Signatures of Magnetospheric Kelvin-Helmholtz Waves in Ground Magnetometer Data

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Abstract

Located at the edge of Earth's magnetosphere, the magnetopause is the boundary between low velocity plasma in the magnetosphere and high velocity plasma in the magnetosheath. Under certain flow shear conditions, vortices begin to form due to a type of flow instability called Kelvin-Helmholtz instability (KHI). As these vortices grow, they become unstable and break like waves on a beach. This process has been expected to excite periodic fluctuations in the Earth's magnetic field, with periods of 1-4 minutes. Observations of such waves at Earth's surface would be very useful in demonstrating the importance of the KHI in magnetospheric energy transport. We studied magnetic field data collected at the Earth's surface during periods where KH waves are known to be present in the magnetosphere. We found fluctuations in the magnetic field with the same period as the magnetospheric KH waves observed 1-7 minutes earlier, which is in agreement with prediction. Thus, we conclude that these waves observed on the surface of the Earth are a direct result of the KHI.

1 Introduction

The Earth is protected from the flow of plasma from the sun by its magnetic field. The field forms a protective cavity around the Earth, which is called the magnetosphere. However, there are certain mechanisms that allow solar wind to enter the magnetosphere. One proposed mechanism is a type of flow instability called Kelvin-Helmholtz instability (KHI). KHI causes vortices to form at the outer layer of the magnetosphere, which could inject solar wind into the magnetosphere. Additionally, the KHI has been expected to perturb the Earth's magnetic field and excite ultra-low frequeny (ULF) waves that propagate throughout the magnetosphere.

Observation of these ULFs at the Earth's surface would help to show that the KHI plays a role in energy transport throughout the magnetosphere. Previous studies have not been able to do this conclusively, in part because KH waves were thought to occur quite infrequently. However, [Kavosi and Raeder, 2015] showed that KH waves are present at the magnetopause nearly 20% of the time, regardless of solar wind conditions.

In this thesis, we will show that ULF waves excited by the KHI are observable by ground magnetometers (GMAGs) on the surface of the Earth. We will do this by first discussing magnetospheric structure in greater detail. Then, we will address the conditions required for KH waves to develop and grow. Third, we will describe the instruments required for this study, namely the network of GMAGs and NASA's THEMIS mission. Next, we will show that with a shift in time, KH waves observed *in situ* by THEMIS can be synchronized with ULFs observed by GMAGs. Finally, we will discuss the implications of our results and possibilities for future work.

1.1 The Magnetosphere[1]

Surrounding the Earth is a magnetic field formed by the flow of iron in the Earth's core. Fortunately for us, this magnetic field shields the Earth from the flow of plasma emitted by the Sun, known as the solar wind. Much like a boulder in a river, the Earth leaves a wake in the solar wind. Figure 1 shows the structure of this wake, called the magnetosphere.

The solar wind-magnetic field interaction is much more violent than the river-boulder interaction. Though greatly variable, the solar wind is typically travelling at about 400 km s^{-1} with a density of 5 cm^{-3} when 1 AU distant from the Sun. It carries with it the interplanetary magnetic field (IMF), which has a strength on the order of 10 nT. As the solar wind draws nearer the Earth, it is resisted by the Earth's magnetic field. Near Earth, the solar wind is supersonic and superaflvénic, meaning that the flow velocity itself exceeds the velocity of any pressure or transverse wave that could travel through it. Because of this, no pressure wave can travel upstream to divert the flow and a shock front forms before the solar wind reaches the Earth. This shock front, called the bow shock, lowers the flow velocity of solar wind but

[1] This section contains a conglomeration of material that can be found in any text on space plasma physics. For ease of reading, the sources used in writing this section will be noted here, as opposed to in the text: [Moldwin, 2008, Russell, 2007, Kivelson and Russell, 1995].

increases its temperature significantly.

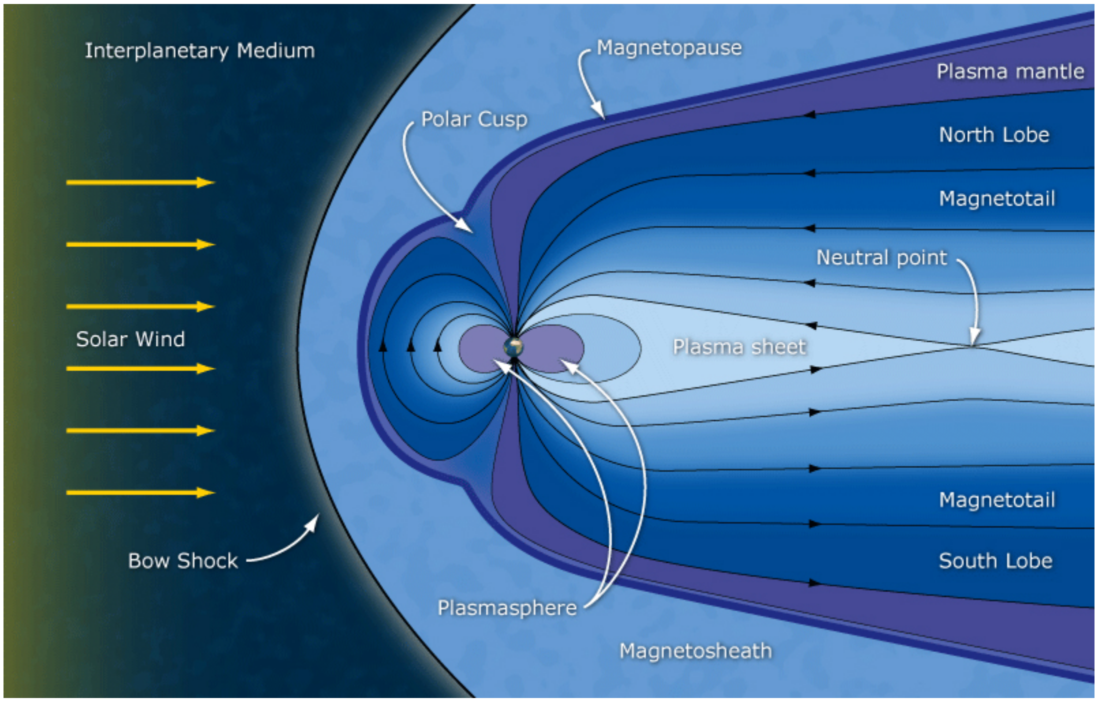

Figure 1: Diagram showing a cross-section of the Earth's magnetosphere. The Sun is at left, and the Earth's magnetic north pole is pointing upward. Image credit: [Russell and ESA, 2011]

