Violation of Hemispheric Symmetry in Integrated Poynting Flux via an Empirical Model

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Abstract

For southward interplanetary magnetic field (IMF) during local summer, the hemispherically integrated Poynting flux estimated by FAST-satellite-derived empirical models is significantly larger for the northern hemisphere (NH) than for the southern hemisphere (SH). In order to test whether the difference is statistically significant, the model uncertainties have been estimated by dividing the data sets for each hemisphere into two nonintersecting sets, and separately constructing the model using each of the four sets. The model uncertainty appears to be smaller than the estimated asymmetry. The asymmetry is mostly absent when the IMF is northward, except there is some evidence that it may actually reverse during local winter. The phenomena is coupled with what appears to be a more distinct two-cell convection pattern in the NH, and a possibly greater cusp contribution in the SH. All this suggests an effect of magnetosphere-ionosphere-thermosphere coupling, probably related to asymmetries in Earth’s geomagnetic field.
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Key Points:

• Empirical models of Poynting flux are separately constructed for the northern and southern hemispheres using satellite data
• During local summer under active conditions, the northern hemisphere supports \(~30\%\) more total Poynting flux
• The most likely cause is the asymmetry in the geomagnetic field, which provides \(~30\%\) more conductance in the northern hemisphere

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Abstract

For southward interplanetary magnetic field (IMF) during local summer, the hemispherically integrated Poynting flux estimated by FAST-satellite-derived empirical models is significantly larger for the northern hemisphere (NH) than for the southern hemisphere (SH). In order to test whether the difference is statistically significant, the model uncertainties have been estimated by dividing the data sets for each hemisphere into two non-intersecting sets, and separately constructing the model using each of the four sets. The model uncertainty appears to be smaller than the estimated asymmetry. The asymmetry is mostly absent when the IMF is northward, except there is some evidence that it may actually reverse during local winter. The phenomena is coupled with what appears to be a more distinct two-cell convection pattern in the NH, and a possibly greater cusp contribution in the SH. All this suggests an effect of magnetosphere-ionosphere-thermosphere coupling, probably related to asymmetries in Earth’s geomagnetic field.

Plain Language Summary

Energy enters Earth’s atmosphere in various forms, including sunlight, fast-moving particles, and also relatively low-frequency electric and magnetic fields. The later component is referred to as Poynting flux (PF), and is important to study because it produces density anomalies that can perturb satellite orbits in unexpected ways. PF is produced by a complex interaction of Earth’s geomagnetic field and particle-populations with the solar wind coming from the sun, and is thus quite difficult to model through first principles physics. Data-based models of PF, known as empirical models, can be used to produce a sort of ground-truth for development and testing of the physics-based models, which demonstrate our understanding of the phenomenon, and which will eventually be needed to develop a predictive capability. A particularly useful feature in this regard is the symmetry, or lack thereof, between Earth’s northern and southern hemispheres. The difference between the hemispheres is relatively subtle, and so successfully modeling the difference using first-principles physics would be a significant demonstration of understanding. In this work we provide an empirical assessment of the hemispheric symmetry of PF that can be used to provide such a discriminator.

