependence, where \(R\) is the orbital radius of Polar and \(\alpha\) depends on \(L\). In the inner plasmasphere \(\alpha = 1\); in the plasmatrough \(\alpha = 4\) [Angerami and Carpenter, 1996]; for the outlying density enhancement between 0 \(\leq L \leq 8.5\), \(\alpha = 0\). The piecewise exponent \(\alpha(L)\) was used solely to determine the equatorial \(n_e(L)\) of Fig. 1. MHD waves spend most of their time at the equator, where the Alfvén speed is lowest, so the field-aligned variation plays only a secondary role in controlling the cavity mode and FLR frequencies. Therefore, \(n_e(L)\) was used for the equatorial profile in the simulation, and the value \(\alpha = 5.5\) was assumed for improved computational efficiency. The mass density function \(\rho_0(L, R) = \rho_0 n_e(L) W_0(R) (R/L)^{5.5}\) was used in the simulation region; \(\rho_0\) is proton mass. \(W_0(R)\) is an empirical mass-weighting formula [Gallaher, private communication], determined from DE1 observations in a fashion similar to Craven et al. [1997]:

\[ W_0(R) = (1.59) - (0.12) R + (0.0075) R^2 + (16.39) R^{-12}. \]

3. Cavity Mode Simulation

Using the mass density \(\rho_0(L, R)\) from the previous section, a numerical simulation was performed on an 80-by-60 dipole grid. The system was perturbed with a 1000-second equatorial impulse in radial velocity. Plate 1 shows dimensionless power spectra for the three linear magnetic components, \(b_y\), \(b_z\), and \(b_u\) (‘poloidal’, ‘toroidal’, and ‘compressional’), normalized to \(b_u\), which has been scaled to roughly match the observations of the next section. The spectra represent the observations of a virtual satellite, flying through the simulation region along a trajectory (labeled ‘Sample pts’ in Plate 1) chosen to mimic that of Polar during the interval 0228 – 0304 UT (the circle marks 0304 UT). The horizontal axis denotes the UT values at which Polar passed through each of the sample points.

As in the work by Allan et al. [1986] and Lee and Lysak [1989], the impulse produced fast-mode (compressional and poloidal) oscillations at discrete frequencies. The fundamental plasmaspheric cavity mode is the lowest spectral line in \(b_y\) and \(b_z\) that peaks at \(f_1 = 3.5\) mHz; the next harmonic is at \(f_2 = 14\) mHz. These numerical eigenmodes model 2D standing waves whose characteristics are determined by the Alfvén profile of a narrow range of \(MLT\). Due to the off-equatorial position of the virtual satellite, \(b_y\) power is weaker than both \(b_y\) and \(b_z\). Prominent in the \(b_z\) spectrum is a chain of field line resonances (FLRs), descending in frequency from 21 mHz to 7 mHz between 0230 and 0304 UT. Spectral power at 3.5 mHz in \(b_z\) is evidence of strong coupling to the cavity mode.

4. Polar EFI and MFE Observations

The 6-second data from the EFI and MFE, recorded between 0228 and 0304 UT, are displayed in Plate 2. On top of a low-frequency (< 2 mHz) response to the 0222 UT pulse, enhanced power between 2 and 5 mHz was observed. To establish a field-aligned coordinate system and extract the > 2 mHz signals, a 6-minute running average of the observed geomagnetic field was used. \(Z\) is along the average magnetic field, \(Y\) points eastward, and \(X = Y \times Z\). The fields shown in Panels (a), (c) and (e) (magnetic in black, electric in red) were detrended by subtracting off 6-minute averages of the raw fields; in the process, wave power < 2 mHz was drastically reduced. The electric fields \(H[E_X]\) and \(H[E_Y]\) were Hilbert-transformed, which shifts time signals in phase by \(\pi/2\). In the case of a standing wave, the magnetic (and Hilbert-transformed) electric signals will be in phase or antiphase. In Panels (b), (d) and (f), dynamic power spectra for unfiltered \(dB_X\), \(dB_Y\) and \(dB_Z\) were computed using FFTs with non-overlapping time windows. In Panel (g) the fractional Doppler uncertainty \(\Delta\) in observed frequency due to Polar’s motion is 0.3% or less, estimated in a fashion similar to P1.

