Travel-time magnetoseismology: Magnetospheric sounding by timing the tremors in space

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[1] This letter introduces the idea of timing the arrival of magnetic impulse signals at different locations to infer the density distribution of magnetospheric plasma. Tanaka’s model of magnetohydrodynamic (MHD) wave propagation is used as the underlying principle of this method. The methodology is similar to timing the arrival of seismic signals to understand the Earth’s interior. A test of this idea on a sudden impulse event shows that the results are in good agreement with an empirical plasma density model as well as with the density estimated independently by the field-line resonance method. Chi, P. J., and C. T. Russell (2005), Travel-time magnetoseismology: Magnetospheric sounding by timing the tremors in space, Geophys. Res. Lett., 32, L18108, doi:10.1029/2005GL023441.

1. Introduction

[2] The distribution of magnetospheric plasma density can undergo a significant degree of variations and is perhaps the least predictable physical parameter of the magnetosphere despite its importance in modeling space weather [e.g., Gallagher et al., 2000]. The difficulty in predicting the magnetospheric density is in part due to the complex nature of this dynamic system—its interchange with isospheric plasma as well as the unsteady convection caused by the varying solar wind—and partly because of the paucity of measurements. Since the space age began, the few spacecraft observations of the magnetospheric density have provided local measurements restricted to limited orbit tracks. Until recently these sparse space observations along with the equally sparse ground observations of ducted whistlers [e.g., Carpenter, 1963] provided the only constraints on our understanding of the plasmasphere. In the past few years, they have been joined by global pictures of the plasmasphere provided by the IMAGE satellite [e.g., Buch et al., 2001], but these images are more useful in giving qualitative understanding.

[3] The above techniques measure either the charge density of magnetospheric plasma or the column density of the outer ion He· in the case of ELV imaging. Little information is given for the mass of the plasma despite the need for such data to understand many magnetospheric processes and their timescales. Recent progress in sounding the magnetosphere by ground magnetometer pair provides a solution to monitoring this additional dimension of plasma density. In particular, the gradient technique allows one to detect the eigenfrequencies of magnetospheric field lines on a routine basis and to use them to infer the mass density of the associated flux tube [Baranovsky et al., 1985; Waters et al., 1994]. The word “magnetoseismo” [Hughes, 1994] has sometimes been used to describe this approach because of its intrinsic similarity to seismology and helioseismology. The field-line resonance (FLR) method has also been useful in monitoring the depletion of the plasmasphere during severe magnetic storms [e.g., Chi et al., 2000]. However, this technique too is limited to the few sites that are properly instrumented with pairs of high temporal resolution magnetometers.

[4] Here we show that the distribution of magnetospheric density can be estimated by an alternative magnetic seismo-seismic approach whose methodology is more akin to terrestrial seismology. The method uses the arrival time of impulsive events observed by ground stations, as well as by satellites if available, to infer the density distribution along the paths in the magnetosphere by which the signals travel. This travel-time magnetoseismic method was motivated by the recent observations that confirm the dominant role of magnetohydrodynamic (MHD) waves in transmitting sudden impulse signals from the magnetopause to the ground [Chi et al., 2001], as well as by the sufficient differentiation in the time of signal arrival seen in these records.

[5] In the following we first show an example of the tremors in the space plasma and the variations in their arrival time observed at different corotates of the magnetosphere. We then discuss how these tremors propagate via MHD waves and introduce a travel-time magnetoseismic method. Using the ground and satellite observations of these tremors, we demonstrate that the density distribution of the magnetosphere inferred from the travel-time technique is in good agreement with an empirical plasma density model as well as with the density estimated by the field-line resonance method.

2. Magnetic Tremors in Space and Their Propagation

[6] An example of the tremors in the magnetosphere is the first fluctuation of a sudden impulse, which is also referred to as a preliminary impulse in ground records. Figure 1 shows a sudden impulse event of which the running average with a 4-min window is removed to better display the first fluctuations. The origin of this sudden impulse on September 24, 1998 was an interplanetary shock in the solar wind that impacted on the Earth’s magnetosphere [Russell et al., 2000]. The data shown in Figure 1, including the GOES-10 satellite and 10 ground stations belonging to the IGP-LANL, CANOPUS, and CPMN magnetometer arrays, were all taken in the afternoon sector. The signal started in the subaural region of the magneto-
pause, reached GOES-10 at geosynchronous orbit, and arrived at various magnetometer stations on the ground shortly after. These electromagnetic fluctuations are akin to seismic tremors in space, and they could be used to infer the density distribution in the magnetosphere as the way the Earth’s interior is understood through seismic waves. [2] The propagation of MHD waves in the magnetosphere can be highly complicated because of the ionosphere-generality of the magnetospheric plasma. A more serious issue with regard to the calculation of travel time is that the wavelengths are usually longer than the density scale length so that the conventional ray theory is inapplicable. Nevertheless, some important understanding about the wave travel time has been obtained in a theoretical work by Tamao [Tamao, 1964], who formulated a first-order model that addresses many essential characteristics of MHD wave fronts. One of the key findings by Tamao is that, although an MHD signal launched from a point source will eventually permeate the magnetosphere, the path that preserves the most wave energy comprises the shortest path from the source to the field line of interest via the fast mode wave and a field-aligned wave that leads to the observation point via the Alfvén wave. An example of this “Tamao travel path” from the subsolar point of the magnetosphere to a ground observer is depicted in Figure 2, in which SC is the fast-mode segment and CG the field-aligned segment. [5] The travel time associated with each Tamao path, or the “Tamao travel time,” can be written as