The hot plasma that has passed through the bow shock is still moving quite quickly, especially when farther from the Earth-Sun line. This region of fast-moving plasma earthward of the bow shock is called the magnetosheath. Some of the magnetosheath plasma is diverted slightly by the bow shock and the strengthening magnetic field as it nears Earth. However, the majority of the plasma is still flowing directly earthward, and thus applies a pressure to the magnetosphere. Opposing the pressure of the incident plasma is the pressure from the Earth's magnetic field. When the plasma becomes close enough to Earth, the plasma pressure will be equal to the magnetic pressure, and the solar wind has little choice but to flow around the Earth. This equilibrium point is called the magnetopause, and is the outer boundary of the magnetosphere. We may calculate the distance from the Earth to the magnetosphere by setting the plasma and magnetic pressure equal to each other and solving for the distance to pressure equilibrium, R_{mp}, in Earth radii. Directly along the Earth-Sun line we find:

$$R_{mp} = 107.4(n_{sw}v_{sw}^2)^{-1/6} \tag{1}$$

where n_{sw} and v_{sw} are the number density and velocity of the solar wind, respectively. For the typical solar wind parameters given above, we find that nose of the magnetopause forms at about 11 Earth radii. Intuitively, the plasma pressure is lower along the flanks of the magnetosphere, and so the distance to pressure equilibrium increases, giving the magnetosphere its bullet-like shape.

The magnetopause itself has several regions that should be noted. At the poles, a cusp forms in the magnetopause because the direction of the magnetic field in this region applies less pressure to the incident solar wind. This cusp extends about 45° to either side of the noon meridian, and is populated mainly with turbulent magnetosheath plasma. Beginning southward, we encounter the high latitude boundary boundary layer, also called the plasma mantle. This region contains tailward flows that gradually decrease in temperature, velocity, and density with distance from the magnetosheath. Conversely, farther southward, there is the low latitude boundary layer (LLBL), which has layers of markedly different densities, velocities, and temperatures, all with very sharp boundaries. Plasma in this region is typically a mix of magnetosphere and magnetosheath plasma.

We now turn our discussion to the structure of the inner layers of the magnetosphere. Working from the inside layers out, we first examine plasmapause. This layer contains cold ($\sim$1 eV) and dense ($\sim 10^3$ cm^{-3}) plasma that reaches out 3-5 Earth radii, where it is bounded by the plasmapause. In essentially the same region, there are the radiation belts, which contain particles that can penetrate into dense materials and cause radiation damage. Moving farther from Earth in the antisunward direction, we examine the plasma sheet and magnetotail. The plasma sheet contains hot ($\sim$1 KeV) plasma that is less dense ($\sim$0.5 cm^{-3}) than in the plasmasphere. Though the plasma is quite hot, motion of particles is not oriented in one particular direction, and so the plasma sheet is quite stagnant relative to the Earth. Conversely, as we move through the plasma-sheet boundary layer and into the tail lobes, flow velocities increase to dominate thermal velocites. Here, densities are typically on the order of 0.1cm^{-3} or less, and flow velocities are on the order of hundreds of km s^{-1}.

At this point we should pause and ask ourselves a question: if the magnetopause is supposed to be the pressure equilibrium point through which no solar wind can pass, how did all this plasma get into the magnetosphere? Currently, magnetic reconnection is thought to be the primary mechanism for solar wind entry, especially when the IMF is pointing southward. In this process, magnetic field lines change their topologies, thereby injecting mass, momentum, and energy into the magnetosphere. However, when the IMF is pointing northward, magnetic reconnection is less efficient than for southward IMF, and other mechanisms may be more important.

1.2 Kelvin-Helmholtz Instability

One possible candidate for plasma injection that would fill the void left by magnetic reconnection is the Kelvin-Helmholtz instability (KHI). KHI is a type of flow instability that can occur in any fluid when two flows with different velocities move past each other at an interface. As a result, KHI is quite common in nature. Shown in Figure 2 are examples of KH waves in clouds on Earth and in the atmosphere of Jupiter.

(a) KH clouds

(b) KH waves in Jupiter's atmosphere

Figure 2: Examples in nature of fluid flow shear causing KH waves to develop. Image credit: [Martner, 2002, NASA and JPL,]

The onset of KHI is possible when the flow velocities on either side of the interface differ enough to overpower any stabilizing factors. In the case of many terrestrial fluids such as water, surface tension can stabilize the interface and suppress the development of KH waves [Chandrasekhar, 1961]. For a plasma, however, the interface can be stabilized by a magnetic field along the direction of flow [Chandrasekhar, 1961]. For an incompressible flow with an infinitesimal boundary, magnetohydrodynamic theory predicts that the condition that must be satisfied for KHI to form is [Chandrasekhar, 1961]:

$$[\vec{V}_1 \cdot \hat{k} - \vec{V}_2 \cdot \hat{k}]^2 > \frac{1}{4\pi}\frac{\rho_1 + \rho_2}{\rho_1 \rho_2}[(\vec{B}_1 \cdot \hat{k})^2 + (\vec{B}_2 \cdot \hat{k})^2] \tag{2}$$

In this inequality, $\vec{V}_{1,2}$ are the velocities, $\rho_{1,2}$ are the densities, $\vec{B}_{1,2}$ are the magnetic fields on either side of the interface, and $\hat{k}$ is the wave vector. However, if the boundary is not infinitesimal, KHI can sometimes arise even when this condition is not met [Gratton et al., 2004]. If the flows are such that KHI can develop, then small perturbations to the boundary between the two flows can grow to form waves, and later vortices. These vortices grow larger and eventually break like waves on a beach. This process can cause turbulence and mixing of the two layers of fluid.

In the case of the solar wind flow around the Earth, the magnetopause is an ideal place for KHI. Specifically, KHI has been expected to occur at the inner edge of the LLBL because of the significant velocity shear and sharp transition between the magnetosphere and the LLBL [Sonnerup, 1980]. Figure 3 depicts the formation of KH vortices at the magnetopause. A theoretical spacecraft, the path of which is shown as a white arrow, would observe distinct quasi-periodic fluctuations in pressure, as well as the component of velocity perpendicular to the magnetopause (i.e. the N-component in Figure 3).

Onset of the KHI was once thought to be infrequent, presumed to occur only during periods of high solar wind velocity. Using data from NASA's THEMIS mission (to which a section is later dedicated) [Kavosi and Raeder, 2015] showed that this was not the case, finding that KH waves are present at the magnetopause $\sim 20\%$ of the time, regardless of solar wind conditions.

