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Standing Alfvén waves at the magnetopause

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[1] We present results from a statistical analysis of the oscillatory motion of the magnetopause based on THEMIS spacecraft observations, yielding the first experimental evidence for the existence of standing Alfvénic surface or Kruskal-Schwarzschild modes at the magnetopause. The magnetopause boundary represents a membrane under tension, which may resonantly interact with magnetospheric cavity or waveguide modes. Ultra-low "magic" geomagnetic pulsation frequencies, often observed in ground-based and ionospheric measurements and attributed to these cavity or waveguide modes, agree with the detected magnetopause oscillation frequencies and are reinterpreted in terms of surface mode eigenfrequencies. **Citation:** Plaschke, F., K.-H. Glassmeier, H. U. Auster, O. D. Constantinescu, W. Magnes, V. Angelopoulos, D. G. Sibeck, and J. P. McFadden (2009), Standing Alfvén waves at the magnetopause, *Geophys. Res. Lett.*, *36*, L02104, doi:10.1029/2008GL036411.

1. Introduction

[2] The solar wind compresses the Earth's magnetic field and confines it to the magnetosphere within the magnetopause (MP) boundary. The location of this boundary is characterized by the pressure balance between the total pressures on the magnetosheath and magnetospheric sides [*Spreiter et al.*, 1966]. The latter is essentially the magnetic pressure. In-situ spacecraft observations confirm this paradigm and have facilitated the empirical modeling of the average static location and shape of the MP at times of different solar wind conditions [e.g., *Fairfield*, 1971; *Sibeck et al.*, 1991; *Shue et al.*, 1997].

[3] The static models, however, are not suitable for the description of the dynamic motion of the MP due to solar wind variations or intrinsic boundary instabilities. Early estimates for the velocity of the magnetopause were first obtained from single spacecraft observations [e.g., *Cahill and Amazeen*, 1963] and were subject to strong assumptions. The determination of the MP velocity using timing techniques became possible when multi-spacecraft observations, namely by the ISEE and AMPTE satellite pairs, became available [e.g., *Elphic and Russell*, 1979]. The four CLUSTER spacecraft flying in a close configuration provided the observations needed to determine three-dimensional velocities [e.g., *Paschmann et al.*, 2005]. Nevertheless, the fact that the distances separating the spacecraft were small with respect to the typical amplitude of MP motion rendered reconstruction of MP motion difficult.

[4] The recently launched THEMIS mission [*Angelopoulos*, 2009], which comprises five spacecraft, offers an opportunity to perform direct MP motion reconstruction. During the early coast phase between February and September 2007, the spacecraft were on extremely similar, highly elliptical, and near equatorial orbits. Their orbital configuration resembled pearls on a string. Apogees lay near the bow shock and swept from dusk to late morning sectors over the entire dayside magnetosphere as the orbit precessed. Because typical MP velocities ($\sim$40 km/s) greatly exceed spacecraft velocities ($\sim$1 km/s) in the vicinity of the MP, the more than 1000 MP crossings observed during these 7 months result primarily from MP motion and not from spacecraft motion. Since the distances separating the spacecraft were comparable to typical MP oscillation amplitudes, the THEMIS spacecraft configuration was well suited for studies of MP motion.

[5] In this paper we present a statistical analysis of MP oscillation frequencies, obtained by reconstructing its motion via spline interpolations between observed MP crossing times and locations. *Plaschke et al.* [2009] discuss in detail other results from this statistical analysis.

2. Data and Methods

[6] Magnetic field [*Auster et al.*, 2009] and particle [*McFadden et al.*, 2009] data were available for all five spacecraft during most intervals of interest from February to September 2007. Both data sets were available from each probe for a total of 6697 MP crossings. The crossing locations were transformed into a 5° aberrated geomagnetic solar magnetospheric (AGSM) coordinate system to take into account the angle of incidence of the solar wind with respect to the Earth-Sun line.

[7] To bridge the gaps between successive MP crossings by spline interpolation, a transformation of the crossing locations to a one dimensional quantity is necessary, for which we chose the MP location model from *Shue et al.* [1997]:

$$r_0 = r\left(\frac{2}{1+\cos\vartheta}\right)^{\alpha} \tag{1}$$

Here r denotes the radial distance of the crossing position from the Earth, ϑ the angle between the AGSM x-line and a line from the Earth to this location and r_0 an equivalent standoff distance of the MP. For our purpose the parameter α can be assumed to be constant (α = 0.5959 for typical solar wind conditions).