\[ t_{\text{Tamao}} = \int \frac{ds}{v_s(r)} + \int \frac{ds}{v_A(r)} \]  

in which \( l_1 \) and \( l_2 \) correspond to SC and CG in Figure 2, \( v_s \) the fast mode speed, \( v_A \) the Alfvén speed, and \( r \) the position vector. In most regions of the magnetosphere, the cold plasma assumption is a good approximation and therefore \( v_s \) equals \( v_A \). The fact that the Alfvén speed controls \( t_{\text{Tamao}} \) also implies that the travel time is a function of the mass density rather than the charge density. If the arrival of wave signals is defined by when the signal’s amplitude reaches its maximum, the time of arrival at a ground station versus its \( L \)-value is expected to follow the distribution shown in Figure 2, for which the calculation assumes a dipolar magnetic field and a density distribution \( n = n_{\infty} (L/L_\infty)^{3.7} \) if \( L > L_\infty \) or \( n = n_{\infty} (L/L_\infty)^{1.5} \) if \( L < L_\infty \), where \( r \) is the distance to the Earth’s center, \( n_{\infty} \) and \( n_0 \) are the equatorial densities at the magnetopause and at the plasmapause, \( L_\infty \) and \( L_0 \) are the \( L \)-values of the magnetopause and the plasmapause, and \( m_1 \) and \( m_2 \) are the density flat-off rates. In calculating the travel time in Figure 2, we set \( n_{\infty} = 1 \text{ cm}^{-3} \), \( n_0 = 50 \text{ au}^{-3} \), \( L_\infty = 10 \), \( L_0 = 5 \), and \( m_1 = m_2 = 3 \). [6] Although in reality the condition may differ in the quantitative sense, Figure 2 possesses the qualitative features of the travel time which increases with increasing \( L \)-value of the ground station in either the outer magnetosphere or the plasmasphere—except at the plasmapause where the signal is significantly delayed as it enters the dense plasmasphere. This model of MHD wave propagation is supported by several recent studies on the travel time of sudden impulses [Lee and Hudson, 2001], Pi 2 pulsations [Ucciani et al., 2000], preliminary reverse impulses (PRI) [Chi et al., 2001], and the Pc 4 waves associated with solar wind pressure pulses [Rygg et al., 2001].

3. Travel-Time Magnetososeismology

[6] The Tamao travel time can be used as the basis of travel-time magnetososeismology, which infers the plasma

Figure 2. The travel path that preserves the most MHD wave energy includes the shortest path from the source to the field line of interest, SC, and the field-aligned propagation along CG. Also shown is the time needed for MHD waves to travel along this type of paths as a function of the \( L \)-value of ground observers.
Figure 3. Equatorial plasma density in the magnetosphere at 2345 UT on September 24, 1998 estimated by the travel-time magnetoionic method by the field line resonance method, and by the Carpenter-Anderson density model. The symbols along the horizontal axis indicate the L-values where the observations were taken.

density by comparing the modeled travel time with the observation, for example, through a χ² fit:

\[ \chi^2 = \sum \left( \frac{t_{\text{model}} - t - \Delta t_{\text{prop}}}{\sigma_t} \right)^2 \]  

(2)

where \( t_0 \) is the time when the signal starts from a point on the magnetopause and \( \sigma_t \) the measurement uncertainty for each observation \( L \). In addition to \( t_0 \), a set of unknown parameters are needed to evaluate the Tanim's travel time \( t_{\text{travel}} \). The indispensable parameters are those for constructing the density distribution. The source location of the signal introduces more variables if \( t_0 \) is unknown. Further complication of the modeling can be avoided by employing a suitable empirical model of the magnetic field. Equations (1) and (2) can easily be generalized for the wave propagation in the three-dimensional space for the observations from satellites, and for the situations where the wave source is not at the subsolar point.

