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# ULF waves at Mercury: Earth, the giants, and their little brother compared

Karl-Heinz Glassmeier [a,*], Dmitri Klimushkin [b], Carsten Othmer [a], Pavel Mager [b]

[a] *Institut für Geophysik und Meteorologie, Technische Universität Braunschweig, Mendelssohnstr. 3, 38106 Braunschweig, Germany*
[b] *Institute of Solar-Terrestrial Physics, P.O. Box 4026, 664033 Irkutsk, Russia*

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**Abstract**

ULF pulsations are magnetohydrodynamic waves in the terrestrial magnetosphere. They are generated by solar wind buffeting of the magnetosphere, Kelvin–Helmholtz instability of the magnetopause, or particle–wave interactions within the magnetospheric plasma. As a major damping mechanism the terrestrial ionosphere has been identified. Wave modes and wave propagation in the inhomogeneous magnetosphere is described in terms of global toroidal and poloidal oscillations or phenomena such as the field line resonance. An attempt is made to compare ULF pulsations with other comparable wave observations in the magnetospheres of Mercury, Jupiter, and Saturn. Special emphasize is paid to low frequency waves in the Hermean magnetosphere as this global system can not be described as a magnetohydrodynamic plasma which alters physical concepts useful in the terrestrial magnetosphere.


*Keywords:* ULF waves; ULF waves at mercury: Earth, and giants compared; Kelvin–Helmholtz instability

## 1. Introduction

There is only one published report about the existence of ULF pulsations in the Hermean magnetosphere, the one by Russell (1989), reporting about a 2-s narrow band ULF pulsation during the first Mariner 10 encounter with Mercury (Fig. 1). The measured signal exhibits a clear compressional component, but is mainly transverse to the ambient magnetic field with an almost linear polarization in the meridian plane. By the time of this event, the Mariner 10 spacecraft was located in Mercury's midnight sector, close to the equatorial plane, at a planetocentric distance of about $1.3R_{\mathrm{Mercury}}$. The narrow bandwidth of the signal suggests a resonant excitation mechanism. Russell (1989) proposes it to be a standing Alfvén wave along a Hermean magnetic field line. Using an electron density of 3 $\mathrm{cm}^{-3}$ and assuming the plasma ions to be protons, he derives an Alfvén velocity of about 1000 km/s. With an estimated field line length of about 4000 km, Russell calculates a period of 8 s for the fundamental of a standing wave on the field line. Thus, according to Russell's interpretation, the observed 2-s waves could be the fourth harmonic of the fundamental.

At this point, this review could be finished due to the sparsity of observational facts. However, in view of the planned space missions MESSENGER and BepiColombo, heading for an exploration of the Hermean system, a more detailed comparative look into the problem of eigenoscillations and ULF waves in the magnetosphere of Mercury is worthwhile.

Over the past five decades topics such as wave modes, excitation, and damping of ULF waves in the terrestrial magnetosphere have been studied in great detail (e.g., Southwood and Hughes, 1983; Samson, 1991; Glassmeier et al., 1999a for a review). ULF waves are thought to be *standing waves* in the magnetospheric system with the northern and southern ionosphere being the boundaries where the oscillations exhibit a node. The phenomenon of *field line resonance*, first described by Tamao (1965), plays the role of a paradigm in the ULF wave community, with *global oscillations* gaining an

* Corresponding author. Tel.: +49-531-391-5214; fax: +49-531-391-5220.
*E-mail address:* kh.glassmeier@tu-bs.de (K.-H. Glassmeier).

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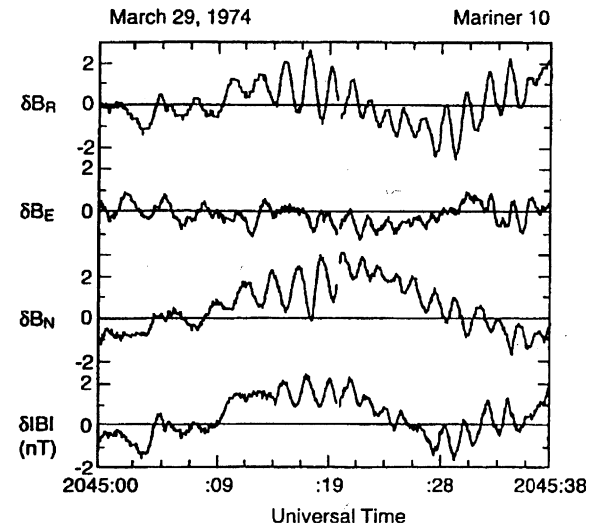


Fig. 1. Time series of the magnetic field recorded by Mariner 10 deep in the magnetosphere of Mercury. The coordinate system is radial from the planet, east and north. The average magnetic field has been removed (after Russell, 1989).

increasing interest (e.g., Kivelson and Southwood, 1985).

