Polar rain as a diagnostic of recent rapid dayside merging

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Abstract. The occurrence of bright (>0.0016 ergs cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)) polar rain is found to be determined by interplanetary magnetic field (IMF) conditions. An automated search of 11 years of DMSP particle precipitation data (1984–1994) was used to identify polar rain. Comparison was made with 30-min segments of appropriately lagged 15-s IMP 8 magnetic field data. Bright polar rain away from the dayside merging line occurred almost exclusively under conditions favorable for rapid merging (\(B_z < 0\) or \(|B_y| > 2.5|B_x|\)). This implies that it occurs only on recently merged field lines and that during northward IMF open field lines have a distinctly different character, threading the magnetopause much further downtail than during southward IMF. The magnitude of this result was found to depend crucially on the distance from the Earth–Sun line of the IMF monitor, suggesting that unless the monitor is restricted to being within \(\sim 10 R_E\) of the Earth–Sun line, statistical correlations with IMF are likely to suffer contamination from roughly one in five events.

1. Introduction

Polar rain is a spatially homogenous precipitation of soft electrons that falls throughout the polar cap [Hardy et al., 1986]. Its origin is the suprathermal (halo) portion of solar wind electrons [Fairfield and Scudder, 1985; Wing et al., 1996]. It has previously been found to evince strong hemispherical asymmetry, with the northern (southern) hemisphere favored for an away (toward) interplanetary magnetic field (IMF) sector structure [Yeager and Frank, 1976; Gussenhoven et al., 1984] and a dawn–dusk gradient controlled by IMF \(B_y\) [Meng and Kroehl, 1977]. For these reasons it has long been regarded as an important but limited diagnostic of open–closed field lines: those with polar rain are surely open, but those without polar rain may nonetheless be open (for example, in the hemisphere not favored or because the solar wind halo component is weak). It is generally believed that polar rain is present for both northward and southward IMF, although Gussenhoven et al. [1984] did show that occurrence for southward IMF is about twice as likely (68% of events occurred for IMF \(B_z\) south). Winningham and Heikkila [1974] similarly commented on polar rain being stronger during magnetic storms than during quiet conditions.

We first argue on theoretical grounds that polar rain should be observed away from the dayside merging line exclusively when dayside merging is active. We then report an observational study using high time resolution IMF data to support this claim. Indeed, we conclude that polar rain is a much more reliable proof that dayside merging has recently been active than is an IMF monitor off the Earth–Sun line, although it remains a sufficient but not necessary diagnostic for reaching that conclusion.

This finding has many consequences for the magnetospheric configuration. For example, it implies that polar cap arcs, at least under conditions of continuously northward IMF, are probably not a result of field-aligned acceleration of polar rain, as is sometimes suggested (see Newell et al. [1997] for more details). It strongly supports the observational claim of Newell and Meng [1993a] that theta-aurora, or at least that subset embedded in polar rain, become isolated from the auroral oval after a southward IMF turning (but originally form under northward IMF conditions [cf. Valladares et al., 1994]). Finally, it observationally establishes that the configuration of open field lines greatly differs between northward and southward IMF conditions, with the former exiting the magnetopause much further downtail than the latter. This latter result also seems to support the idea that the electric field on open field lines in the ionosphere is at least partially decoupled from the solar wind electric field (as argued by Cowley and Lockwood [1992]).

Our result is strongest when the IMF is monitored within 10 \(R_E\) of the Earth–Sun line. This suggests that an error is built into statistical results that do not appropriately restrict the location of their solar wind monitor.