1 Introduction

Empirical models of the incident Poynting flux, associated with auroral processes, have been separately constructed for the northern and southern hemispheres using data from the Fast Auroral SnapshoT (FAST) satellite [Carlson et al.(1998)]. The models are constructed by fitting a set of basis functions to the Poynting flux measured by the electric and magnetic field sensors on board FAST [Ergun et al.(2001); Elphic et al.(2001)], using 7301 orbits for the NH and 4953 orbits for the SH, where the basis function coefficients are expressed as quadratic equations in a chosen set of geophysical parameters. The modeling methodology was explained in detail by Cosgrove et al.(2014), and the data has recently undergone a process of quality control that has reduced somewhat the number of orbits deemed usable, with the benefit of providing additional confidence in the results presented here (which were noted earlier, but not published). The models output flux maps for the regions above 60° magnetic latitude (MLAT) and below −60° MLAT as a function of (1) clock angle of the interplanetary magnetic field (IMF), (2) magnitude of the IMF in the GSM y-z plane ($B_y$), (3) solar wind speed ($V_{sw}$), (4) solar wind number density ($N_{sw}$), (5) magnetic dipole tilt angle (Dip angle), and (6) the IMF GSM $B_x$ component. Here is presented an analysis of the hemispherically integrated Poynting flux, based on the empirical models, which finds that the NH supports significantly more Poynting flux during active conditions (∼30% more), under the mirror symmetries in Dip angle and $B_y$. The effects of IMF and Dip angle are presented, with $V_{sw}$, $B_y$, $N_{sw}$, and $B_x$ held constant ($V_{sw} = 450$ km/s, $B_y = 5$ nT, $N_{sw} = 4$ cm$^{-3}$, $B_x =$
0 nT), since the latter four parameters do not seem to affect the symmetry (i.e., when $B_x = 0$ [Stubbs et al.(2005)]).

To our knowledge this is the first article to find an overall asymmetry in the hemispherically integrated Poynting flux. However, there have recently appeared two articles that find asymmetries in regional Poynting flux related by magnetic conjugacy [Pakhotin et al.(2021); Knipp et al.(2021)]. The most comparable of these is the analysis by Knipp et al. (2021), which considers what is sometimes called “quasi-static Poynting flux,” that is, inclusive of all frequencies down to zero. This quantity represents the total incident Poynting flux. Knipp et al. (2021) use measurements from the Defense Meteorological Satellite Program (DMSP) to statistically compare localized conjugate regions (with > 50% coverage) in the northern and southern hemispheres, and find that the NH tends to have more Poynting flux.

In the present study based on FAST data, we extend this result to a statement about the total hemispherically integrated Poynting flux, and also add some statistical rigor. By fitting the data to a parameterized model we are able to compare the two hemispheres under equivalent IMF and seasonal conditions, whereas the other studies must rely on the sheer size of the data sets to limit the effects of the sampling bias associated with the satellite passing through the hemispheres under different conditions. This approach also allows for the finding that the asymmetry is mostly associated with southward IMF, and is stronger during local summer. To make the conclusions more rigorous, we consider independent subdivisions of the FAST data and use them to make an estimate of the likelihood that the determination of asymmetry may be false. We find only a 5% chance of false alarm.

The second article [Pakhotin et al.(2021)] analyzes what is know as Alfvenic Poynting flux using data from the SWARM satellites. Alfvenic Poynting flux refers to the Poynting flux in a certain category of observed events with wave-like signatures [e.g., Janhunen et al.(2005); Hartinger et al.(2015); Luhr et al.(2015); Hatch et al.(2017); Keiling et al.(2019); Keiling(2021)], which are sometimes referred as Alfven or Alfvenic waves, where the later terminology is meant to capture the distinction from the low-frequency Alfven waves that are involved in setting up the steady-state ionospheric conductance [e.g., Lysak and Dum(1983); Cosgrove(2016); Pakhotin et al.(2018); Pakhotin et al.(2020); Keiling(2021)]. Pakhotin et al. (2021) identify Alfvenic events in SWARM data and process the Poynting flux in three different ranges of spatial scale, as part of an argument that there is significant energy in the Alfvenic component (compare with Hartinger et al.(2015)). Then, making a statistical comparison of localized conjugate regions, Pakhotin et al. (2021) find that there is more Alfvenic Poynting flux in the NH.

In the present article we analyze the total Poynting flux, which includes the Alfvenic part as a component. The main reason to divide the Poynting flux into different frequency ranges is to sort it according to source regions and source types [e.g., Wing et al.(2010); Luhr et al.(2015)], which is beyond the scope of the Cosgrove et al.(2014) empirical model. It would seem that the total electromagnetic energy contribution is an appropriate subject for analysis, in addition to studies of the separate contributions.