Possible source mechanisms for terrestrial ULF waves are the *Kelvin–Helmholtz instability* at the magnetopause (e.g., Engebretson et al., 1998), *particle–wave interactions* within the magnetosphere (e.g., Southwood, 1973; Glassmeier et al., 1999b), or *solar wind buffeting* of the magnetosphere (Kepko and Spence, 2001). Once generated, the excited waves are propagating in the magnetospheric system and need to be dissipated somewhere. A minor part of their energy is processed and lost via *wave–particle interactions*, however, most of the energy is finally dissipated by *Joule heating* in the terrestrial ionosphere, causing significant temperature changes there (Glassmeier et al., 1984; Lathuilliere et al., 1986).

Here, we shall concentrate on a comparison of the three wave modes mentioned, i.e., standing waves, global oscillations, and field line resonances, as well as a discussion of the importance of solar wind buffeting as a source mechanism and wave–particle interaction as a dissipation mechanism for the wave energy.

## 2. Standing waves

ULF waves in the terrestrial magnetosphere have very early been interpreted as standing waves in the magnetosphere bounded by the ionosphere. Due to the large Pedersen conductivity, the wave electric field is almost shortcut in the boundary, inhibiting any field line motion there (Dungey, 1954). In this sense ULF waves are a global phenomenon in the terrestrial magnetosphere. Typical periods of such standing waves are of the order of minutes, that is of the order of the travel time of Alfvén waves between conjugate ionospheric regions. These periods are significantly less than, for example, the rotation period of the Earth or timescales governing substorm activity in the magnetosphere. Therefore, eigenoscillations can built up in the terrestrial magnetosphere.

The first systematic search for ULF waves in another magnetosphere was presented by Khurana and Kivelson (1989), studying observations from the Voyager 2 spacecraft in the Jovian magnetosphere (Fig. 2). ULF pulsations with periods of about 10–20 min have been detected and interpreted as standing waves in the tail plasma sheet of Jupiter. These waves are actually not standing waves in the sense discussed above. The eigenperiod of a field line oscillation in the Jovian system, determined as the travel time between conjugate regions of the northern and southern ionosphere, is of the orders of hours (e.g., Glassmeier et al., 1989), a time scale comparable to other magnetospheric time scales such as the rotational period of the planet Jupiter itself. Thus, "global" *standing waves* are not to be expected in the Jovian system. However, if there are regions with enhanced mass density, e.g., decreased Alfvén velocity in the magnetospheric system, standing waves can be excited in such wave guides. Khurana and Kivelson (1989) interpreted their observations as such "local" *standing waves*. The Io plasma torus with its large mass density along the Io orbit around Jupiter is another regime where "local" *standing waves* can exist. Glassmeier et al.

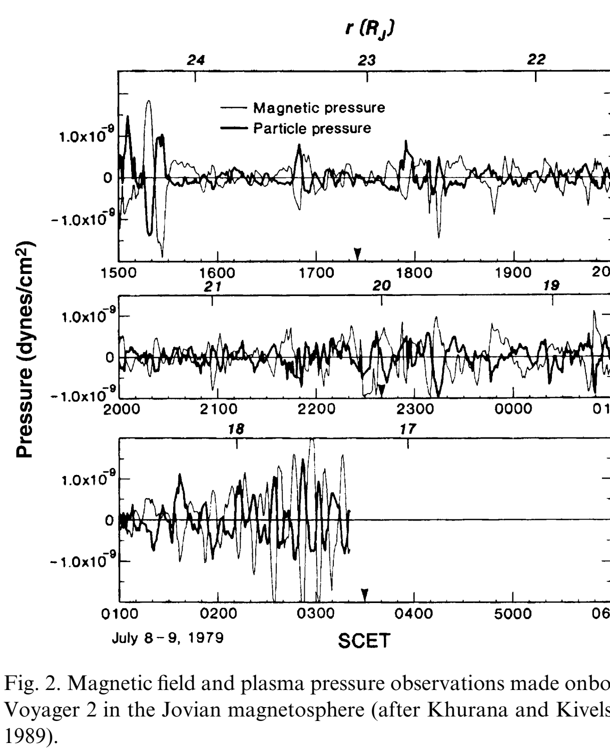


Fig. 2. Magnetic field and plasma pressure observations made onboard Voyager 2 in the Jovian magnetosphere (after Khurana and Kivelson, 1989).

(1989) report about the existence of decoupled toroidal and poloidal oscillations of the entire Io torus.

At Saturn Alfvén wave travel times are also of the order of the rotational period of the planet. Thus "global" *standing waves* are not expected to exist and have also not been reported. Also, the existence of "local" *standing waves* has not yet been confirmed.

At Mercury, the ULF wave travel time is of the order of a few seconds due to the small spatial extend of its magnetosphere. "Global" *standing waves* can exist, and the Russell-event is a nice example. However, these standing waves differ from those usually observed in the terrestrial magnetosphere in that the boundary is not an ionosphere, but the planet's surface or some photoemission layer (e.g., Grard et al., 1999). A low-conducting boundary implies an open end boundary, that is the mode structure along the oscillating field line is different at Mercury and Earth.