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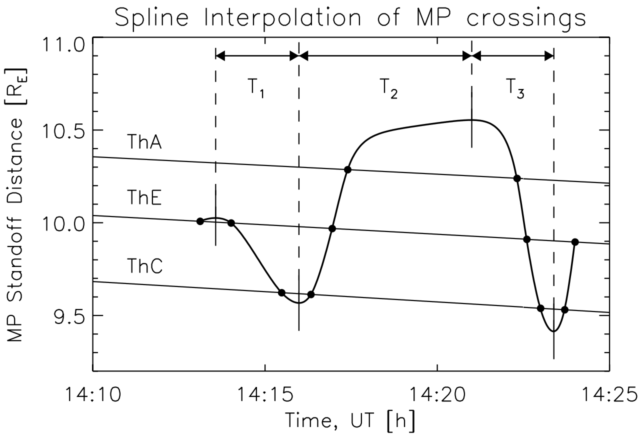

Figure 1. Example of spline interpolated MP crossings and times. The model estimated equivalent standoff distance r_0 of the MP is shown against the time of observation between 14:12 UT and 14:24 UT on May 27, 2007 (thick solid wavy line). The straight lines show the motion of the spacecrafts ThA, ThC and ThE in this coordinate system. The crossing positions are depicted with filled circles. Maxima and minima of the equivalent standoff distance of the MP are used for the estimation of oscillation half periods T_1, T_2 and T_3.

[8] Before applying the spline interpolation to the equivalent standoff distances r_0 and times of MP crossing observations [*Glassmeier et al.*, 2008], we subdivided the MP crossing database into several subgroups to ensure that time gaps between two consecutive crossings were not too large: In our case we chose 10 minutes to be the longest gap duration permitted. The inbound and outbound crossing sequences were checked for soundness: If a spacecraft detects outward MP motion, then the next crossing should either be detected by the next spacecraft outward (continued outward MP motion) or by the same spacecraft (a reversal to inward MP motion). More than two subsequent crossings detected by the same spacecraft were rejected, because a spline interpolation on these points would only resemble the radial motion of the observing spacecraft. Finally, the minimum number of crossings in a subgroup was set to 4. Applying these criteria, we subdivide the full database of 6697 MP crossings into 452 subgroups for individual application of the spline interpolations.

3. Results and Discussion

[9] As illustrated by the example covering the interval from 14:12 UT to 14:24 UT on May 27, 2007, in Figure 1, the spline interpolations yield analytical functions for the MP location $r_0(t)$. From this function half oscillation periods T_i can be easily obtained. The distribution of oscillation frequencies, defined by $f_i = 1/(2T_i)$ and shown in Figure 2, exhibits prominent frequencies at 1.3, 1.9, 2.5, 3.1 and 4.1 mHz (±0.1 mHz). These frequencies agree very well with the set of discrete frequencies first observed in high latitude radar measurements of ionospheric signatures that map to phenomena on the flanks of the magnetosphere [*Samson et al.*, 1992] and later in ground-based magnetometer observations at various geomagnetic latitudes [e.g., *Francia and Villante*, 1997].

[10] These stable and recurrent frequencies have been interpreted as eigenmodes of a magnetospheric cavity or waveguide [*Harrold and Samson*, 1992] confined within the boundaries set by a static MP, the ionosphere and a turning point field line shell beyond which magnetohydrodynamic (MHD) compressional waves are evanescent. They have been called CMS (sometimes "magic") frequencies after the cavity mode model of *Samson et al.* [1992]. The stability of the CMS frequencies has been questioned [*Ziesolleck and McDiarmid*, 1995] as well as the cavity models themselves, since no striking in situ evidence in form of spacecraft measurements of standing compressional cavity-mode MHD waves has been found to date [e.g., *Sarafopoulos*, 1995]. *Viall et al.* [2008] recently found the scale lengths of some periodic solar wind (SW) density fluctuations appear more frequently than others, leading to the possibility that the prominence of some geomagnetic pulsation frequencies results from typical driving frequencies.

