Investigating the Magnetosphere through Magnetoseismology

Abstract

Based on the physics of normal-mode oscillations and signal travel time, magnetoseismology is a unique and well demonstrated method to investigate the structure and dynamics of the magnetosphere. Normal-mode magnetoseismology makes use of the widespread field line resonance in the magnetosphere and has successfully shown the variability of the plasmasphere in timescales ranging from within an hour to over a solar cycle. Travel-time magnetoseismology analyzes impulse propagation and has enabled new capability of remotely monitoring sudden impulses and substorm onsets, which are important magnetospheric phenomena that are rarely measured on site. The two methods of magnetoseismology bear substantial resemblance to the techniques used in terrestrial seismology and helioseismology which have advanced our understanding about the interior of the Earth and the Sun.

For decades, individual teams around the world have been using normal-mode magnetoseismology techniques to estimate the plasma density of the inner magnetosphere, but the source data in each study are limited to a specific spacecraft mission or a regional ground-based magnetometer array. Travel-time magnetoseismology is a relatively new approach for investigating the impulsive phenomena in the magnetosphere, analogous to detecting the earthquake location through timing signal arrival. Several new efforts aim to simulate the impulse propagation in the considerably inhomogeneous magnetotail to facilitate the forward modeling of travel-time magnetoseismology. This ISSI team represents an international collaboration on magnetoseismic research at an unprecedented scale, and its major goals are to establish a unifying framework for estimating plasma mass density from field line resonance observations as well as to fill the knowledge gap in using travel-time magnetoseismology to remotely detect substorm initiation and other impulsive events in the magnetotail.

1. Scientific Rationale

1.1 Magnetoseismology as a science discipline

It is well known that seismological methods have substantially advanced our understanding of the Earth and the Sun. Terrestrial seismology can trace back to the measurements of earthquake arrival at different locations in the 19th century, which led to the discovery of the interior structure of the Earth. Inspired by the so-called "5-minute oscillations" of the solar surface associated with a normal mode of the Sun, helioseismology is now an important discipline for probing the interior and improving understanding of the physics of the Sun and other stars.

To many, terrestrial seismology seems to deal only with the propagation of seismic waves, and helioseismology focuses only on normal-mode oscillations. In fact, similar physics is used in both disciplines. The normal-mode method of seismology can infer the Earth's deep interior by analyzing free oscillations of the Earth that can be detected during major Earthquakes. Time-distance helioseismology allows detailed investigation of the subsurface structure underneath sunspots.

Both normal-mode and travel-time methods have also been demonstrated as ways to investigate the magnetosphere, forming a discipline called "magnetoseismology." The idea of normal-mode magnetoseismology arguably started in late 1950s, soon after the concept of magnetospheric field line resonance was conceived. The surge in this research area, however, did not occur until 1991 when *Waters et al.* demonstrated the power of the crossphase technique that could reliably detect field line resonance frequencies in ground magnetometer data [1]. Normal-mode magnetoseismology makes use of observations of field line resonance – a phenomenon frequently occurring in the magnetosphere – to infer the equatorial plasma mass density. Existing ground-based magnetometer arrays enable continuous monitoring of the variations in plasma mass in the magnetosphere in timescales from hours to the solar cycle. Travel-time magnetoseismology was developed more recently in 2005 by *Chi and Russell*, motivated by the analysis of propagation of sudden impulses excited by the impact of the interplanetary shocks on the Earth's magnetosphere [2]. In this framework, ground observatories and satellites detect the passage of the sudden impulse at multiple locations, much like seismometers timing the arrival of seismic signals. The two seismological methods for investigating three celestial structures are demonstrated in Figure 1.

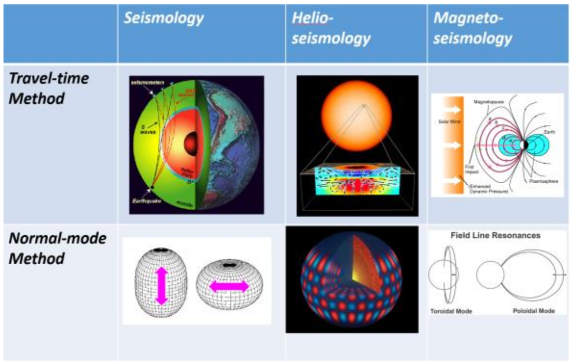

Figure 1. Seismologies for the Earth, the Sun, and the magnetosphere.