## 3. Field line resonances

The concept of *the field line resonance* process has first been suggested by Tamao (1965). It describes the propagation of fast mode MHD waves in a non-uniform plasma and its subsequent resonant mode coupling to a *standing wave* in a magnetospheric system. The actual coupling point is determined by the local eigenperiod of the resonating field line. Field line resonance is a theoretically very well developed concept in magnetospheric physics (for a recent review see Glassmeier et al., 1999a). Comparing planets it is of great interest to study the question whether field line resonances also occur in other planets magnetosphere.

No reports about field line resonances in the Jovian magnetosphere have been published. All what can be concluded is that coupling to "global" *standing waves* is not likely as these modes do not exist at Jupiter. The size of the Kronian magnetosphere is comparable to that one of the Jovian magnetosphere. Thus, field line resonances in their traditional meaning are also not expected in the magnetosphere of Saturn.

However, Cramm et al. (1998) report about magnetic field observations at Saturn which resemble all ingrediences of a field line resonance: spatially localized wave activity in the toroidal field component with a phase shift of about 180° across the amplitude maximum in the radial direction (Fig. 3). The wave event discussed by Cramm et al. (1998) is related to surface wave activity observed at the Kronian magnetopause (Lepping et al., 1981). The interpretation of the Cramm-event as a field line resonance is hampered by the fact that standing waves should not exist in the magnetosphere of Saturn. Furthermore, the region where the Cramm-event has been detected is not a region where significantly increased mass densities are expected, which rules out the

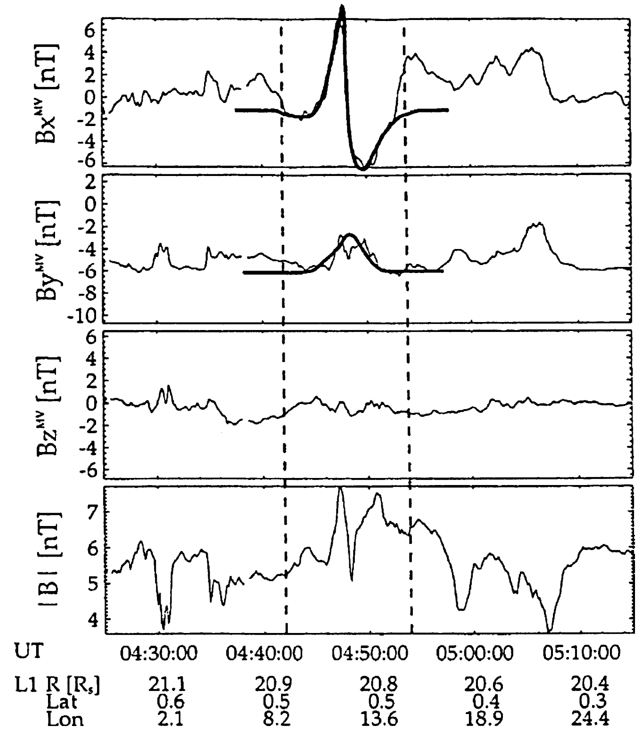


Fig. 3. Voyager magnetic field observations of a field line resonance oscillation in the magnetosphere of Saturn, displayed in a minimum variance coordinate system. $B_z$ is the component of minimum variance and $B_x$ denotes the component of maximum variance direction. A modelled field line resonance signal is displayed as a solid line on top of the $B_x$ and $B_y$ components (after Cramm et al., 1999).

coupling to a "local" *standing wave*. Cramm et al. (1998) offer an alternative explanation: field line resonance is only a special case of a resonant mode coupling between a fast mode and an Alfvén mode. A more general discussion exhibits that resonant mode couplings require the two interacting wave partners to have their phase velocity (components) coinciding at the resonant point. For the coupling to a *standing Alfvén wave*, this is consistent with requiring equal oscillation frequencies for field line resonance to occur. If the magnetospheric system is huge enough, coupling to a *propagating Alfvén wave* becomes possible. Obviously such a coupling is the most likely explanation for the Cramm-event (see Cramm et al., 1998 for a more detailed discussion). Field line resonances as discussed here have also been treated by Fedorov et al. (1998).

The question arises whether the field line resonance concept is applicable to Mercury as well or in which way it has to be modified in order to take into account of the particular conditions in the Hermean magnetosphere. The fundamental difference to be considered is the frequency range of magnetospheric eigenoscillations. The frequency of the wave event displayed in Fig. 1 lies between the local gyroperiods of protons (0.8 s) and sodium ions (18.3 s), that is well outside the MHD frequency range. Field line resonance or resonant mode coupling considerations thus require the study of higher frequency waves in a multi-ion plasma. Such a treatment has been presented by Othmer et al. (1999). A necessary condition for field line resonance is the matching of the field-aligned component of the fast mode wave phase velocity and the phase velocity of the Alfvén mode. A sufficient condition requires the existence of a strictly guided mode (the Alfvén mode in an MHD plasma) to which the non-guided (the fast mode in an MHD plasma) can couple its energy. For frequencies in the range of the ion gyrofrequencies, as in Mercury's magnetosphere, a strictly guided mode needs to identified. Detailed descriptions of wave propagation in a multi-ion plasma are given by, e.g., Smith and Brice (1964), Gurnett et al. (1965), and Rauch and Roux (1982). According to these authors each further ion species causes the same principal modifications in the plasma dispersion characteristics with the extent of these changes depending on the respective ion abundances. Since next to protons, sodium ions are presumably the main ion species in the Hermean magnetospheric plasma, only their importance for the field line resonance phenomenon will be discussed here.