[11] Based on our findings we suggest another interpretation for the existence of the discrete frequency spectrum observed: Local pressure perturbations in the magnetosheath lead to a local displacement of the MP boundary. This displacement is associated with a local perturbation of the Chapman-Ferraro current system $\delta\mathbf{j}_{CF}$ (see Figure 3), which needs to be closed either by field perpendicular electric currents (generation of a fast mode propagating into the magnetosphere), or by field aligned currents within the MP region, associated with the generation of an Alfvén wave pulse, much as *Glassmeier and Heppner* [1992] already noted when discussing travelling convection vortices.

[12] This pulse propagates along the MP towards the Earth and sets up an Alfvén surface wave as described by *Kruskal and Schwarzschild* [1954]. In their pioneering work, the planar boundary is characterized by a jump in the magnetic field strength balanced by an inverse jump in the static pressure of the plasma. MHD and jump equations are solved after linearization using a plane wave ansatz.

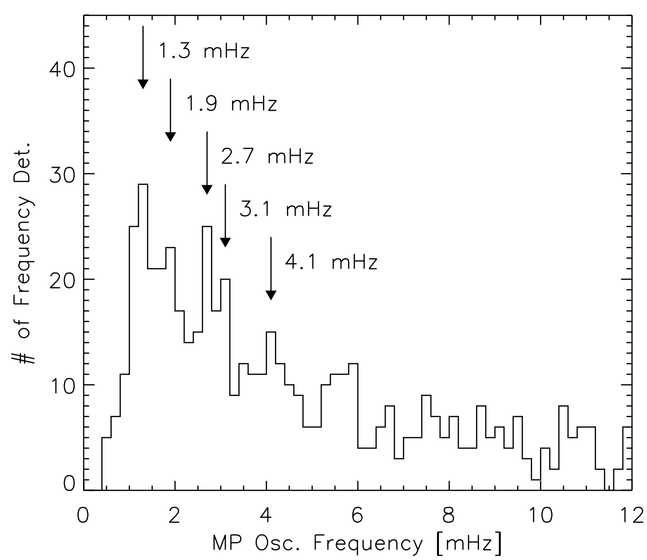

Figure 2. Distribution of oscillation frequencies obtained from the estimation of the MP motion by spline interpolation. Binsize used: 0.2 mHz. Maxima of the distribution are marked with arrows.

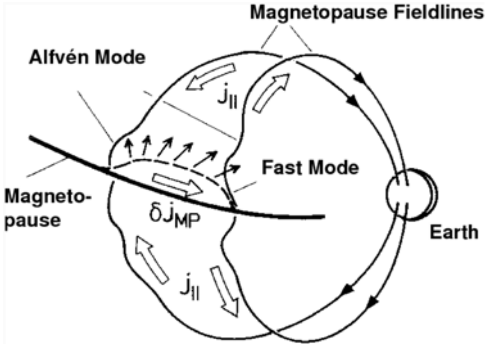

Figure 3. A pressure pulse acting locally on the MP leads to a local disturbance $\delta \mathbf{j}_{CF}$ of the Chapman-Ferraro current system. The additional current is closed via field aligned currents associated with an Alfvén wave propagating along the boundary. Figure modified after *Glassmeier and Heppner* [1992].

Stable oscillatory solutions are found and are applicable to the MP case. The corresponding dispersion equation for the surface Alfvén waves is given by *Kruskal and Schwarzschild* [1954] and *Hasegawa and Chen* [1974]:

$$\omega = k_z \sqrt{\frac{B_0^2 + B_1^2}{\mu_0(\rho_0 + \rho_1)}} \tag{2}$$

where the subscripts 0 and 1 denote quantities in the pressure and magnetic field dominated half spaces respectively; ω, B and ρ represent, as usual, the frequency, magnetic field strength and mass density.

[13] Tension in the magnetic field lines provides the restoring force that counters local displacements of the boundary. Thus, the dayside MP can be regarded as a stressed membrane with boundaries in the northern and southern ionosphere. Because of the almost perfect reflection of Alfvén waves there [e.g., *Glassmeier*, 1983], this membrane can support eigenoscillations. The system is sensitive to a discrete spectrum of frequencies [*Hasegawa and Chen*, 1974] in agreement with our experimental findings.

[14] Although the Alfvén surface waves or Kruskal-Schwarzschild modes bear similarities to Alfvén waves generated by field line resonances (FLRs) [e.g., *Southwood*, 1974], they must not be confused with them. The step-like jump in magnetic field strength and plasma density at the MP causes magnetosheath pressure variations to couple to Alfvénic perturbations. The predominant oscillation frequencies are given by the propagation velocity of the Alfvén pulses generated and the length of the MP field lines. By contrast, in the FLR case frequencies and radial (latitudinal) locations for the geomagnetic pulsations are determined by the frequencies of the driving compressional wave.