The components \(dB_X\), \(dB_Y\) and \(dB_Z\) in Plate 2 correspond respectively to \(b_y\), \(b_z\) and \(b_u\) in Plate 1. As in the simulated spectra, the observed spectral power in the fast mode (\(dB_Y\) and \(dB_Z\)) is mostly between 2 and 5 mHz; although this spectral concentration is real, the low spectral power below 2 mHz is exaggerated by the detrending procedure. The observed toroidal-mode dynamic spectrum \(dB_Y\), which possesses FLR-like enhancements falling gradually in frequency from 20 mHz at 0228 UT, compares favorably to the simulation as well. For reference, the FLR frequencies seen in the simulation results (\(b_z\), Plate 1) are overplotted in Plate 2 (d) as filled circles. The horizontal ‘error
Plate 1. MHD simulation results: power spectra along virtual Polar satellite orbit (‘Sample pts’ curve) during 0228 – 0304 UT on 01/11/97.

bars’ represent the uncertainty in each simulated UT bin associated with mapping Polar’s trajectory to a discretized grid. The time signals in Panel (c) are predominantly 5.5 mHz during 0250 – 0304. A toroidal FLR at 5.5 mHz would have $\mathcal{H}[E_X]$ and $dB_Y$ in phase or antiphase in the vicinity of the resonance location ($L \approx 5.4$ at 0302 UT); vertical lines drawn at the peaks and troughs of $dB_Y$ illustrate that $\mathcal{H}[E_X]$ and $dB_Y$ are out of exact antiphase by approximately $36^\circ$. A FLR interpretation can still be applied, with the assumption of significant isospheric dissipation; a perfect standing wave would not form on the field line because the reflected wave would be attenuated. Attempts to examine the phase relations of the FLR-like spectral enhancements between 0228 and 0250 were unsuccessful because the extremely small signals could not be isolated without phase distortion.

From 0230 – 0237 UT (between the vertical dotted lines in Panels (a) and (e)) the fast-mode time signals $dB_X$, $dB_Z$, and $E_Y$ are predominantly $3.5 \pm 0.3$ mHz, although higher frequencies are evident as well. During this time, $\mathcal{H}[E_Y]$ is roughly in phase with $dB_Y$ and $dB_Z$, indicating a standing wave relationship. Since the observed frequency $3.5$ mHz matches $f_1$ from the simulation, we interpret this apparent standing wave as the signature of a plasmaspheric cavity mode, triggered by the large 0222 UT magnetic disturbance. The time delay between the disturbance and the appearance of the standing wave can be attributed to the time necessary to set up the standing wave (approximately, the wave period) and for the perturbed plasmapause to become stable enough to support a standing wave. Before 0230 (not shown) there is wave power at $3.5$ mHz, but the $E-B$ phase cannot be clearly determined.

During 0230 – 0237 UT, the spectral amplitude ratios $b_y/b_\mu$ (simulated) and $dB_X/dB_Z$ (observed) are both about 3, in agreement. The simulated $b_y$ is about 25 times smaller than $b_\mu$ during 0230 – 0237 UT; the observed ratio $dB_Y/dB_Z$ during this interval is under 1/500. Smaller relative amplitudes of observed toroidal waves are consistent with the assumption that isospheric damping of FLRs is high.

5. Discussion and Conclusions

Linear, cold ideal MHD theory may be used to characterize the ULF wave coupling problem in the inner and middle magnetosphere, where the ambient magnetic field is only weakly perturbed (e.g. Kivelson et al. [1984]; Zhu and Kivelson [1989]; Lee and Lysak [1989]). Examination of Polar MFE data reveals that the deviation of the observed geomagnetic field strength $B_{\text{observed}}$ from that of a dipole is 10% or less between 0228 and 0304 UT on January 11.