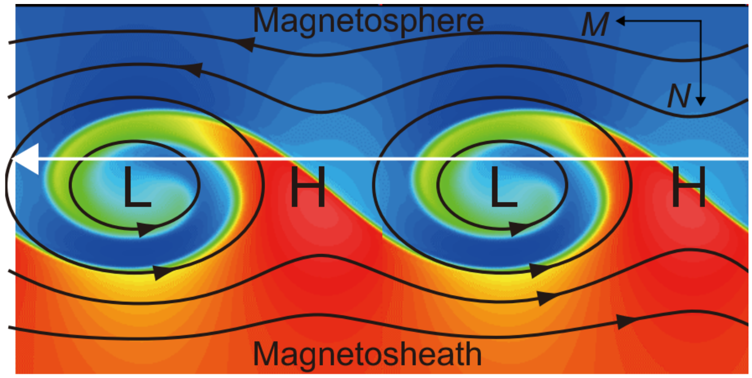

Figure 3: Depiction of a KH vortex, oriented such that the Sun would be at left and the Earth would be above. Red represents areas of high density plasma whereas blue represents areas that are less dense. Black arrows represent the direction of plasma flow, and the white arrow represents the path of a theoretical spacecraft through the KH vortices. The total pressure is minimized at the center of the vortex. Image credit: [Hasegawa, 2012]

Consequently, the KHI may prove to play a larger role in the dynamics of the magnetosphere than previously thought.

As addressed above, KH vortices could cause magnetosheath plasma to be injected and mixed with magnetospheric plasma. KH waves may also induce a certain kind of magnetic reconnection, called type I reconnection [Pu et al., 1990, Nakamura et al., 2011]. Like the reconnection discussed above, type I reconnection may accelerate plasma across the magnetopause, thus being responsible for some mass transport.

In addition to transport of plasma across the magnetopause, the KHI has been suggested as a magnetospheric energy transport mechanism. The KHI is known to create turbulence, which itself is a known transporter of energy. The instability may generate field aligned currents that may help to generate ionospheric phenomena, such as dayside aurora [Sonnerup and Siebert, 2003]. The KHI could also excite kinetic Alfvén (tranverse) waves that aid in the development of auroral arcs [Hasegawa, 1976].

[Atkinson and Watanabe, 1966] also suggested that the KHI may be a driver of magnetospheric ULFs. These ULFs could interact with electrons in the radiation belts, thus providing the energy needed for various space weather phenomena. However, it has been unclear whether these ULFs would be capable of propagating to the ionosphere. [Rae et al., 2005] found large amplitude ground magnetic field oscillations (∼100nT) on November 25, 2001 that they postulated to be associated with the KHI. They observed these oscillations to have periods on the order of 650 seconds. KH waves observed at the magnetopause typically have periods of 1-4 minutes[Hasegawa et al., 2006] however, so though the fluctuations observed by [Rae et al., 2005] may still be associated with the KHI, it could prove difficult to demonstrate.

1.3 Objective of this Study

Ground observations of ULFs with frequencies that match KH waves observed *in situ* would be easier to associate with the KHI. The detection of such waves would be very helpful in demonstrating the role of the KHI in magnetospheric energy transport, since it would indicate that KH waves are capable of travelling large distances throughout the magnetosphere. With this aim, we searched for common frequencies between KH waves observed *in situ* and waves in GMAG data observed a short time later. We have been able to correlate oscillations of the ion velocity observed *in situ* with oscillations of the magnetic field observed on the Earth between 1 and 7 minutes later.

2 Methods

To demonstrate the ability of KH waves to propagate to Earth, we compared the frequency of KH waves observed in the magnetospheric ion velocity with magnetic field waves observed by GMAGs. Naturally, a KH vortex at the magnetopause will contain plasma moving both parallel and perpendicular to the magnetopause, but observation of the perpendicular component can give more distinct results, as discussed earlier (See Figure 3). With this in mind, we use the GSM[2] y-component of the ion velocity as our *in situ* data. Any perturbations seen in y-component of the velocity should correspond to a perturbation in the H-component[3] of the magnetic field at Earth.

2.1 The THEMIS Mission

In situ data for this study was provided by the probes of NASA's THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission. Launched in February of 2007, THEMIS consists of five spacecraft lettered A through E (THA, THB, etc.). The probes were originally designed to designed to study the development of substorms, where energy stored in the magnetotail moves Earthward and intensifies the aurora. To this end, the probes have apogees varying from 12-30 Earth radii [Angelopoulos, 2008]. The semi-major axes of the orbits are fixed in space, but undergo a rotation relative to the Earth due to the motion of Earth around the Sun.

These orbits are ideal for studying the KHI because in the spring and autumn, they frequently cross the flanks of the magnetopause at the LLBL[Kavosi and Raeder, 2015]. Using THEMIS data, [Kavosi and Raeder, 2015] assembled a large database of KH events spanning from 2007-2013. Kavosi then selected a number of longer events with particularly well defined waves for

[2]The Geocentric Solar Magnetospheric coordinate system has its x-axis pointing from the Earth to the Sun. The y-axis is perpendicular to the Earth's magnetic dipole axis and points towards dusk. The z-axis completes a right handed orthogonal set, such that the the dipole axis is contained in the x-z plane.

[3]This is a component of the HDZ coordinate system used by GMAG stations. H is horizontal, and points towards magnetic north. Z points vertically downward. D points horizontally towards magnetic east, thus completing a right handed orthogonal set.

analysis. These are presented below in Table 1.

Date	Time Range (UTC)	Observing Probe
April 15, 2008	07:00-09:30	THC
April 19, 2008	04:00-06:00	THC
October 6, 2011	00:00-01:30	THA
February 10, 2012	15:30-18:00	THE
February 18, 2012	17:00-19:00	THA
March 15, 2013	14:30-16:00	THD/THE
March 15, 2013	17:30-19:30	THD
May 6, 2013	10:30-13:30	THA

Table 1: The KH events that were used in this study from the database assembled by [Kavosi and Raeder, 2015].

2.2 The GMAG Network

In addition to the spacecraft, there are a number of ground based observatories associated with the THEMIS mission. These are spread across the United States and Canada, and act in conjunction with other organizations across the globe to form a network of GMAGs. While this network does provide reasonably good coverage of many areas of Earth, there are many other areas where coverage is poor, and observation would not be possible. Time resolution for the stations ranges from 0.5s-60s. Since the periods of interest are 1-4 minutes, we limited our search to GMAGs with 1 second time resolution or better to give sharper results.