A comprehensive description of magnetoseismological research prior to 2012 is given in the book by *Menk and Waters* [3]. Since then, important development has taken place in both normal-mode and travel-time magnetoseismologies, and a summary of recent advances and outstanding questions is described below. **This ISSI team aims to advance our understanding in key outstanding areas in order to develop the framework needed to realize a global monitoring system of the magnetosphere through magnetoseismology.**

1.2 Normal-model magnetoseismology

Recent advances: In the past, research groups around the world each conducted normal-mode studies using the observations made by their individual magnetometer array, and the identification of field line resonance frequencies in data was done mostly in a manual fashion. Sponsored by the European Union Seventh Framework Programme during 2011-2014, the PLASMON project made a substantial advancement on this topic by combining observations from multiple magnetometer arrays and automating many of the data analyses [4]. In the meantime, new magnetometer stations in both North and South Americas have begun operating, making observations suitable for magnetoseismic studies. The analyses of field line resonance observations by these stations have also become more automatic, allowing statistical surveys of the plasmaspheric density [5].

Normal-mode magnetoseismology has opened a special window to view the plasma environment in the magnetosphere. The power unleashed by this method comes in part from the vast number of ground-based magnetometers around the globe that can monitor field line resonance frequencies and consequently the plasma densities. These observations have created many new findings, such as the ionospheric control of the internal plasmaspheric depletion during magnetic storms, the fast enhancement of plasmaspheric density in afternoon hours, and the longitudinal structure of the plasmasphere (Figure 2). Many of these phenomena discovered by normal-mode magnetoseismology are under active investigation and still await definitive interpretations.

The plasma mass density obtained through the normal-mode method can be a valuable data product for understanding the cold plasma reservoir, which varies with space weather activity and can affect particle energization. It is worth noting that the plasma mass density derived from magnetoseismology is unique, not only because no instrument can currently directly measure the cold plasma mass density but also because comparison with electron density information can provide important inference to the ion composition remotely.

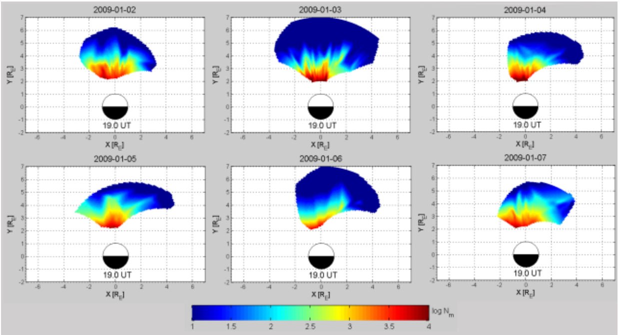

Figure 2. Longitudinal structure of plasmasphere monitored by normal-mode magnetoseismology with magnetometer arrays in North America.

Outstanding questions: At present, we have the data, physics principles, and some essential algorithms for data analysis in place. However, we still do not have a reliable, *fully* automated, and validated algorithm for identifying field line resonance frequencies, which is necessary for routinely extracting the relevant information from the vast amount of magnetometer data, paving a way to monitor the plasma environment in near real time. The outstanding technical issues include decisions on the best type of cross-spectrum and necessary statistical tests to use, as well as in how to improve the algorithm for use in data covering a large range of *L*-values. We also need to characterize the roles of hemispheric asymmetries, ionospheric conductivities, quarter-wave modes, and nonlinear effects in field line resonance to properly estimate plasma mass densities from wave frequencies. The results should be validated by comparing with spacecraft measurements of resonant frequency and plasma density. **Establishing a unifying framework is critical in avoiding artificial differences in the results and in combining regional networks into global observations.**

1.3 Travel magnetoseismology

Recent advances: Travel-time magnetoseismology was originally developed for understanding the propagation of sudden impulses in the dayside magnetosphere, and was soon expanded into investigations in the magnetotail where the initiation of substorms is an important source of impulsive signals. It has been found that ground observations of the arrival of the substorm-triggered magnetic perturbation can infer the start time and location of substorm initiation in the magnetotail, providing valuable timing information for identifying substorm onset mechanisms [6].

The propagation of a substorm-triggered impulse was first modeled by using the Tamao travel path [7] modified for the nightside magnetosphere (Figure 3, top). Based on a rather descriptive model, this approach predicts that an MHD signal would take between one and five minutes to travel from common locations of substorm initiation to the Earth [6,8]. More rigorous calculations based on 3D MHD models have found not only shorter propagation time but also the full waveform of magnetic fluctuations [9,10] (Figure 3, bottom). Furthermore, the simulation of signal propagation based on a 2D hybrid Gyrofluid ion-Kinetic Electron (GKE) model has demonstrated a still shorter propagation time when the perpendicular scale length of the wave is on the order of the ion gyroradius [11].