The $Q$ (quality factor) of a driven plasmaspheric cavity mode is limited by at least two effects: (1) Joule dissipation resulting from cavity mode energy being channeled via FLRs to the finite-conducting ionosphere, and (2) leakage of wave energy through the Alfvén barrier at the plasmapause and into the outer magnetosphere, where it can be lost either through the magnetopause or down the tail. These two processes limit the lifetime of an impulsively excited resonance and, in extreme cases, cannot prevent resonances from forming at all. The observed standing wave relationship persisted for only seven minutes (approximately 1.5 wave cycles). Because of this short interval, a cavity mode interpretation of the data is not unequivocal, even though the agreement with the model is good. Such a short lifetime implies large energy loss; a damping

Plate 2. Polar EFI (courtesy F. Mozer) and MFE (courtesy C. Russell) observations, 0228 – 0304 UT on 01/11/97. Compare spectra of $dB_X$, $dB_Y$, and $dB_Z$ with $b_\mu$, $b_\phi$, and $b_\rho$ (respectively) of Plate 1.
rate of $\gamma \approx 0.0025 \, \text{s}^{-1}$ was deduced for the 3.5 mHz signal observed from 0230 – 0237 UT. This value implies $Q \approx 4.4$ for the provisional cavity mode, and is consistent with a theoretical estimate of the ionospheric FLR damping rate by Crowley et al. [1987] and with observed FLR damping [Fenrich and Samson, 1997]. The phase analysis of the 5.5 mHz toroidal wave, and the relative amplitude of the $20 \, \text{mHz}$ spectral line during 0230 – 0237 UT, are also consistent with high ionospheric damping. These results suggest that ionospheric dissipation may be a major cause of energy loss in the plasmaspheric cavity, although leakage must certainly contribute as well. If it is a consistent feature of this region, the high damping rate might help explain why in situ observations of cavity modes are so rare.

An important element in this study is the inference of the ambient plasmaspheric density. Deriving number density from the UHR line is a well-established technique, although its accuracy depends crucially on the quality of the observed resonance line, and the absence of other obscuring signals. On the other hand, uncertainties in the model potential-density relation used to obtain $N_{sc}$ in Fig. 1 imply that by itself, the $N_{sc}$ density estimate becomes progressively more uncertain as it increases above about $20 \, \text{cm}^{-3}$. The model ambient density also depends upon the mass-weighting and field-aligned profile, both of which have been assumed. In this regard, it is encouraging that the model FLR frequencies seem to agree with the observed toroidal-mode spectrum in Plate 2(d), since FLR frequencies depend strongly upon ambient density.

The observed and modeled spectra and amplitudes show good agreement, especially considering the uncertainties involved. Within the framework of the cavity mode hypothesis, analysis of the observed fields implies that there is substantial energy loss, possibly from ionospheric dissipation. Future advances in understanding cavity mode formation and evolution will likely require models that treat the physics of this energy loss.

Acknowledgments. We are grateful to D. Gurnett (Polar PW1), J. Scudder (potential-density curve), D. Gallagher (mass-weighting formula), F. Mozer (Polar EFI), C. Russell (Polar MPE), and R. Denton and all of the above for their input. This work was supported by NASA NGR 35-00001, NAG5-2252, NAG5-7442, NAG5-7869, NAG8-8443, NAG5-3182, NAG5-2231 and NSF ATM 9622071.

References


J. Goldstein, and M. K. Hudson, Department of Physics and Astronomy, Dartmouth College, Hanover, N.H. 03755, U.S.A. (e-mail: jerru@chaos.dartmouth.edu)

W. Lotko, Thayer School of Engineering, Dartmouth College, Hanover, N.H. 03755, U.S.A.

(Received July 8, 1999; revised September 15, 1999; accepted October 15, 1999.)