There are also a few other kinds of north-south comparisons that are less directly related to the current study. Various authors have found an overall north-south asymmetry in the cross polar cap potential [Pettigrew et al.(2010); Förster and Haaland(2015)], or in the field aligned current (FAC) [Coxon et al.(2016); Workayehu et al.(2019); Shi et al.(2020)], or in the ion or convection velocities [Förster et al.(2007); Förster and Haaland(2015); Chosen and Förster(2016)]. Förster and Haaland(2015) also find an asymmetry in the appearance of the flow patterns. Also, some authors compare the summer and winter hemispheres [e.g., Papitashvili and Rich(2002)], or dark versus illuminated regions [Liou and Mitchell(2020)], or instantaneous conditions [Hong et al.(2021), a model-
based study]. Although less directly relevant, these kinds of studies provide complimentary information that may be useful in sorting out the causes of asymmetry.

We conclude the article with a simple argument for invoking differences in magnetosphere-ionosphere (MI) coupling as the source of the asymmetry, likely driven by the well-documented asymmetry in the geomagnetic field configuration. In particular, we note that the geomagnetic field asymmetry should lead to a roughly 30% larger conductance for the NH ionosphere, based on amplitude alone.

2 Results from Empirical Model

Using the empirical models for the northern and southern hemispheres, plots of the hemispherically integrated Poynting flux are presented in the top panel of Figure 1, as a function of the IMF clock angle, for three different Dip angles (shown in inset). Examining the panel, it is apparent that the NH supports significantly more Poynting flux during southward IMF and local summer (i.e., Dip angle of 27° in the NH, and −27° in the SH). For a Dip angle of ±27° (local summer) the maximum (over IMF) from the NH model is 30% more than the maximum from the SH model. However, for Dip angles of 0° and ±27° this percentage is decreased to 23% and 14%, respectively. The maxima in all cases is very near 180°, except for small offsets possibly associated with the GSM y-component of the IMF, which is opposite in the two hemispheres, in accordance with the geometrical mirror symmetry. When the clock angle is near 0° the Poynting flux asymmetry appears absent, except in the case of local winter, when the Poynting flux levels are much lower; it is possible that the asymmetry reverses during local winter and northward IMF.

Estimation of the parameters that define the models is subject to uncertainty associated with the finite size of the FAST data set. To bound the associated uncertainty in the integrated Poynting flux we divide the orbit-sets for each hemisphere into two non-intersecting sets, each half the size of the original set, by taking every other orbit from the time sequence or orbits. Hence, for each hemisphere we have the set of even orbits and the set of odd orbits, which have an essentially identical sampling of the epoch, but are non-intersecting. The modeling methodology is applied to these half-sized data sets to produce two new models for each hemisphere: the “even models” and the “odd models,” which do not share any data.

Using the same format as before, the results from the even and odd models are presented in the left hand column of Figure 1. Roughly, we can interpret the region between the even and odd model estimates as the confidence interval for the original model estimate (top panel of Figure 1). In the vicinity of southward IMF, for Dip angles of ±27° and 0°, the confidence intervals do not come close to overlapping, and for a Dip angle of ±27° there is still no overlap. Also, the confidence intervals do not overlap in the vicinity of northward IMF when the Dip angle is ±27° (local winter), although the Poynting flux levels are much lower. A detailed analysis is given in Section 4.

A potential pitfall in making a conclusion based on these results is the possible existence of a systematic bias. The only systematic bias that we have been able to imagine arises from FAST’s precessing elliptical orbit. Histograms of the orbit altitudes for the northern and southern data sets are shown in the top two panels of Figure 2. It is

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evident that the SH orbits are on average higher in altitude, and this is a likely source of systematic bias.