2. Polar Rain IMF Dependence: Theoretical Considerations

2.1. Background: Current Knowledge

The most recent dayside merging corresponds to field lines which thread the low-altitude cusp (or perhaps just equatorward of the cusp un open field line low-latitude boundary layer (LLBL)). Such field lines can be shown to have merged within the last few minutes by the presence of low-energy ion cutoffs [Lockwood et al., 1993; Newell and Meng, 1995b]. As the high-altitude portion of a newly open field line convects away from the merging site, the
precipitation becomes “mantle,” because ions lose energy as they cross the magnetopause current layer [Hill and Reiff, 1977] and because the magnetosheath plasma that is their source is cooling, expanding, and accelerating tailward [Spreiter et al., 1966]. (As the ion distribution cools and its bulk flow speed increases, the number of ions with an earthward velocity decreases). As the high altitude end convects further downstream, the flux of precipitating ions decreases to levels that are quite difficult to observe. As the flux of ions diminishes, the electron flux gives rise to a charge imbalance resulting in an electric field that retards electron entry. The core component of solar wind electrons (about 95% of the total) is excluded, and only the suprathermal portion (the halo) can reach the Earth (the strahl is part of the halo). This process can be modeled with quantitative success [Wing et al., 1996].

It is known that the polar rain has a noon–midnight gradient, with the density of polar rain electrons steadily declining from dayside to nightside in the ionosphere [Torbert et al., 1981; Gussenhoven et al., 1984]. The most likely explanation is that in moving in that direction across the ionosphere, one is encountering field lines that cross the magnetopause at increasing downtail distances and so are populated by decreasing densities of ions. The polar rain gradient then corresponds to a continuation of the ion gradient in the cusp–mantle transition, where field lines that have lower ion densities permit fewer electrons to enter. The gradient is such that by the time the nightside auroral oval is reached, polar rain at times can be below measurable thresholds [Torbert et al., 1981; Foster and Burrows, 1976].

2.2. A Prediction Based on Current Theoretical Developments

Section 2.1 discussed only the high-altitude end of the field line, which moves steadily downstream. Ideas about ionospheric convection have become more sophisticated recently. Siscoe and Huang [1983], Southwood [1987], and Cowley and Lockwood [1992] have all stressed a basic consideration, namely that for a newly merged field line to flow across the polar cap, it is necessary to have additional merging. If the closed field line just equatorward of a recently merged field line does not merge, then the open–closed boundary remains between them. The only way for a newly open field line to progress into the center of the polar cap is for more merging (ionospheric flow through the merging gap) to occur behind it.

Consider a given location, say the center of the polar cap. If the rate of dayside merging is high, the low-altitude end of a field line will have reached that point only a few minutes after merging. During these few minutes, the high-altitude portion of the field line cannot have gone so far downstream that the suprathermal solar wind electrons are not still able to reach the ionosphere. Thus, sector structure and halo density permitting, one can see a good polar rain signature.

Consider the same location, but when the merging rate is low. By the time enough subsequent merging occurs to push a newly merged field line into the center of the polar cap, the high-altitude portion will have convected far downstream. No polar rain is possible under such conditions. Therefore even field lines that are open for northward IMF will be in a much more stretched configuration, without polar rain.

The merging rate can, of course, vary continuously from very small to very large values, determining the rate at which polar rain intensity decreases as the polar cap is traversed, from the dayside merging gap to the nightside merging gap. This study makes a coarse separation between cases of expected slow and rapid merging according to the upstream IMF and then examines the correlation with observed occurrences of polar rain.

Note that if the ionospheric footprint were fully coupled to the solar wind electric field (contrary to our results and the reasoning of Cowley and Lockwood [1992]), the motion of an open field line across the polar cap would not depend upon subsequent merging. There would be no reason to expect that a field line in the center of the cap was more stretched for northward than for southward IMF.

3. Identification of Polar Rain and IMF Conditions

3.1. Intensity of Polar Rain

Polar rain energy fluxes commonly vary from $J_{PR} \approx 0.05$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ all the way down to instrument noise levels. (We define the energy flux of the polar rain $J_{PR}$ as the energy flux of precipitating electrons having energies from 32 eV up to 1 keV (channels 1 through 10); to include the higher-energy channels would make this measure less meaningful, since the energy flux at the one count level of the higher-energy channels can be comparable.) Polar rain-like precipitation with very low energy fluxes is classified as void. The difference between polar rain and void is somewhat arbitrary, and a more sensitive detector can certainly see polar rain-like precipitation at lower intensities than a less sensitive detector. In our case, polar rain-like precipitation begins to fail our smoothness criterion due to the small number of counts at $J_{PR} = 10^{8.8}$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. We choose the polar rain–void threshold a little below this at $J_{PR} = 10^{8.5}$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ ($= 0.0005$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$).