We then needed to determine which stations would be most likely to observe the KHWs. This meant taking the position data from the THEMIS probes and then tracing that position along the Earth's magnetic field lines to coordinates on the Earth's surface. This is a fairly common procedure, so there are a number of resources available to do this. In this study, the NASA software package 4DOrbitViewer[4] was used for field line tracing.

The main stations of interest are those that are as near as possible to the THEMIS footprint, since this is where the propagation of the KH waves should be focused, and the wave amplitude should be the greatest. For each KH event, we would typically study 5-10 GMAG stations, but this was dependent on the number of GMAGs in proximity to the THEMIS footprint. Further, some GMAGs had gaps or glitches in the data, which reduced the number of GMAGs available. In addition to the 5-10 GMAGs in close proximity to the THEMIS footprint we also examined stations at similar longitudes, but at lower latitudes to detect any possible latitude dependence. This was a secondary objective, however, so it will not be treated in detail.

[4] 4DOrbitViewer is available for download at `http://sscweb.gsfc.nasa.gov/tipsod/`

2.3 Data Processing and Analysis Techniques

Comparing the data observed by THEMIS with the data observed by GMAGs presents two main issues. First, both datasets contain fluctuations with frequencies that we are not particularly interested in. The ion velocity observed by THEMIS has many high frequency oscillations that casue the signal to be quite noisy. Conversely, the GMAG data has large-scale fluctuations over the course of the day that obscure the more subtle KH waves that we are searching for.

To address this, both datasets were band-pass filtered to focus on waves with 1-4 minute periods. The datasets were first smoothed using the boxcar smoothing algorithm from SPEDAS[5], THEMIS's dedicated data analysis package. This low-pass filtering algorithm replaces each datapoint with the average value of the surrounding datapoints. For example, using a smoothing window of 60 seconds would replace each data point with the average of the data from 30 seconds before to 30 seconds after the point of interest. After one round of smoothing with a 60 second smoothing window, the data was still a bit noisy, so the smoothing was repeated twice more with the same smoothing window. The data was then high-pass filtered using an algorithm that first computes a smoothed dataset, which is then subtracted from the orignal dataset to remove any low frequency fluctuations. The averaging window for the high-pass filter was 240 seconds, and was only applied once.

With both datasets having been cleaned, we sought to synchronize the datasets so that the waves in the THEMIS data are aligned with the waves in the GMAG data. The KH events that were used in this study were typically quite long, ranging from 90 to 180 minutes in length. In one sense, this was helpful, since there were many oppurtunities for good wave alignment. However, with a larger dataset, wave alignment would prove to be tedious. To combat this, a wavelet transform[6] was performed to highlight areas where the frequencies in both datasets were the same. Using the results of the wavelet transform as a starting point, we examined 20-40 minute sections of data to determine what sort of shift would be required to synchronize the data. Computer simulations have predicted that a perturbation originating at the magnetopause would take anywhere from 1-27 minutes to reach 3.6 Earth radii, and not significantly longer to be detectable on the Earth's surface [Dougal et al., 2013].

It should be noted at this point that we are not generating a prediction for the time shift needed to synchronize each event. The simulations in [Dougal et al., 2013] show that the magnetic field model used to predict travel time plays a large role in the predicted travel time. In most cases, the travel times computed for the two models used (OpenGGCM and BATS-R-US) differed by at least 100s. With this in mind, it not be very beneficial to make specific travel time predictions for each event because the travel time uncertainty would be much too large in comparison to the wave period. Therefore, we merely use the results from [Dougal et al., 2013]

[5]SPEDAS is available for download at: `http://themis.ssl.berkeley.edu/software.shtml`

[6]A wavelet transform is a signal processing technique used to break a signal down into its component frequencies, somewhat like a Fourier transform. However, it differs from a Fourier transform in that wavelet transforms are time dependent, and can thus show the evolution of the frequencies over time.

as a search window for possible wave alignment.

3 Findings

Beginning on the following page, we present plots from six KH events observed by THEMIS that show a frequency correlation with GMAG observations. We only present results for which we were able to match waves for at least three consecutive periods. This decision is fairly arbitrary, but seemed to be a reasonable number to show whether the waves remained in phase. Shown above each of these plots are the footprints of the spacecraft observing the KH event that were found using 4DOrbitViewer. We also present a wavelet transform from the February 18, 2012 event that shows the dependence of wave amplitude on magnetic latitude. Following the presentation of the plots, we draw conclusions from these results, and address possible reasons for not observing a KH signature in two of the events studied. Finally, we discuss opportunities for future work.

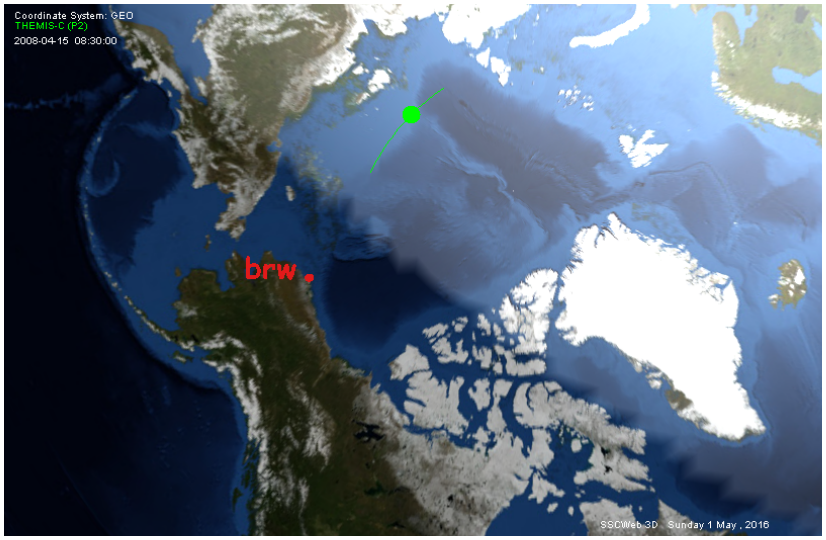

Figure 4: Footprint of THEMIS C (green) while observing KH waves on April 15, 2008.