To investigate this potential bias divide the orbit-sets for each hemisphere into high and low altitude sets, where the altitude threshold is chosen to equally divide the number of orbits. The thresholds for the northern and SH are shown in the top two panels of Figure 2. As for the even and odd orbit sets, the modeling methodology is applied separately to these high and low altitude sets to produce two new models for each hemisphere. Using the same format as before, the results from the high and low altitude models are shown in right hand column of Figure 1. Although there are some deviations, it is evident that the models made from the high altitude orbits generally have higher peak values than the models made from the low altitude orbits. This is consistent with the idea that downward Poynting flux can be converted to other forms of energy, such as particle kinetic energy flux, in the auroral acceleration region [e.g., Richmond (2010)]. In conclusion, the bias associated with FAST’s precessing elliptical orbit is toward higher Poynting flux in the SH, which is opposite to the main observed effect, that is, the effect during southward IMF. However, the bias does place doubt on the evidence for the reversal of the effect during local winter and northward IMF, and so we do not make this conclusion.

3 Results from Orbit Averaging

As a “sanity check” for the model results presented in Section 2, Figure 3 shows simple orbit-averages of the Poynting flux data for the northern and southern hemispheres, without regard for the geophysical conditions. The data are averaged inside the cells of two 24 × 30 polar grids, one for the NH and one for the SH, and then a smoothing algorithm is applied for presentation. It is verified that the smoothing algorithm does not in any way corrupt the results.

The numbers in the top left corners of the panels of Figure 3 indicate the hemispherically integrated Poynting flux, which is 22% larger for the NH. Because the data is not sorted by the geophysical conditions, this slightly smaller asymmetry is consistent with the finding that the amount of asymmetry depends on the geophysical conditions, and that asymmetry is most severe under the most active conditions (southward IMF and local summer).

Figure 3 also suggests that the asymmetry arises from an asymmetry in the auroral electrojet contribution, whereas the cusp contribution is actually greater for the SH. (The same result can be gleaned from the empirical model.) It appears that the NH tends to have a more fully developed two-cell convection pattern, and somewhat less energy flowing in through the cusp. The findings of Knipp et al. (2021) tend to support these findings, although lacking full coverage of the SH cusp region.

4 Analysis of Statistical Significance

Assume that there is no difference between the northern and southern hemispheres (with respect to integrated Poynting flux under the Dip-angle and $B_y$ mirror symmetries), then the four Poynting flux peaks in the top-left panel of Figure 1, together with the two associated peaks in the upper panel, constitute six estimates of the expectation value for the Poynting flux peak. Each estimate can be regarded as a random number (sample) drawn from a probability distribution function (PDF), with standard deviation determined according to the square-root of the number of data points used to form the model, and with mean equal to the expectation value for the Poynting flux peak (assumed the same for north and south). From these six can be formed three statistically independent increment samples: (1) the difference between the peaks of the even and odd models for the NH (17.6 GW); (2) the difference between the peaks of the even and
odd models for the SH (27.0 GW); and (3) the difference between the peaks of the full models for the northern and southern hemispheres (54.3 GW).

Assuming Gaussian statistics, we will use a random number generator to determine the probability that the absolute value of the third increment (absolute increment) might have a ratio to the first equal to or greater than \( \frac{54.3}{17.0} \), while having a ratio to the second equal to or greater than \( \frac{54.3}{27.0} \), under the assumption that the underlying PDFs have the same mean (i.e., assumption of north-south symmetry). For some constant \( C \), the standard deviations for the three PDFs are \( \frac{C}{\sqrt{1001}} \), \( \frac{C}{\sqrt{4953}} \), and \( \frac{C}{\sqrt{1001+4953}} \), respectively; these choices reflect the number of FAST orbits used to derive the increment samples. Using the random number generator, 200,000,001 samples are generated for each of the three distributions, and then 100,000,000 independent absolute increments formed for each as

\[
|X_{1,1} - X_{1,2}|, |X_{1,3} - X_{1,4}|, \ldots, (|X_{2,1} - X_{2,2}|, |X_{2,3} - X_{2,4}|, \ldots), \text{ and } (|X_{3,1} - X_{3,2}|, |X_{3,3} - X_{3,4}|, \ldots)
\]