It is our contention that during strong dayside reconnection, the polar rain on a newly opened field line does not have a chance to substantially decrease in intensity before the field line reaches the center of the polar cap. Since the initial intensity of the polar rain varies due to the variability in the halo portion of the solar wind electron distribution function, we look for a wide range of intensities at the center of the cap, but not so weak that more intense polar rain could have decreased “substantially” to that value. There are small numbers of autodetected intervals of polar rain with energy fluxes as high as $10^{10.4}$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, but large numbers of intervals are not available until energy fluxes below $10^{9.5}$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ are considered. For this reason we search for bright polar rain (Plate 1), which we define to have energy fluxes above $J_{PR} = 10^{9.0}$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ ($= 0.0016$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$). We define weak polar rain (Plate 2) to have energy fluxes below this threshold.
Plate 1. An example of autodetected bright polar rain. The region marked contains ten 30-s intervals identified as bright polar rain having an average energy flux of $10^{6.4}$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. There is polar rain outside of the marked area as well, but the search is restricted to a region near the magnetic pole.

3.2. Automated Identification of Polar Rain

We identify polar rain by examination of the spectra of precipitating electrons and ions as observed by DMSP F6–F12 with the SSJ/4 detector [Hardy et al., 1984]. This detector measures the flux of electrons and ions in 19 energy channels ranging from 32 eV to 30 keV, from which a differential energy flux is computed. An example of polar rain is given in Plate 1. The top two panels give the total energy flux and the average energy of precipitating electrons and ions, and the bottom two panels are color spectrograms of their differential energy fluxes.

We use an automated routine to search DMSP particle spectra for occurrences of polar rain during the times from 1984 through 1994 for which there are IMP 8 solar wind observations. Much work has been done on the classification and identification of ionospheric precipitation [Newell et al., 1991, 1996]. Even so, the degree of confidence in such identifications varies. In this study, we sought a very high level of confidence in our identification and so were happy to exclude cases that were ambiguous or unusual.

Succinctly, the criteria used for identifying an occurrence of polar rain are that it be a smooth, relatively weak flux of sub-keV electrons accompanied by very little ion flux, that it fall within $10^\circ$ of the magnetic pole (but not more than $5^\circ$ sunward of it), and that it must be at least 2 min in duration. The restriction to being within $10^\circ$ of the magnetic pole reduces the chance of misidentification, since in this region polar rain and void predominate. It also reduces overcounting for conditions under which the interior of the oval is large and thus more likely to be overflown. We are searching for polar rain away from the dayside merging gap, so the search is restricted to being no more than $5^\circ$ sunward of the magnetic pole. The region to be searched is depicted in Figure 1; using a Cartesian rendering of altitude-adjusted corrected geomagnetic coordinates [Baker and Wing, 1989], x and y are defined:
Plate 2. An example of autodetected weak polar rain. The region marked contains five 30-s intervals identified as weak polar rain with an average energy flux of $10^{6.6}$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The region marked void has an average energy flux of $10^{4.4}$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

Figure 1. The automated search for polar rain is restricted to the region shown. The coordinates used are a Cartesian rendering of altitude-adjusted corrected geomagnetic coordinates.

$$x = \chi \cos(\text{MLT} - 12)$$

$$y = \chi \sin(\text{MLT} - 12)$$

and $\chi$ and MLT are corrected geomagnetic colatitude and magnetic local time. At their origin the $x$ and $y$ axes are roughly parallel to the $x_{SM}$ and $y_{SM}$ axes, respectively, and their units are degrees of magnetic latitude.