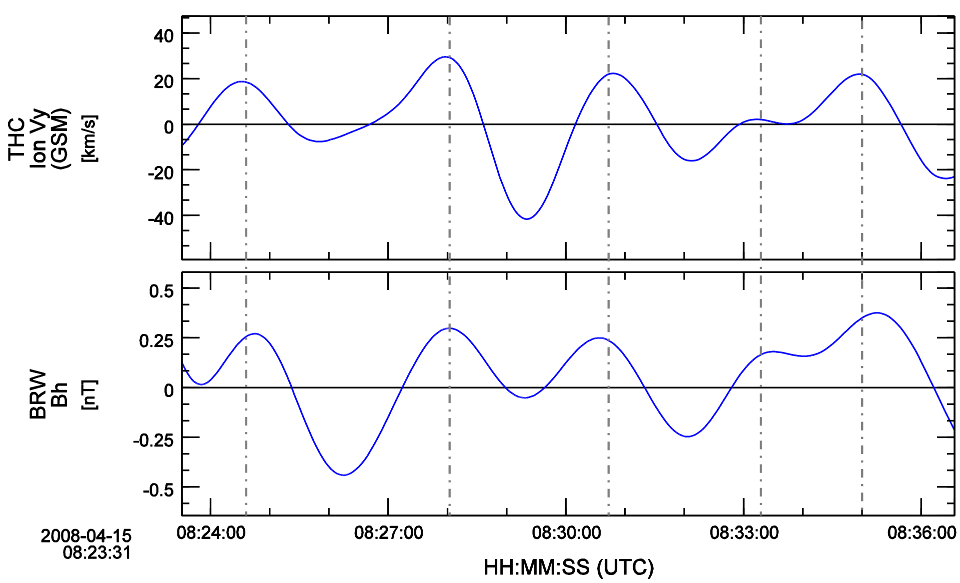

Figure 5: Band pass filtered THEMIS ion velocity (y-component in GSM) and GMAG magnetic field (H-component) data from April 15, 2008. The THEMIS data is shifted forward in time by 115 seconds.

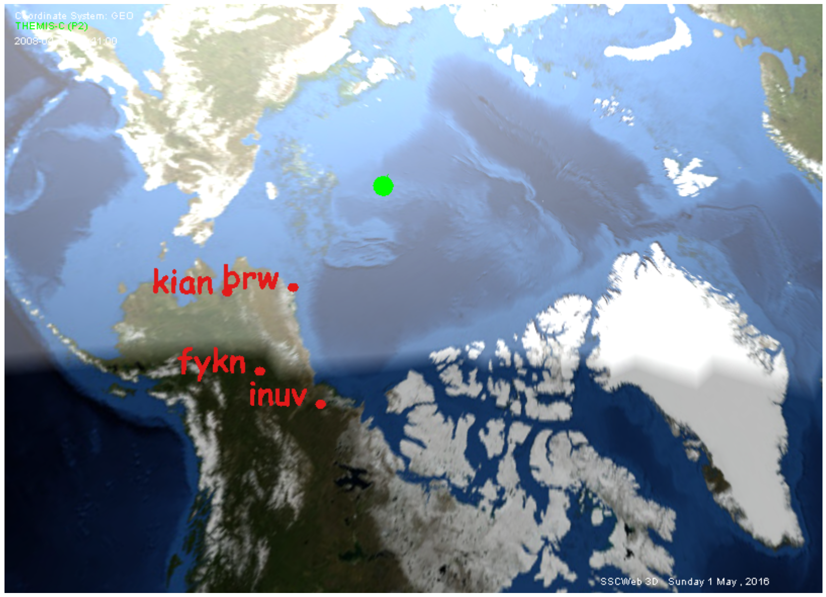

Figure 6: Footprint of THEMIS C (green) while observing KH waves on April 19, 2008.

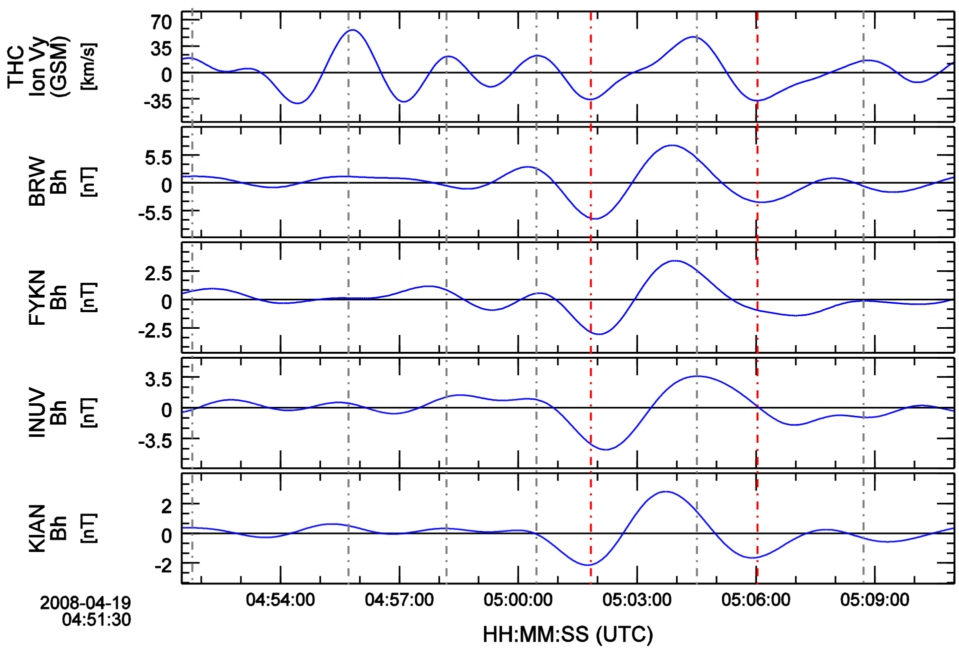

Figure 7: Band pass filtered THEMIS ion velocity (y-component in GSM) and GMAG magnetic field (H-component) data from April 19, 2008. The THEMIS data is shifted forward in time by 400 seconds. Dotted red lines indicate that though the wave peaks do not align, there is a frequency in both datasets that is in phase.

Figure 8: Footprint of THEMIS A (violet) and THEMIS D (cyan) while observing KH waves on February 18, 2012.