The bottom panel of Figure 2 shows a histogram of the statistic \( \tau = \frac{|X_{3,2n-1} - X_{3,2n}|}{\sqrt{|(|X_{1,2n-1} - X_{1,2n}| + |X_{2,2n-1} - X_{2,2n}|)|/2}} \) for \( n = 1, 2, \ldots, 100,000,000 \). The value calculated from the data (Figure 1) for this statistic is \( \tau = \frac{54.3}{27.0} = 2.4 \). As indicated in the bottom panel of Figure 2, only 9% of the randomly generated test statistics are equal to or greater than 2.4. Therefore, if we were to conclude north-south asymmetry based on the “detection” criteria \( \tau \geq 2.4 \), there would be a 9% chance of a false alarm.

A slightly more discriminating test is the percentage of samples with \( \tau_1 = \frac{|X_{3,2n-1} - X_{3,2n}|}{|X_{1,2n-1} - X_{1,2n}|} \geq \frac{54.3}{17.0} \) and \( \tau_2 = \frac{|X_{3,2n-1} - X_{3,2n}|}{|X_{2,2n-1} - X_{2,2n}|} \geq \frac{54.3}{27.0} \), which turns out to be only 5%. Therefore, if we were to conclude north-south asymmetry based on the detection criteria \( \tau_1 \geq \frac{54.3}{17.0} \) and \( \tau_2 \geq \frac{54.3}{27.0} \), there would be only a 5% chance of a false alarm.

5 Discussion and Conclusions

Comparing empirical models of Poynting flux for the northern and southern hemispheres gives evidence that for southward IMF during local summer, there is significantly more downward Poynting flux in the NH, specifically, 30% more (Figure 1, top panel). The asymmetry arises primarily as an asymmetry in the auroral electrojet contribution, whereas the cusp contribution may actually be greater for the SH. This can be seen either in the model-generated Poynting flux patterns or in the orbit-averaged patterns shown in Figure 3, and similar findings have been presented by other authors [e.g., Shi et al. (2020)]. The result suggests a difference in the nature or strength of the two cell convection pattern, for the northern and southern hemispheres. During equinox and local winter the asymmetry percentages decrease to 23% and 14%, respectively.

Putting the question “is there more downward Poynting flux in the NH?” into the framework of statistical detection theory, and assuming that Gaussian statistics apply to the model estimates, it is found that there is between a 5% and 9% chance of a false conclusion in the affirmative.

The PDF for Poynting flux “events” is far from Gaussian [Cosgrove et al. (2014)]. However, because model-fitting is essentially a process of averaging over many events, the central limit theorem should apply to the quantities assumed Gaussian in Section 4. The degree of convergence to Gaussian statistics remains as an unknown, and this is a weakness in the analysis of Section 4. Another weakness concerns the degree to which the Poynting flux is correlated from orbit to orbit, which affects the degree to which the even and odd orbit-sets are uncorrelated. However, the 7301 orbits (and the 4953 orbits) were selected from an original set of 20,000, which significantly reduces the number of back to back orbits. Neither weakness appears critical and so the computed false-alarm probability carries weight.
Although causes for asymmetry are not addressed in this work, it seems appropriate to relate some basic observations. Since the result has been derived using a data set collected over 4.5 years, a first step in analysis is to divide the system into components that possess memory over this time scale, which can be considered as the conditions that might cause the asymmetry. Any components that do not persist over most of the 4.5 years cannot be considered as possible causes. For example, the configuration of Earth’s geomagnetic field, and surface terrain with associated climate, are persistent conditions that seem the most likely cause of any hemispheric asymmetry. By contrast, if these conditions were to change abruptly, the magnetosphere and ionosphere would reconfigure within a time scale much less than 4.5 years, and probably less than an hour; there is no need to consider any long term memory in their configurations that could bias a data set collected over 4.5 years. Between these two extremes lies the sun and the solar wind it produces; it is less clear if these components possess any significant memory. However, since the model adjusts for the solar wind, it seems unlikely that the asymmetry results could be caused by any condition of the sun that favors Earth’s NH over its SH.