[1] We tested the above travel time method by using the observations of the first magnetic field perturbation associated with the sudden impulse event on September 24, 1998 as shown in Figure 1. In modeling the signal's travel time, the start time \( t_0 \) and the source location were obtained from the observed shock normal vector in the solar wind [Russell et al., 2000] and the Perinçek-Russell magnetopause model [Perinçek and Russell, 1996]. The 1996 Tsyganenko model [Tsyganenko, 1996] was used to trace magnetospheric field lines as well as to evaluate the magnetic field values along travel paths. The density distribution is again described by a power-law function, and no local time dependence of the density function is assumed because all observations were made in the afternoon sector. These conditions result in a model that has five parameters: \( n_m, m_1, f_{lep}, n_0, m_2 \), all associated with the density function. The inversion (through Equation (2)) results in the following solutions of the modeled parameters: \( n_m = 0.09 \pm 0.05 \text{ cm}^{-3}, m_1 = 4.0 \pm 0.2, f_{lep} = 3.51 \pm 0.05, n_0 = 1100 \pm 200 \text{ cm}^{-3}, \) and \( m_2 = 4.1 \pm 0.5 \). Because of the use of the non-analytic Tsyganenko magnetic field, the errors of the estimation were calculated by the Monte-Carlo method, in which the replication of data is generated by appending a normally distributed random noise that is consistent with the measurement uncertainty of each observation. The distribution of the estimated parameters and the associated plasma density were obtained from 1000 re-calculations, and the standard errors were determined by taking the central 68.3% of each distribution.

[2] The validity of these results is evidenced by the good agreement with other independent estimates of the magnetospheric density. Figure 3 compares the equatorial densities obtained by the travel-time inversion, by the field line resonance (FLR) method, and by the Carpenter-Anderson empirical density model [Carpenter and Anderson, 1992]. For consistency, the density fall-off rates (\( m \)) along the field line used in the FLR method are identical to those obtained previously from the travel-time method. In reality, the equatorial density inferred from FLR observations is rather insensitive to these fall-off rates. For example, changing \( m \) by only alters the estimate of equatorial density by less than 10%. In Figure 3, the two magnetosensitive methods yield the mass density whereas the Carpenter-Anderson density is expressed in target charge density. In the outer magnetosphere, all three density profiles are very close agreement. In contrast to the inner magnetosphere where the majority of ions are protons, the plasmasphere has a higher percentage of heavy ions such as He\(^+\) and O\(^+\) whose proportions can be variable [Farquhar et al., 1989]. The existence of heavy ions in the plasmasphere explains the deviation between the results from the two magnetosensitive methods and that from the Carpenter-Anderson model. A typical composition of the plasmasphere estimated by previous satellite observations can be 94% \( \text{He}^+\), 5% \( \text{He}^+\), and 1% \( \text{O}^+\), which will give an average ion mass 3.1 amu.; a value consistent with the result in Figure 3.

[3] The agreement in the plasma density location \( L_{\text{erp}} \) estimated by the travel-time method and by the Carpenter-Anderson model may seem fortuitous because of the considerable distance between the two stations \( L = 2.2 \) and 4.2) that straddle the plasmapause latitude. In fact the inversion was able to reasonably estimate \( L_{\text{erp}} = 3.5 \) despite the large station separation because \( L_{\text{erp}} \) is a key parameter that determines the delay of the signal seen at low-latitude stations. The satellite data available to verify this argument is the electron density inferred from the upper hybrid frequency observed by the Plasma Wave and Sounder (PWS) Experiment on the Akebono satellite [Oya et al.,

Figure 4. The electron density inferred from the upper hybrid frequencies observed by the Plasma Wave and Sounder (PWS) instrument on board the Akebono satellite. The plasmapause was observed at \( L = 3.5 \) approximately 7 hours prior to the PR1 event analyzed in this study.
4. Discussion

[1] The above results demonstrate that timing the im- pulsive electromagnetic signals in the magnetosphere, or tremors in space, is a feasible method to infer the density distribution of the magnetosphere. Travel-time magnetose-ismology can pave the way to the remote sensing of the nightside magnetosphere, as both ground and satellite observations show that the Pi 2 pulsations propagate via MHD waves [Kepko and Kivelson, 1999; Urrutia et al., 2000]. Extending the spatial coverage of mass density measurements is crucial since the normal-mode (FLR) method is generally applicable to the dayside magnetosphere. The mass density of plasma derived from travel- time magnetoseismology can also be compared with the charge density measured or inferred by in situ satellite observations, ducted whistlers, and EUV images of He+ as observed by the IMAGE satellite, to investigate the ion content of the magnetosphere and its variations. The inter- change among observations, numerical modeling of MHD waves in inhomogeneous plasma, and magnetoseismic inversion could facilitate the understanding in all these aspects of the subject.

[2] It is worthy to note that both the travel-time method and the normal-mode method have been in use in each of terrestrial and helio seismologists. Not only has timing the arrival of seismic waves been the sine qua non of crustal research, but also the study of global oscillations of the Earth has provided some of the best constraints on the large-scale structure of Earth’s interior. Helioseismology was used initially to infer the Sun’s internal structure from the normal modes seen on the solar surface, but recently the time- dependent method was adapted as a tool to obtain information of sub-surface flows [Davall et al., 1996]. Now the magnetosphere has become an object that can be explored by these two independent methods.

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