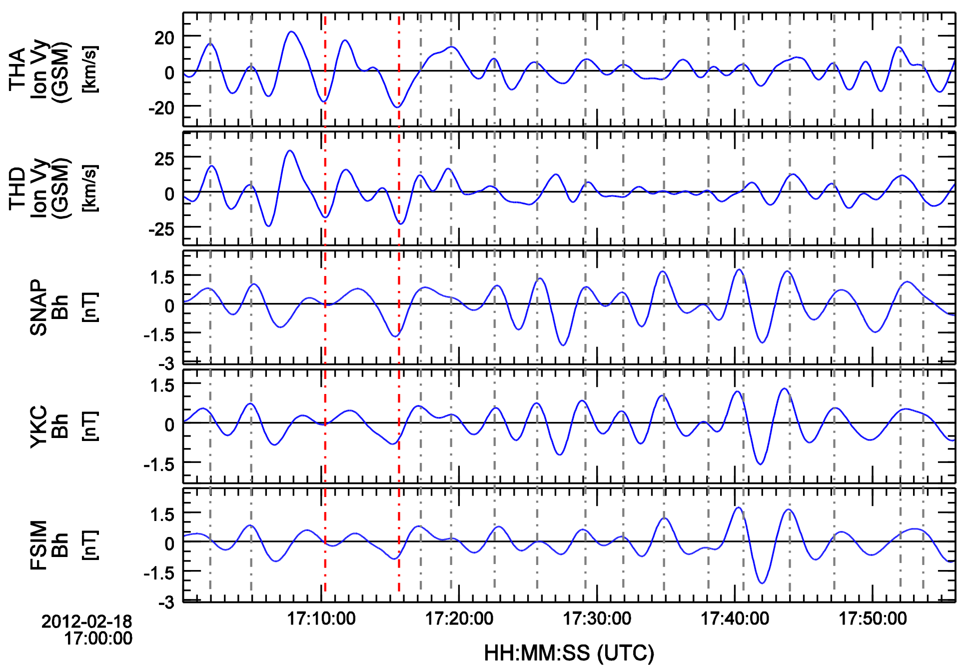

Figure 9: Band pass filtered THEMIS ion velocity (y-component in GSM) and GMAG magnetic field (H-component) data from February 18, 2012. The THEMIS data is shifted forward in time by 465 seconds. Dotted red lines indicate that though the wave peaks do not align, there is a frequency in both datasets that is in phase.

Figure 10: Footprint of THEMIS D (cyan) while observing the first KH event on March 15, 2013.

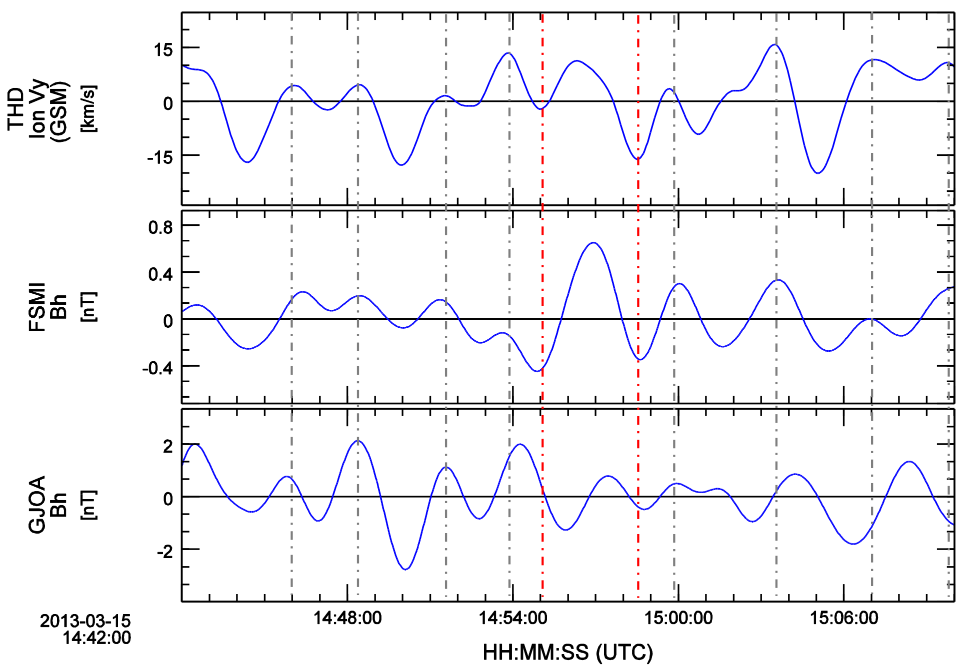

Figure 11: Band pass filtered THEMIS ion velocity (y-component in GSM) and GMAG magnetic field (H-component) data from the first March 15, 2013 KH event. The THEMIS data is shifted forward in time by 95 seconds. Dotted red lines indicate that though the wave peaks do not align, there is a frequency in both datasets that is in phase.

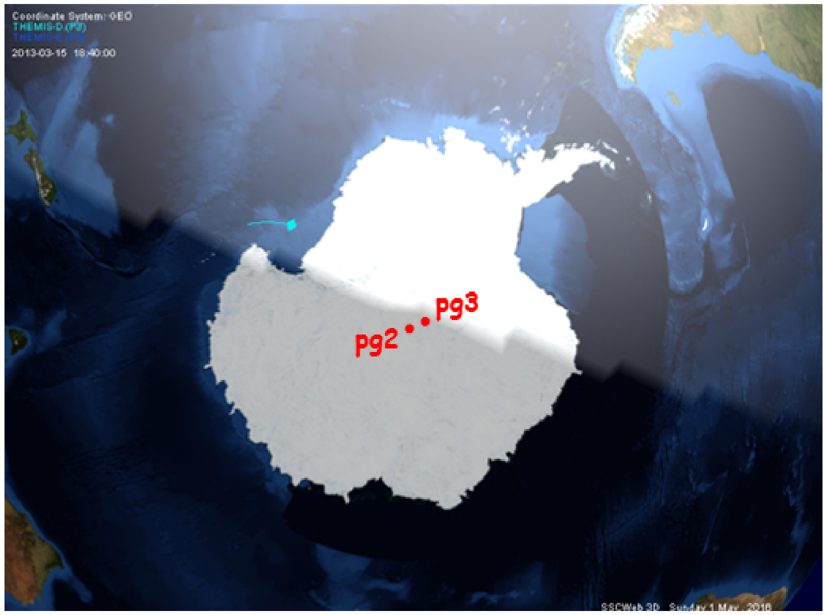

Figure 12: Footprint of THEMIS D (cyan) while observing the second KH event on March 15, 2013.