From these basic considerations, focus now on Earth as the cause of asymmetry. The Dip angle is defined in the NH, and because the geomagnetic field is not actually a dipole field, this means that the effective (negated) Dip angle in the SH is actually somewhat different. The difference is on the order of the angle between the magnetic dipole and the axis of rotation. However, this variation is small compared to the variation from winter to summer, and so this should only slightly degrade the modeling of the SH Dip angle dependence. Given that the simple orbit averages (Figure 3) also show the asymmetry, and are not subject to this effect, we deem it to be minor.

Another consideration is that there is more wobbling of the Dip angle in the SH, due to a greater angle between the magnetic dipole and the axis of rotation. However, the period of this wobbling is 24 hours, whereas the time scale for magnetosphere/ionosphere reconfiguration is thought quite fast, for example 10-20 minutes [Sneekvik et al. (2017)]. This reconfiguration time-scale is much shorter than the time scale for the wobbling, and so it does not seem that the wobbling should disrupt the ionospheric state. Hence, one would think that the wobbling effect would average out with respect to integrated Poynting flux, assuming the response is relatively linear with changes in Dip angle.

However, it is possible that the response is actually very non-linear, such that the wobbling effect does not average to zero. Pakhotin et al. (2021) have made an argument along these lines, and indicated the wobbling effect as a probable cause of the asymmetry they find. They argue that the wobbling affects the average ionospheric conductance, and thus leads to a different effect of MI-coupling in the two hemispheres. Greater conductance in the NH is also cited as a likely cause of the greater northern hemispheric Poynting flux found by Knipp et al. (2021).

However, Knipp et al. (2021) also mention the possible importance of the fact that the field-aligned current configurations appear to be different in the two hemispheres, citing studies by Coxon et al. (2016), Shi et al. (2020), and Sangha et al. (2020). These findings are consistent with our finding that the two-cell convection pattern is more distinct in the NH, as can be seen in Figure 3, and a similar finding has been made by Förster and Haaland (2015). Given that we have argued for focusing on Earth as the source of the asymmetry, this leads us to ask what property of Earth might have a different and less regular distribution over the SH than over the NH. And this leads us back to the geomagnetic field, except with a focus on its distribution over the hemispheres, instead of on the wobbling effect. These distribution effects have been analyzed by Gasda and Richmond (1998), who find some potentially important differences between the two hemispheres. Förster and Haaland (2015) have invoked differing geomagnetic field distributions to explain the hemispherical asymmetry they find, and provide maps of the geomagnetic field in their Figure 12.
Looking at Figure 12 from Förster and Haaland (2015) there are two apparent features: (1) The NH map is significantly more homogeneous over the polar cap and auroral region; and (2) the magnitude of the geomagnetic field is around 20% smaller in the NH over most of the polar cap and auroral region. Feature (1) seems a likely explanation for the different appearance of the two-cell patterns in the two hemispheres, and one would expect that differing patterns imply differing integrated effects. However, Feature (2) suggests a potentially more direct explanation for the asymmetry in integrated Poynting flux: a 20% decrease in the geomagnetic field magnitude implies, according to Richmond (1995), a 30% increase in the ionospheric conductance. We also note that the magnetic anomaly (deviation from a dipole field) is a near-field effect, which decrease with distance [Laundal et al. (2017)], and so should have much less of an affect on phenomena occurring at great distances, such as magnetic reconnection. Hence, the conductance effect seems likely to be important.