When IMP 8 is in the solar wind, sunward of the terminator plane ($x > 0$), and tracked, the segment of a DMSP orbit that is in the allowed region (see Figure 1) is divided into intervals consisting of 32 consecutive 1-s measurements. The data are smoothed by constructing 4-s averages. Each interval is then provisionally judged as to whether or not it is polar rain. If four such 32-s intervals are judged to be polar rain and at least three of them are bright polar rain and at least three of them are consecutive, then the DMSP pass in question has found a clear indication that bright polar rain is present.
The judgment as to whether a given 32-s interval is provisionally polar rain is made on the basis of several criteria. The electron spectrum must be smooth, the flux of ions must be low, and the flux of electrons above 1 keV must be low. (By restricting the polar rain to energies of 1 keV or less, we exclude any occasional occurrences of unusually energetic polar rain [Newell and Meng, 1990].) The judgment as to whether or not the spectrum is smooth is made using the correlation coefficient of the 4-s spectra with the average spectrum of the entire 32-s interval. The correlation coefficient must be above roughly 0.9 (this and other thresholds vary slightly from spacecraft to spacecraft). The energy flux of all ions is required to fall below approximately $10^{13.5} \text{ eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ and the energy flux summed over just channels 5 through 10 (0.2 keV to 1 keV) must be less about $10^{17.2} \text{ eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. The energy flux of all electrons is required to fall below approximately $10^{11.2} \text{ eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, and the energy flux summed over just channels 11 through 16 (2 keV to 10 keV) must be less about $10^{13} \text{ eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$.

This is a fairly extensive list of criteria. Most of the intervals satisfying the smoothness constraint pass the other tests as well, but one can imagine (and sometimes see) examples that require the additional criteria.

3.3. Characterizing the IMF Using 15-s IMP 8 Data

In this section we attempt to characterize the dayside merging rate according to solar wind conditions. Merging is expected to be strong when the average IMF is southward and weak when the average IMF is northward, but the average IMF can be northward and still contain a period of southward IMF and strong merging. Also, if IMF $B_z$ is much bigger than IMF $B_y$, then significant merging can occur even for northward IMF. We have tried to take these factors into account in classifying the IMF into three pairs of symmetric/weak/strong merging categories that are admittedly somewhat arbitrary. They are northward/southward, clearly northward/southward, and non-IMF $B_z$ dominated clearly northward/southward. These classifications are defined below.

We use 30 min of appropriately lagged IMF data to characterize the solar wind as belonging to up to three of the following categories: northward, southward, clearly northward, clearly southward, and/or IMF $B_z$ dominated. If the IMF is parallel to the Earth–Sun line ($B_z > 2.5 \sqrt{B_x^2 + B_y^2}$, using 30-min averages), then the case is thrown out since estimates of the lag are less reliable and there can be large fluctuations behind parallel shocks. To estimate the lag, we first extrapolate the measured magnetic field to the Earth–Sun line, following the component of the magnetic field that falls in the spacecraft–Earth–Sun plane, since features in the solar wind tend to be aligned with the field. If this extrapolation is predominantly cross field, then the extrapolation is made at constant $x_{GSM}$. Also, the extrapolation is limited to approaching the Earth–Sun line at no less than 45°, since small angles can introduce large errors. Once an equivalent position on the Earth–Sun line is estimated, the travel time to the bow shock ($x_{GSM} = 15 R_E$) is calculated using the average solar wind velocity as given by the National Space Science Data Center’s OMNI database or, if unavailable, $v_{SW} = 400 \text{ km/s}$. The lag (the amount of time that should pass before an effect is seen in the ionosphere) is then estimated to be the sum of the travel time to the bow shock, plus 5 min to traverse the sheath, plus 2 min to reach the ionosphere.

The 30-min interval of 15-s magnetic field data that ends at the beginning of the first polar rain interval, minus the lag, is used to characterize the IMF that precedes the observed polar rain. This characterization is based on $<B_y>$, the average IMF $B_z$ for the interval, its standard deviation $\sigma_{B_y}$, the total time of any data gaps $g$, the amount of time $t_g$ for which $B_y < 0.5 \text{ nT}$, the amount of time $t_f$ for which $B_z > -0.5 \text{ nT}$, and the amount of time $t_o$ for which $|B_y| > 2.5 |B_z|$. Any interval for which $g > 3 \text{ min}$ is thrown out. An interval is classified as northward if $<B_y> > 0$ and southward if $<B_y> < 0$. Furthermore, an interval is classified as clearly northward if $<B_z> - \sigma_{B_y} > 0.5 \text{ nT}$ and $g + t_f < 5 \text{ min}$. Likewise, an interval is classified as clearly southward if $<B_z> + \sigma_{B_y} < -0.5 \text{ nT}$ and $g + t_f < 5 \text{ min}$. If the magnitude of $B_z$ exceeds the magnitude of $B_y$, by a factor of more than 2.5 for more than 5 min ($t_o > 5 \text{ min}$), then the interval is said to be $B_z$ dominated.