Fig. 4 displays Friedrichs diagrams for the R-, L-, and X-modes up to the proton gyrofrequency of a plasma consisting of electrons, protons, and sodium ions for realistic Mercury conditions. The R-mode (L-mode) is the right-hand (left-hand) circularly polarized mode, whose wave vector is parallel to the background magnetic field; the wave vector of the X-mode as well as of the O-mode is perpendicular to the background magnetic field. The O-mode does not appear as this mode is not supported for frequencies less than the plasma frequency, which is much higher than the proton gyrofrequency for typical magnetospheric plasmas. The effect of the sodium ions onto the dispersion of a pure electron–proton plasma consists essentially in the formation of four new characteristic frequencies: (1) the L-mode has got a new resonance at the sodium gyrofrequency $\Omega_{\mathrm{Na}}$, (2) there is a new resonance of the X-mode, the so-called bi-ion resonance $\omega_{\mathrm{bi}}$, (3) at the bi-ion cut-off frequency $\omega_{\mathrm{CF}}$ above these two resonances, both the L- and the X-mode reappear, and (4) very important for the resonance problem, the dispersion branches of the L-, R-, and X-mode intersect at the *crossover frequency* $\omega_{\mathrm{CR}}$. The wave normal surfaces and the polarization of the wave modes within the different frequency regimes are displayed in Fig. 4. Their topology contains information about the Poynting flux characteristics of the wave modes: a mode that is guided along the background magnetic field is characterized by a dumbbell lemniscoid, whereas a spheroid belongs to a non-guided mode.

Of particular interest for our problem is the region around the crossover frequency. For $\omega_{\mathrm{CR}} < \omega$, the non-guided mode is left-handed and the guided mode is right-handed elliptically polarized. For $\omega < \omega_{\mathrm{CR}}$, the conditions are reversed. At $\omega = \omega_{\mathrm{CR}}$, the wave modes supported by the plasma are linearly polarized, and the phase velocities of both modes in the direction of the background magnetic field are equal (cf. Fig. 4). The crossover frequency is the only frequency outside the MHD frequency range to exhibit these properties. At $\omega = \omega_{\mathrm{CR}}$, the dielectric tensor takes the form

$$\underline{\underline{\varepsilon}} = \begin{pmatrix} S & 0 & 0 \\ 0 & S & 0 \\ 0 & 0 & P \end{pmatrix}, \qquad (1)$$

where $S$ and $P$ are defined in the usual way (e.g., Stix, 1962). Its non-diagonal terms vanish much as they do in the MHD range. Rauch and Roux (1982) studied the propagation of waves in a multi-ion plasma extensively and found that at $\omega_{\mathrm{CR}}$, the group velocity of the guided mode and the Poynting flux are directed along the background field for any direction of the wave vector. In other words, at the crossover frequency, a multi-ion plasma supports a strictly guided mode which is comparable to the Alfvén mode of magnetohydrodynamics. This distinguishes the crossover frequency from all other frequencies outside the MHD range. The requirement of

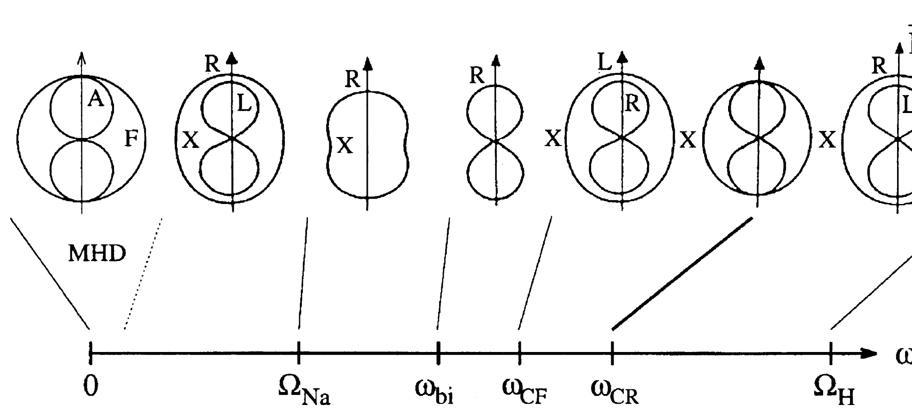

Fig. 4. Friedrichs diagrams for the low frequency modes in the Hermean plasma (after Othmer et al., 1999).