As is well known [e.g., Kelley (2009)], the ionospheric conductance is associated with the Pedersen conductivity, and the Pedersen conductivity is dominated by the ion term (it is an ion current). Hence, using the well know formulas [e.g., Kelley (2009)], the Pedersen conductivity can be written as,

\[ \sigma_P = \frac{en}{B} \frac{\rho_i}{1 + \rho_i^2}, \]

where \( \rho_i \) is the ratio of the ion-neutral collision frequency (\( \nu_{in} \)) to the ion gyro-frequency, \( e \) is the absolute value of the electron charge, \( n \) is the ion number density, and \( B \) is the geomagnetic field strength. The quantity \( \rho_i \) has a strong altitude dependence coming through \( \nu_{in} \), along with a dependence on \( B \). The ionospheric conductance is generally thought to be the field line integrated conductivity. Hence, to make a simple estimate for the geomagnetic field dependence of the ionospheric conductance, we evaluate the dependence of the conductivity at the altitude where the Pedersen mobility (\( \sigma_P/n \)) maximizes. This is the altitude where a given density of plasma makes the greatest contribution to conductance, and is sometimes called the “Pedersen peak.” To find the Pedersen peak we ignore the weak altitude dependence of \( B \) (as compared with that of \( \nu_{in} \)), differentiate \( \sigma_P \) with respect to \( \rho_i \), and set the result equal to zero. We find the well-known result that the mobility maximizes where \( \rho_i = 1 \). Inserting this result gives \( \sigma_P = \frac{en}{2B} \). Hence, we can expect the ionospheric conductance to vary roughly as the inverse of the geomagnetic field strength.

For comparison, Laundal et al. (2017) have analyzed the effects of north-south asymmetries in the geomagnetic field and refer to two, more-detailed studies of the geomagnetic field dependence of conductance. A study by Richmond (1995) finds a dependence of \( B^{-1.6} \), and a later study by Cnossen et al. (2011) finds a dependence of \( B^{-1.5} \). Hence, both studies find an even stronger dependence then results from the simple arguments of the previous paragraph. The Richmond (1995) result, for example, provides that a 20% smaller geomagnetic field produces a 30% larger conductance. The Laundal et al. (2017) paper also provides a map of the geomagnetic field asymmetry (their Figure 2) that supports the 20% difference that was inferred above from Figure 12 of Förster and Haaland (2015). Hence, based on magnetic field strength alone, the spatially-averaged conductance of the NH should be roughly 30% larger than that for the SH.

Therefore, while acknowledging that there exist other possibilities, we find two sources that seem especially likely for the asymmetry reported here: (1) the greater homogeneity of the geomagnetic field in the NH, which may produce a more pure two-cell convection pattern; and (2) the smaller geomagnetic field magnitude in the NH, which can be traced directly to a (roughly) 30% larger ionospheric conductance.
Figure 1. Plots of the integrated Poynting flux for the northern and southern hemispheres, as a function of the IMF clock angle. The upper panel shows results for the original model, for three different Dip angles. The remaining panels compare results for models separately constructed from two nonintersecting data sets, with the even/odd comparison shown in the left hand column, and the high-altitude/low-altitude comparison shown in the right hand column. The individual traces are identified in the insets, according to Dip angle and data-set. The downward progression runs from local summer, to equinox, to local winter.
Figure 2. Histograms used in the study: The top two panels show altitude histograms for the orbits used in model making, for the northern (top panel) and southern (middle panel) hemispheres. The bottom panel shows the histogram for the test statistic described in Section 4, assuming Gaussian statistics.
**Figure 3.** Orbit averages of Poynting flux for the northern (top) and southern (bottom) hemispheres, using all available orbits (after screening), without regard for geophysical conditions.
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The geophysical parameters (time shifted to the magnetopause in a way consistent
with \cite{Weimer2005}) are obtained from the OMNIWeb data set, available at https://omniweb.gsfc.nasa.gov/.
The FAST data is available at
http://sprg.ssl.berkeley.edu/fast/scienceprod/welcome.html

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