Outstanding questions: Travel-time magnetoseismology is a very young research field where a wide range of questions still await answers. The necessary next step that will have the greatest impact is a coordinated investigation of impulse propagation time incorporating both observations and models. While using the Tamao propagation model in the dayside magnetosphere may currently be on a solid foundation [12], the same approach in the nightside has triggered many questions due to the much more complicated magnetic field and plasma configurations. Previous calculations of the Tamao travel time in the magnetotail have not adopted the newer and much improved empirical magnetosphere models that are more suitable for substorm studies [13,14]. We also need to investigate how the impulse propagation may depend on the type of sources, such as dipolarization fronts, reconnections, and shock impacts. A detailed comparison between the notional Tamao propagation, various types of numerical models, and observations, is critical in establishing a valid forward model of impulse propagation in the magnetotail for travel-time inversion. **When these outstanding issues are**

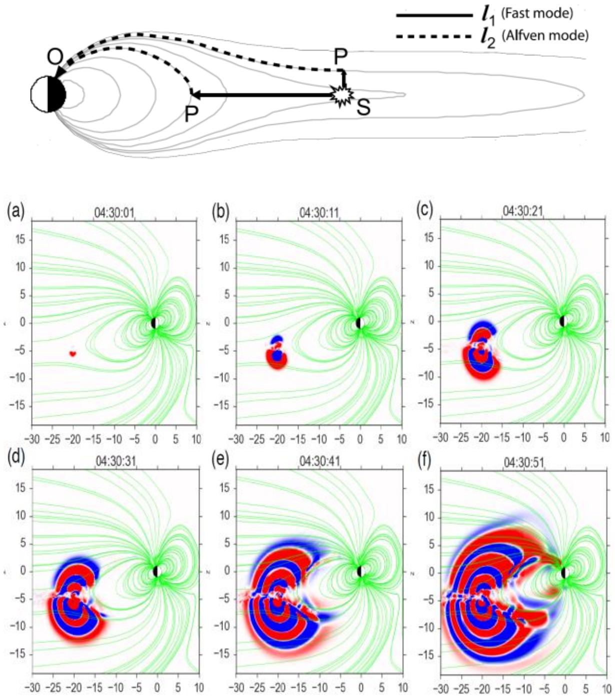

Figure 3. (Top) A schematic diagram showing two examples of Tamao travel paths associated with an earthward impulse in the magnetotail. (Bottom) Simulated Poynting flux intensity associated with an impulse started in the magnetotail.

resolved by this ISSI team, travel-time magnetoseismology will be a powerful new tool for the international community to investigate magnetospheric dynamics through collaboration in space missions (e.g., Cluster, THEMIS, MMS, etc.) and ground-based networks.

2. Goals

The major goal of this ISSI team is to resolve the above outstanding issues that hinder advances in magnetoseismology and the science enabled by it. The table below lists the specific goals in the normal-mode and travel-time focus areas to be achieved through international teamwork.

Focus Area	Normal-mode magnetoseismology	Travel-time magnetoseismology
Goals	• Determine quantitative criteria for identifying field line resonance frequencies as suggested by observations and model predictions • Characterize the local time and longitudinal extent of the normal-mode techniques due to the effects of the ionosphere and wave mode • Establish a unifying normal-mode magnetoseismology framework suitable for near-real-time operation • Validate plasma density estimation with spacecraft measurements	• Compare results of impulse propagation in the nightside magnetosphere based on different model frameworks (empirical with Tamao path, global MHD, and hybrid models) • Establish the relation between the nature of the sources and the resulting waveform • Compare model results with spacecraft and ground-based observations • Assess uncertainty in time and location of substorm initiation estimated by travel-time inversion

We should note that the two sets of goals are complementary and that the developments in one area are expected to benefit the other. For example, the modeling of MHD waves, with realistic outer and inner boundaries, is useful for understanding not only field line resonance at all local time sectors but also the resonance following impulses. The hybrid modeling for investigating impulse propagation in the magnetotail can also be used to understand ion gyroradius effect on field line resonances. The investigation in both areas by the same team can bring in unprecedented synergy.