[15] *Hasegawa and Chen* [1974] employed the *Kruskal and Schwarzschild* [1954] solutions to study the case of a smooth transition boundary with large gradients in the respective quantities. The general solutions are composed of heavily damped modes with a continuous spectrum and undamped discrete frequency modes determined from the sharp jump Kruskal-Schwarzschild solution. Any reduction in the transition region gradient leads to higher damping of the oscillations and the disappearance of the discrete spectrum, which may be the main reason for the continuous spectrum underlying the spectral peaks in Figure 2.

[16] From the observed spectrum we infer that the fundamental frequency of the MP oscillator should be on the order of 0.65 mHz. We can check if this frequency agrees with that expected for typical values of the magnetic field strength and mass density using equation (2). *Phan et al.* [1994] reported B_0 = 27.5 nT, B_1 = 57.2 nT, ρ_0 = 2.84 kg/m^3 and ρ_1 = 1.67 kg/m^3 for MP crossings with high magnetic shear. The magnetic field values were obtained from magnetic pressure (p_{B0} = 0.3 nPa, p_{B1} = 1.3 nPa) and number density values (N_0 = 17 cm^{-3}, N_1 = 1 cm^{-3}) presented in the paper; the latter ones have been multiplied with the proton mass.

[17] Using these values and equation (2) we estimate the wave propagation velocity to be:

$$v = 326 \text{ km/s} \tag{3}$$

The length Λ of a MP field line can be estimated with the help of the Tsyganenko 89 [e.g., *Tsyganenko*, 1990] magnetic field model by tracing field lines to the ionosphere from the subsolar point with a standoff distance of r_0 = 11.6 R_E, which is the mean equivalent standoff distance of the THEMIS observed MP crossings used in this study and in the study by *Plaschke et al.* [2009]:

$$\Lambda = 2.73 \cdot 10^5 \text{ km} \tag{4}$$

Taking into account that half a wavelength has to be equal to Λ for the fundamental period, the propagation speed equation for the Kruskal-Schwarzschild modes given above yields an expression for the frequency f:

$$f = \frac{v}{2\,\Lambda} = 0.6 \text{ mHz} \tag{5}$$

If we also take into account that the propagation velocity of the Kruskal-Schwarzschild waves is not constant but increases towards the ionospheric ends of the field lines, it can be stated that the estimated frequency f should come close to but be lower than the actual fundamental frequency. Hence, we conclude that our frequency estimate is in very good agreement with the claimed fundamental frequency of 0.65 mHz, supporting our idea.

4. Conclusions

[18] The solar wind constantly buffets the MP and provides a broad-band source of energy. Local displacements of the MP drive standing Alfvén waves (or Kruskal-Schwarzschild modes) with frequencies of the characteristic spectrum obtained with our analysis (see Figure 2). The Kruskal-Schwarzschild modes are confined to the MP boundary layer. Hence, the question has arisen of why these waves and the associated frequencies can be observed on the ground at different latitudes. One possibility is the coupling of these modes to compressional waves due to non-uniformities or the curvature of MP field lines. Furthermore, the spatial integration effect for magnetometer measurements on the ground (where the ionosphere acts as

a low-pass filter) provides for a significant signal strength of geomagnetic pulsations over an area wider than that where the oscillating field line shell connects to the ionosphere. Energy dissipation mechanisms include ionospheric joule heating and the coupling of toroidal and poloidal modes via the ionospheric Hall effect [e.g., *Allan and Knox*, 1982].

[19] This model does not contradict the formation of cavity or waveguide modes, nor are they needed to explain the experimental findings, which is important due to the lack of spacecraft evidence in their favour. The MP may act as a first filter to solar wind pressure variations. If the solar wind pressure is itself oscillatory [see *Viall et al.*, 2008], the MP will act as a driven oscillator, enabling other frequencies to enter the magnetosphere. In any case a thicker MP will cause the filter to be less selective and the prominent frequencies to blur into a continuous spectrum. Our findings also suggest, that magnetospheric waveguide models need to treat the outer boundary (the MP) as non-rigid and capable of supporting discrete standing Alfvén or Kruskal-Schwarzschild modes, to which cavity modes should be coupled.

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