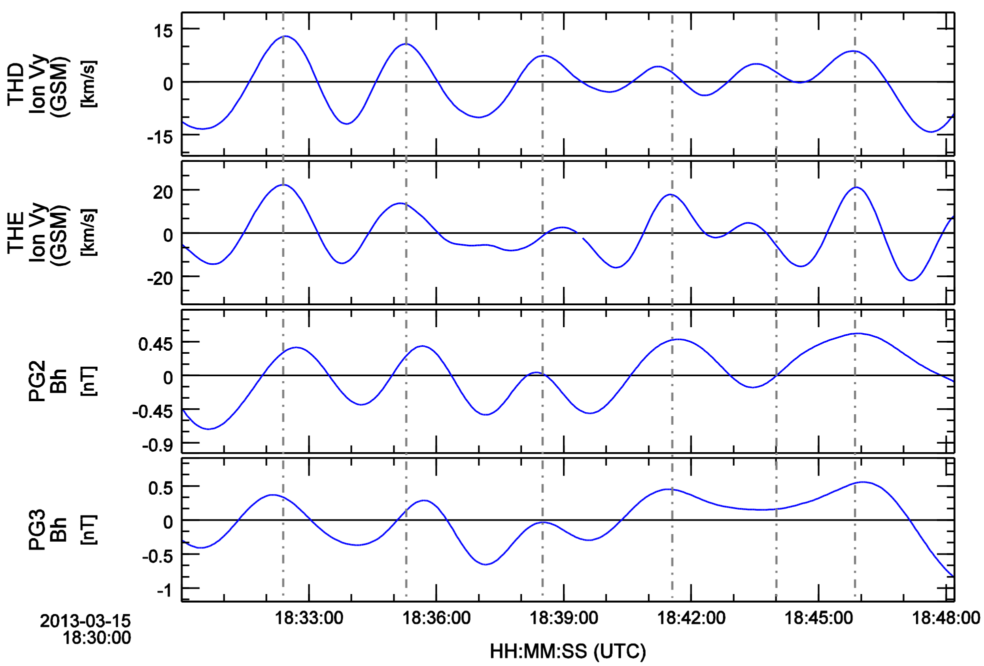

Figure 13: Band pass filtered THEMIS ion velocity (y-component in GSM) and GMAG magnetic field (H-component) data from the second March 15, 2013 KH event. The THEMIS data is shifted forward in time by 170 seconds for THD and 130 seconds for THE.

Figure 14: Footprint of THEMIS A (violet) while observing KH waves on May 6, 2013.

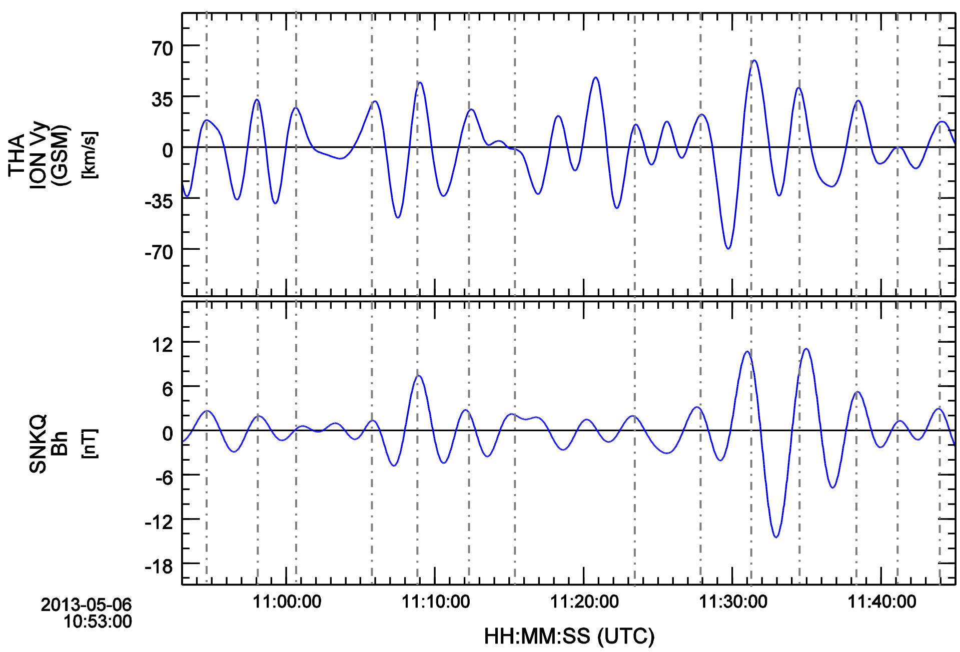

Figure 15: Band pass filtered THEMIS ion velocity (y-component in GSM) and GMAG magnetic field (H-component) data from May 6, 2013. The THEMIS data shifted forward in time by 140 seconds.