a strictly guided mode thus gives rise to a frequency selection rule for field line resonances in the inhomogeneous plasma at Mercury. The crossover frequency is given by $\omega_{CR} = \sqrt{1 + 528\alpha_{Na}}\Omega_{Na}$, where $\alpha_{Na}$ is the ratio of the sodium to proton particle number density and $\Omega_{Na}$ is the sodium gyrofrequency. It should be noted that the crossover frequency depends on the sodium abundance and is proportional to the magnetic field strength. Provided that the gradient of the plasma composition is not too big, the crossover frequency thus rises monotonically from the Hermean magnetopause towards the planet. If one generates a broadband signal at the magnetopause or somewhere in the outer fringes of the Hermean magnetosphere travelling inward and considers a fixed field-aligned wave number $k_{\parallel}$, the necessary condition for field line resonance is in general fulfilled for every frequency component of the broad band source signal at some location $\vec{r}$ . The fact however, that the crossover frequency is a preferred frequency for critical coupling favours one frequency out of the spectrum.

The location where this favoured frequency equals the local crossover frequency is the field line resonant point. This point is identical to the point where the curves of the spatially varying resonance frequency and the crossover frequency intersect each other (see Othmer et al. (1999) for details). This has the interesting consequence that observations of resonant pulsations in Mercury's magnetosphere allows one to infer local plasma properties provided the frequency of any observed resonant wave is interpreted in terms of the local crossover frequency. As this frequency is determined by the magnetic field strength and the abundance of sodium ions, the local value of the sodium ion percentage can be calculated provided the magnetic field magnitude is known. Othmer et al. (1999) try such an interpretation using the observations of ULF pulsations made by Mariner 10 (Fig. 1) and conclude about 14% sodium abundance which is well in accord with estimates by Ip (1986) or Cheng et al. (1987). This demonstrates that ULF waves are also a very useful diagnostic tool in the Hermean magnetosphere.

## 4. Global oscillations

The seminal theoretical paper of ULF pulsations in the terrestrial magnetosphere is Dungey's (1954) study on the electrodynamics of outer space. Studying eigenoscillations in a dipole magnetosphere Dungey derived a set of partial differential equations allowing a detailed discussion of toroidal and poloidal eigenoscillations. A particular finding is *decoupled toroidal and poloidal modes*, provided the perturbations are axisymmetric. In particular, the toroidal global oscillations are interesting as they represent oscillations of individual field

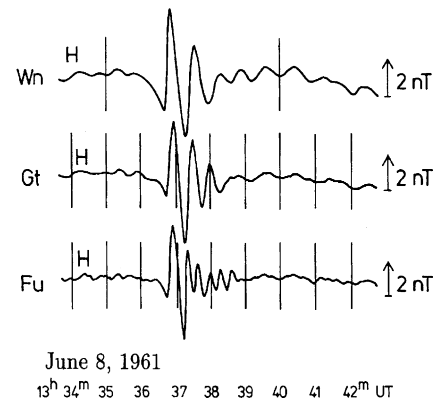


Fig. 5. Geomagnetic pulsations recorded at the mid-latitude magnetic observatories Wingst, Göttingen, and Fürstenfeldbruck. The pulsation period is decreasing with decreasing latitude of the observatory (after Voelker, 1962).

line shells at their respective eigenfrequencies. Voelker (1962) was the first to report about observations of such decoupled toroidal modes (Fig. 5). Magnetic field observations of a damped ULF event from the three German observatories Wingst, Göttingen, and Fürstenfeldbruck clearly indicate the different oscillation periods expected for decoupled axisymmetric eigenmodes.

Do such decoupled oscillations also exist in others than the terrestrial magnetosphere? At Jupiter and Saturn such modes are not expected as their eigenperiods will be comparable to other magnetospheric time scales such as the rotation period. Only in the Io plasma torus *decoupled toroidal and poloidal oscillations* corresponding to the Dungey modes have been identified by Glassmeier et al. (1989). In the Hermean magnetosphere, spatial scales are more favourable for these modes, however. But it should be taken into account that an MHD description of the Hermean plasma is prohibited as all relevant frequencies will be close or are comparable to the gyroperiods.

Glassmeier et al. (2003) tackle the Dungey problem using a more general plasma model. The wave equation reads

$$\nabla \times \nabla \times \vec{E} = \frac{\omega^2}{c^2} \underline{\underline{\varepsilon}} \vec{E}, \tag{2}$$

where $\underline{\underline{\varepsilon}}$ is the dielectric tensor, given by

$$\underline{\underline{\varepsilon}} = \begin{pmatrix} c^2/v_A^2 & 0 & 0 \\ 0 & c^2/v_A^2 & 0 \\ 0 & 0 & -\omega_{pe}^2/\omega^2 \end{pmatrix} \tag{3}$$

for a cold plasma at MHD frequencies. As the third diagonal element is much larger than the two other elements, the field-aligned component may be neglected. Then the wave electric field is represented by the two scalar potentials $\Phi$ and $\Psi$ (e.g., Klimushkin, 1994; Klimushkin, 1998)

$$\vec{E} = -\nabla_\perp \Phi + \nabla_\perp \times \Psi \vec{e}_\parallel, \tag{4}$$

and using curvilinear coordinates the wave equation separates into two partial differential equations for the toroidal and poloidal part of the oscillation field:

$$\partial_1 \boldsymbol{T} \partial_1 \Phi - k_2^2 \boldsymbol{\Pi} \Phi = \mathrm{i}k_2 \left( \partial_1 \frac{\omega^2}{v_\mathrm{A}^2} \right) \Psi, \tag{5}$$

$$\left[ \partial_1 \frac{g_2}{\sqrt{g}} \boldsymbol{\Pi} \frac{g_2}{\sqrt{g}} \partial_1 - k_2^2 \frac{g_1}{\sqrt{g}} \boldsymbol{T} \frac{g_1}{\sqrt{g}} \right] \Psi - \Delta_\perp \frac{g_3}{\sqrt{g}} \Delta_\perp \Psi = \mathrm{i}k_2 \left( \partial_1 \frac{\omega^2}{v_\mathrm{A}^2} \right) \Phi, \tag{6}$$

where $\boldsymbol{T}$ and $\boldsymbol{\Pi}$ denote the toroidal and poloidal operators defined by (see Klimushkin, 1998)

$$\begin{aligned} \boldsymbol{T}(\omega) &= \partial_3 \frac{g_2}{\sqrt{g}} \partial_3 + \frac{\sqrt{g}}{g_1} \frac{\omega^2}{v_\mathrm{A}^2}, \\ \boldsymbol{\Pi}(\omega) &= \partial_3 \frac{g_1}{\sqrt{g}} \partial_3 + \frac{\sqrt{g}}{g_2} \frac{\omega^2}{v_\mathrm{A}^2}, \end{aligned} \tag{7}$$

with $g_1$, $g_2$, $g_3$, and $g$ denoting the diagonal elements of the metric tensor in radial, azimuthal, and meridional direction and its determinant, respectively. Eqs. (5) and (6) are equivalent to Dungey's equations. In case of an axisymmetric perturbation, $k_2 = 0$, Dungey's equations read

$$\partial_1 \frac{g_2}{\sqrt{g}} \boldsymbol{\Pi} \frac{g_2}{\sqrt{g}} \partial_1 \Psi - \Delta_\perp \frac{g_3}{\sqrt{g}} \Delta_\perp \Psi = 0, \tag{8a}$$

$$\partial_1 \boldsymbol{T} \partial_1 \Phi = 0, \tag{8b}$$

denoting decoupled toroidal and poloidal oscillations as observed by Voelker (1962).

In a similar way Dungey's equations for the Hermean magnetosphere can be derived. To simplify matters the plasma is approximated as a cold plasma consisting of protons and electrons only. For frequencies smaller, but close to the proton gyrofrequency, $0 < \omega \ll \Omega_\mathrm{p}$, the dielectric tensor reads

$$\underline{\underline{\varepsilon}} = \begin{pmatrix} \varepsilon_1 & -\mathrm{i}\varepsilon_2 & 0 \\ \mathrm{i}\varepsilon_2 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix}, \tag{9}$$

with

$$\varepsilon_1 \cong \frac{c^2}{v_\mathrm{A}^2} + \frac{c^2}{v_\mathrm{A}^2} \frac{\omega^2}{\Omega_i^2}; \quad \varepsilon_2 \cong -\frac{c^2}{v_\mathrm{A}^2} \frac{\omega}{\Omega_i}; \quad \varepsilon_3 \cong -\frac{\omega_\mathrm{pe}^2}{\omega^2}.$$

The third diagonal element of the dielectric tensor is still very large compared to the other two diagonals, which allows to neglect the field-aligned electric field also in this approximation. The same algebra as used to derive Dungey's equations for the MHD case can be used to derive the corresponding equations for the Hermean case discussed here (see Glassmeier et al., 2003, for details). The toroidal equation then reads

$$\begin{aligned} &\partial_1 \boldsymbol{T} \partial_1 \Phi - k_2^2 \boldsymbol{\Pi} \Phi + k_2 \partial_1 \left( \sqrt{g_3} \frac{\omega^2}{v_\mathrm{A}^2} \frac{\omega}{\Omega_i} \phi \right) - k_2 \sqrt{g_3} \frac{\omega^2}{v_\mathrm{A}^2} \\ &\times \frac{\omega}{\Omega_i} \partial_1 \Phi = -\mathrm{i} \partial_1 \frac{\omega^2}{v_\mathrm{A}^2} \frac{\omega}{\Omega_i} \sqrt{\frac{g}{g_1}} \partial_1 \Psi + \mathrm{i}k_2 \left( \partial_1 \frac{\omega^2}{v_\mathrm{A}^2} \right) \Psi \\ &+ \mathrm{i}k_2 \left( \partial_1 \partial_3 \frac{g_2}{\sqrt{g}} \partial_3 \frac{g_1}{\sqrt{g}} - \partial_3 \frac{g_1}{\sqrt{g}} \partial_3 \frac{g_2}{\sqrt{g}} \partial_1 \right) \Psi \\ &+ \mathrm{i}k_2^2 \frac{\omega^2}{v_\mathrm{A}^2} \frac{\omega}{\Omega_i} \sqrt{\frac{g_1}{g}} \Psi, \end{aligned}$$

and in the axisymmetric perturbation case

$$\partial_1 \boldsymbol{T} \partial_1 \Phi = -\mathrm{i} \partial_1 \frac{\omega^2}{v_\mathrm{A}^2} \frac{\omega}{\Omega_i} \sqrt{\frac{g}{g_1}} \partial_1 \Psi. \tag{10}$$