3. Timeliness

This ISSI team collaboration comes at a critical juncture in magnetoseismological research. It provides a timely platform for the magnetoseismic element in the recently concluded PLASMON project to continue and expand its expertise together with other leading research teams in the world that have been working on the same subject. The operating Van Allen Probes have been delivering *in situ* measurements of electron density valuable for comparing with the mass density obtained through the normal-mode method. The MMS mission has just begun detailed observations of reconnection and other types of impulsive events in the nightside magnetosphere. **The recent progress in international collaboration in ground magnetometer and satellite observations, facilitated in part by the ULTIMA and SuperMAG consortia and the Heliophysics System Observatory (HSO), make the observations needed by this ISSI team available to achieve its goals.**

4. Expected output

Two major contributions by this ISSI team are (1) a unifying framework in estimating plasma mass density in the magnetosphere from field line resonance observations, and (2) a quantitative assessment on the travel-time inversion for estimating the time and location of substorm initiation in the magnetotail. These two contributions will permit future developments in magnetoseismology and provide fresh input to magnetospheric research and implications on applying similar techniques to other planets.

After our first team meeting, we will write a commentary for publication in a leading journal, highlighting the important issues in magnetoseismology to receive feedback from the community. Our team work in observations, modeling, and model-data comparisons in the two focus areas will lead to a number of new studies. Before the conclusion of this ISSI team in 2018, we plan to bring together these results as well as contributions from beyond the ISSI team for publication in a suitable monograph or in a special issue by a leading journal (e.g. Space Science Reviews). ISSI's support will be acknowledged on publications and presentations resulting from this teamwork.

5. Added value of ISSI

ISSI provides an ideal and necessary platform for coordinated in-depth discussions needed for setting up an international standard and for properly comparing different modeling and data analysis methods. It is unlikely that achieving the proposed goals would be possible without forming an international team via ISSI. In addition, team members are planning to develop future projects on global monitoring of the magnetosphere with magnetoseismology techniques during the ISSI teamwork. In the end, ISSI will play a critical role in catalyzing the growth of magnetoseismology as a science discipline.

6. List of Confirmed Team Members

Our team includes two groups of top experts to make this effort a success. The core team consists of 12 leading experts from five countries, and these members will attend team meetings at ISSI and have responsibilities in bringing together various aspects of the research. The additional experts may not attend all meetings in person but would attend meetings via teleconference or video conference.

Core Team: The team members and their primary roles in this ISSI team are described below. The team includes all the key personnel for the magnetoseismology part of the EU-PLASMON project (Jorgensen, Heilig, Vellante). More detailed descriptions of their expertise and achievements can be found in the appended CV's.

Peter Chi *UCLA, USA* Leader; Coordinator of travel-time magnetoseismology	Peter Damiano *Princeton Plasma Physics Lab, USA* Hybrid simulation of wave propagation	Balázs Heilig *Tihany Geophysical Observatory, Hungary* Ground observations of field line resonance	Anders Jorgensen *New Mexico Tech, USA* Plasmaspheric density modeling
Dong-Hun Lee *Kyung Hee University, Korea* ULF waves and impulse propagation modeling	Robert Lysak *University of Minnesota, USA* MHD model of wave propagation	Fred Menk *University of Newcastle, Australia* Co-Leader; Coordinator of normal-mode magnetoseismology	Jimmy Raeder *University of New Hampshire, USA* Global MHD magnetosphere modeling
Kazue Takahashi *JHU Applied Physics Lab, USA* Spacecraft observations of field line resonance and plasma density	Massimo Vellante *University of L'Aquila, Italy* Ground observations for normal-mode magnetoseismology	Colin Waters *University of Newcastle, Australia* Normal-mode magnetoseismology and MHD modeling	Eftyhia Zesta *NASA Goddard Space Flight Center, USA* Plasmapause detection with field line resonance observations

Additional Experts (roles): Athanasios Boudouridis (automated detection of field line resonance); Ian Mann (ULTIMA Chair, ULF waves); Yuki Obana (quarter-wave mode); Robert Rankin (field line resonance and auroral arcs).

7. Project Schedule (number and duration of meetings)

We plan to hold two one-week meetings at ISSI (Bern, Switzerland) over the course of ~18 months. The first meeting would be focused on identifying outstanding issues in field line resonance detection and in estimating plasma mass density, as well as on planning data and model comparisons for travel-time analysis. The second meeting would be focused on comparing results and finalizing the standard framework in performing magnetoseismology. In addition, we will hold scheduled teleconference and will leverage opportunities at large international conferences (e.g., EGU General Assembly and AGU Fall Meeting) to discuss the Team's progress.

8. Facilities Requested: We request nominal meeting facilities and internet access as described in Call for Proposals.

9. Financial Support Requested: We do not require financial support beyond what would be expected for most ISSI teams. We plan to nominate two young scientists who actively participate in magnetoseismological research to join the team once the proposal is selected.

SUPPLEMENTAL INFORMATION

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