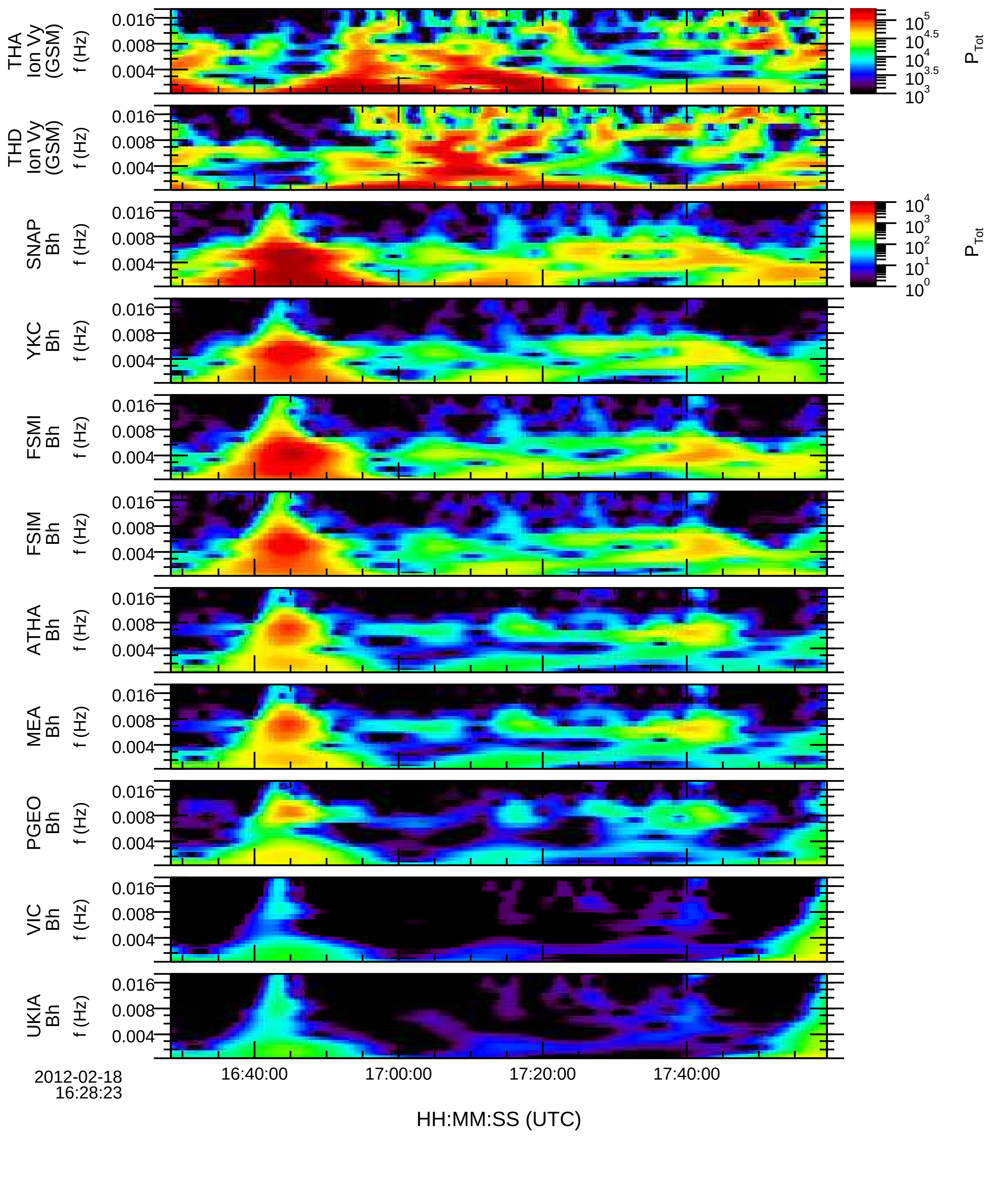

Figure 16: Wavelet transform of the THEMIS and GMAG data from February 18, 2012. Data from the THEMIS probes are on the same z-scale as each other and have been shifted forward in time by 465 seconds. GMAG stations are listed in order of decreasing magnetic latitude and have the same z-axis scale as each other. Higher latitude stations (i.e. those nearer the THEMIS footprint) have brighter hotspots, indicating larger amplitude in the frequencies of interest. Wavelet analysis of the other events yielded similar results.

3.1 Discussion and Open Issues

The data appears to support the hypothesis that KH waves are capable of propagation to the the Earth's surface. In six of the eight events that were studied, we were able to detect frequencies in the GMAG data that matched the frequencies observed by THEMIS. Further, the time lag needed to synchronize these two signals is well within the range that was predicted by [Dougal et al., 2013]. For this reason, we conclude that these waves observed on the Earth's surface are a result of the KHI.

However, we were unable to find any correspondance between the GMAG and THEMIS data for the remaining two events. There are several possible explanations for this, first of which is that there are still many holes in the GMAG network. Increasing the density of these GMAG stations would help to reduce the number of KH waves that are unobservable. In particular, there are vast regions of land across Russia and the southern hemisphere were there are no working GMAGs, or have GMAGs with insufficient time resolution to observe KH waves clearly. This would cause us to not observe a signature, even though the waves had reached ground level.

Another explanation for not observing waves for these two events is that they may be obscured by other magnetospheric phenomena. Waves of similar frequencies have many causes in the magnetosphere and on Earth, so if a larger amplitude wave with a similar, but slightly different period was observed, it would render the KH wave nearly undetectable. This is very likely the case for the two events that we were unable to synchronize. In these cases, after filtering, we had quite large amplitude waves in the GMAG data, but the waveform was perturbed, and was of a different frequency than the THEMIS waves. This is consistent with what a KH wave superposed on another sort of wave may look like. We attempted to filter out the interference that obscured the KH wave, but this proved to be ineffective, as it decreased the amplitude of both waves too drastically, and essentially destroyed the KH signature.

There are some cases in the data where the two signals go out of phase, only to align again a short time later. This could be easily explained by other magnetic perturbations caused in the magnetosphere or on the surface of the Earth that were out of phase with the THEMIS data. Alternatively, these phase modulations could be a consequence of filtering the higher frequencies out of the THEMIS data. When the data is filtered, the algorithm used (see the section titled Data Processing and Analysis) may slightly shift a wave's peak if there was a high amplitude spike on one side of the peak or the other. That is, when the data is averaged over the given interval, an especially large high frequency spike in the data would increase the value of the filtered data on one side of the true wave peak. In turn, this would appear to shift the peak of the wave in the filtered data towards the spike.

For the events where matching is possible, the amplitude of the waves observed by the GMAGs is typically on the order of 1 nT. The wave power tends to drop off with latitude, as is demonstrated in Figure 16. Despite this, we can still see in the wavelet transform that there is some power in the frequencies of interest at lower latitudes. With respect to this issue, we must still determine the true area over which these waves are observable. Observations by [Lui, 1989] and [Farrugia et al., 1994] and predictions by [Dougal et al., 2013] show that that vorticity at the ionosphere is typically several hundred km across, which gives a general idea of the scale of the effects of the KHI near Earth. However, for a variety of reasons, this does not necessarily mean that magnetic field perturbations will be detectable over the same area.

In addition to finding the area over which KH waves are visible, it is also important to determine what proportion of magnetospheric KH waves penetrate to ground level. The events analyzed here were chosen because they were particularly long and well defined, so that observation of a ground signature would be more probable. Accordingly, nearly all of the events provided quite well defined results. For smaller scale events that produce less intense waves, however, ground observation of a signature may be less probable.

Analysis of a larger sample of events could allow us to determine what propotion of the time KH waves reach the ground, and over what area they are visible. Answering both of these questions could help to indicate the degree to which KH waves facilitate energy transport. For example, if only the most intense KH waves are able to reach the ground (and thus the ionosphere), or are only observable over a relatively small area, then other mechanisms may be more important for these phenomena than the KHI. Should it be found that KH waves often do reach ground level, we would also need to uncover exactly what role they play in magnetospheric energy transport. Such a GMAG study may prove difficult however, due to the challenges in observing KH waves discussed above, namely GMAG scarcity and KH waves being convoluted with other magnetic fluctuations. Further, to complete such a study, we must decide on a fairly arbitrary number of wavelengths to align to consider the data to match. This decision could drastically affect the number of events that can be correlated.

4 Summary

In this thesis, we showed that KH waves originating at the magnetopause are capable of exciting magnetic field perturbations that are observable on the surface of the Earth. The perturbations observed were typically detectable at ground level between 1 and 7 minutes after being observed *in situ* by THEMIS, which is in agreement with the predictions made by [Dougal et al., 2013]. Despite what we have shown, there are still a number of open questions on this topic to be answed. First, over what area are KH waves observable? Secondly, what percentage of the time do they truly reach the ground? Thirdly, what role do KH waves actually play in energy transport? However, these questions may be difficult to answer given the current infrastructure. In the coming years, new spacecraft, additional GMAGs, and increasingly accurate magnetic field models may be able to better address these questions.

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