This latter equation exhibits a very interesting result: there are no decoupled toroidal and poloidal axisymmetric oscillations in the Hermean magnetosphere! This also holds when applying a more complex plasma model. The reason for the absence of *decoupled toroidal and poloidal oscillations* is the appearance of finite off-diagonal elements in the dielectric tensor.

## 5. The magnetospheric bulk modulus and solar wind buffeting

The solar wind is constantly changing its velocity and its mass density, that is the solar wind dynamic pressure is highly variable. This *solar wind buffeting* of planetary magnetospheres can be an important source of ULF waves and causes the question to what extend a planetary magnetosphere is compressible. A typical length scale of a magnetospheric system is the subsolar standoff distance of the magnetopause $R_\mathrm{MP}$, given by the pressure equilibrium between the dynamic pressure $p_\mathrm{ram} = \rho_\mathrm{SW} v^2$ and the magnetic pressure of the planetary magnetic field via

$$R_\mathrm{MP} = \left( \frac{B_0^2}{\mu_0 p_\mathrm{ram}} \right)^{1/6}. \tag{11}$$

The *bulk modulus K* of the magnetosphere is defined here as the ratio of the solar wind dynamic pressure change required to obtain a specified relative change in the magnetopause position:

$$K = R_\mathrm{MP} \frac{\mathrm{d}p_\mathrm{ram}}{\mathrm{d}R_\mathrm{MP}}. \tag{12}$$

With the above definition of the stand-off distance, we have $K \propto p_\mathrm{MP} = p_\mathrm{ram}(r = R_\mathrm{MP})$. Thus, the *magnetospheric compressibility* $\kappa$ is given as

$$\kappa = 1/K \propto -1/p_\mathrm{MP}. \tag{13}$$

We conclude that the compressibility of a planetary magnetosphere is only depending on the solar wind dynamic pressure, not on the planetary magnetic field. As the solar wind mass density along Mercury's orbit is much larger than along Jupiter' s orbit by about a factor of 200, the compressibility of the Hermean magnetosphere is much less than that one of the Jovian magnetosphere. Mercury has a very stiff, Jupiter a very fluffy magnetosphere.

The same solar wind dynamic pressure change causes a very different reaction of the magnetospheres of Mercury, Jupiter, or Earth. At Mercury small-amplitude oscillations will be the result, while at Jupiter major variations of the overall Jovian magnetosphere occur because of the large compressibility. Solar wind buffeting thus causes a *ringing* of the Hermean magnetosphere, that is small-amplitude oscillations are more easily generated by the solar wind in the Hermean magnetosphere than in the Jovian magnetosphere.

When compressing a planetary magnetosphere the solar wind needs to do work against the magnetic field

$$\mathrm{d}W = -p_{\mathrm{ram}} A \mathrm{d}R_{\mathrm{MP}} \tag{14}$$

or, with $\mathrm{d}\varepsilon$ the work per unit area,

$$\mathrm{d}\varepsilon = -p_{\mathrm{ram}} \mathrm{d}R_{\mathrm{MP}} \propto R_{\mathrm{MP}} \mathrm{d}p \propto p_{\mathrm{ram}} R_{\mathrm{MP}} \frac{\mathrm{d}p}{p_{\mathrm{ram}}}. \tag{15}$$

For the same relative change of the dynamic pressure, the compression work on the magnetosphere or the energy transfer per unit area is about a factor 3 larger when comparing Jupiter and Earth and about a factor 7 smaller when comparing Mercury and Jupiter. This is intuitively consistent with Mercury being the much stiffer object.

Solar wind buffeting will be an important ULF wave source at Mercury as its magnetosphere is a very stiff one, which allows ringing of the whole magnetosphere. At Jupiter, solar wind buffeting will cause major reconfigurations and large-amplitude variations of the entire magnetosphere which do not allow these variations to be interpreted as ULF waves. Furthermore, as the scale of the Hermean magnetosphere is small solar wind buffeting should be a source of global oscillations of which some may be quasi-axisymmetric requiring a formulation of Dungey's equations as described above.

## 6. Wave damping

Independent of the wave source, most of the energy of ULF pulsations in the magnetospheres of Earth, Jupiter, and Saturn will finally be dissipated in the ionospheres of these planets due to *ionospheric Joule heating* (e.g., Glassmeier et al., 1984). At Mercury the situation is more complicated as there is no or only a very tenuous ionosphere with a very low Pedersen conductivity (e.g., Grard et al., 1999). Joule heating in the solid planet, its crust or metallic core, can be a means of wave energy dissipation.

However, the Hermean magnetosphere is much smaller than the terrestrial, Jovian, or Kronian one. Major ion populations are protons and sodium ions (e.g., Ip, 1986; Othmer et al., 1999; Killen and Ip, 1999). Assuming ion temperatures of the order of 1 keV allows one to estimate a sodium thermal ion gyroradius of about 150 km. Thus, the ratio of the system scale, taken here as $1R_{\mathrm{Mercury}} = 2450$ km, to the sodium ion gyroradius is about 16 in the Hermean magnetosphere. The corresponding terrestrial value is of the order of 600. A ratio as small as 16 suggests that any wave activity generated by solar wind induced magnetospheric ringing or other processes is associated with *kinetic Alfvén waves*, not with conventional MHD Alfvén wave modes.

Kinetic Alfvén waves are strongly dispersive due to electron inertia and finite gyroradius effects. Their dispersion relation is given by (e.g., Hasegawa and Uberoi, 1982; Lysak, 1990)

$$\omega \approx v_{\mathrm{A}}^2 k_{\|} (1 + k_{\perp}^2 r_{\mathrm{ion}}^2), \tag{16}$$

where $r_{\mathrm{ion}}$ is the thermal ion gyroradius and $k_{\perp}$ and $k_{\|}$ are the wave vector components transverse and parallel to the ambient magnetic field. Finite electron inertia and ion gyroradius effects cause kinetic Alfvén waves to carry a significant parallel electric field component $E_{\|}$. For a low $\beta$ plasma, this parallel component is related to the transverse field component $E_{\perp}$ via (Goertz and Boswell, 1979; Lysak, 1990; Leonovich and Mazur, 1995)

$$E_{\|} \approx r_{\mathrm{gia}}^2 \frac{\partial E_{\perp}}{\partial s_{\perp}\, \partial s_{\|}}, \tag{17}$$

where $r_{\mathrm{gia}}$ is the ion acoustic gyroradius and $\partial s_{\perp}$ and $\partial s_{\|}$ denote derivates along the transverse and longitudinal directions with respect to the ambient magnetic field. Approximating

$$\frac{\partial E_{\perp}}{\partial s_{\perp}\, \partial s_{\|}} \approx \frac{\partial E_{\perp}}{L_{\perp} L_{\|}}, \tag{18}$$

assuming $L_{\perp} = L_{\|} = R_{\mathrm{Mercury}}$, and choosing $r_{\mathrm{gia}} = 0.2$ $R_{\mathrm{Mercury}}$, one has $\delta E_{\|} \approx 0.0004 \delta E_{\perp}$. The transverse electric field may be estimated via $\delta E_{\perp}/\delta B \approx v_{\mathrm{A}}$. With $v_{\mathrm{A}} = 1000$ km/s (Russell, 1989) and $B = 5$ nT (see Fig. 1), we have $E_{\perp} \approx 5$ mV/m, and the parallel electric field component $E_{\|}$ is of the order of 0.2 mV/m. Potential differences of about 0.5 keV will be associated with ULF waves induced by, e.g., solar wind buffeting of the Hermean magnetosphere. Particle acceleration due to kinetic Alfvén waves will help to damp and dissipate the energy associated with low-frequency waves. ULF waves are an important means to heat the Hermean electron population.

## 7. Summary and comparison

ULF pulsations in the magnetospheres of Mercury, Earth, Jupiter, and Saturn have been compared. In the terrestrial magnetosphere, *global eigenoscillations* can be excited as the eigenperiods are much smaller than other important magnetospheric time scales. The huge magnetospheres of Jupiter and Saturn do not support such *global oscillations* as travel times between conjugate ionospheric boundaries are of the order of the rotation periods of the planets and eigenoscillations are not likely to build up. However, *local eigenoscillations* are observed in regions of low Alfvén velocity such as the Jovian plasma sheet. *Field line resonances* in their classical meaning, that is coupling of a fast mode to a standing Alfvén mode, are only observed in the terrestrial magnetosphere, while in the magnetospheres of the giants resonant mode coupling between propagating fast and Alfvén waves is possible and observed. Special conditions exist in the Hermean magnetosphere, where a description of the plasma as an MHD plasma is not suitable as this magnetospheric system is rather small and its eigenperiods are close to the gyroperiods of protons and sodium ions. *Resonant mode coupling* occurs at the *crossover frequency*, not at the *local eigenfrequency* of a *standing wave.* Decoupled *toroidal and poloidal global oscillations* are also not expected to be observed in the Hermean system as the off-diagonal elements of the dielectric tensor matter and couple these two modes.

Defining a *magnetospheric compressibility*, it is found that the magnetosphere of Mercury is a rather stiff magnetosphere while the giants have very fluffy magnetospheres. Solar wind buffeting thus leads to major reconfigurations of the giant magnetospheres while the Hermean magnetosphere will start to ring under the influence of solar wind dynamic pressure variations. The associated ULF waves are most likely kinetic Alfvén waves with significant field-aligned electric field components causing electron heating. Solar wind excited ULF waves are thus a possible candidate for heating the Hermean plasma.

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