A survey of IMP 8 solar wind data for the 11 years in question was made irrespective of any ionospheric input. Every 30-min interval (on the half hour) for which there were at least 25 min of data and for which IMP 8 was sunward of the dawn–dusk meridian was examined. There were 30,189 such intervals nearly evenly divided between northward (14,971) and southward (15,218), their difference being less than 1% of the total. For individual years, differences of about 10% were quite common. There were 6914 clearly northward and 7107 clearly southward intervals, with 5399 and 5157 remaining, respectively, after the $B_z$ dominated intervals were eliminated. If IMP 8 is restricted to be within 10 $R_E$ of the Earth–Sun line, then only 1824 of these intervals remain, 966 northward, 858 southward, 333 clearly northward, 413 clearly southward, 226 non-$B_z$ dominated clearly northward, and 341 non-$B_z$ dominated clearly southward. Ideally, the symmetric pairs would be divided evenly between north and south. The largest asymmetry is for the non-$B_z$ dominated clearly northward/southward category, for which the split is 40–60%. These 30-min intervals begin on the half hour, while the intervals associated with occurrences of solar rain do not, so there is no direct correspondence between the two. Nonetheless, this analysis estimates the sizes of possible spurious results. The results presented in the next section are larger than the corresponding asymmetries found here and hence are valid.

We have been somewhat cavalier in our classification of the IMF. The thresholds that we have set (5 min, 0.5 nT, and a factor of 2.5, in several places) are loosely based on current understanding of the reconnection process and on our experience with data. These definitions seem to work since our result gets monotonically stronger as our criteria get stricter (see “Results” section). We have not experimented with very many of the possible permutations of different values, but the small changes that we did try had little effect on our result.

4. Results

Using the above characterizations of solar wind IMF conditions and our procedure for identifying polar rain, the
correlation between the two was examined. An automated search was made for the 11 years from January 1984 to December 1994. If IMP 8 was located sunward of the dawn–dusk meridian ($z > 0$) and tracked, then a search for polar rain was made in the available DMSP data. If bright polar rain was found, then the appropriately lagged 30-min interval of 15-s magnetic field data was used to categorize the IMF. Instances of bright polar rain under the same IMF conditions were required to be separated by 2 hours to be counted. The results are presented in the first half of Table 1, according to the polarity of the average IMF $B_z$ ($\langle B_z \rangle$), the polarity of IMF $B_z$ when it is clear (Clearly N/S), and the polarity of IMF $B_y$ when it is clear and the large IMF $B_y$ cases have been excluded ($|B_y| < 2.5|B_z|$). Bright polar rain was found to occur 65% of the time for southward average IMF. This compares to 68% from Gussenhoven et al. [1984] for 1 year of data in 1977–1978. One might expect to get a higher percentage using 30 min of appropriately lagged data rather than hourly averages, but one might also expect to get a lower percentage when the search is confined to the center of the polar cap since this reduces a systematic bias toward finding polar rain when the oval is larger during southward IMF $B_z$. Also, we frequently found 10% northward/southward asymmetries in the IMF when only 1 year was examined. Comparing clearly northward to clearly southward, we find that bright polar rain occurred 73% of the time for clearly southward IMF and 78% of the time when $B_y$ dominant cases were excluded.

Another effect to consider is the quality of a solar wind monitor that may lie as far as $40 R_E$ from the Earth–Sun line. We selected events according to IMP 8’s distance from the Earth–Sun line and found that for $\rho = \sqrt{x^2 + y^2} < 10 R_E$, the correlation of bright polar rain with southward IMF $B_z$ was much improved (see the bottom half of Table 1). In fact, there was only one occurrence of bright polar rain for non-$B_z$ dominant clearly northward IMF $B_y$ (at $\rho = 8 R_E$); it was borderline $B_z$ dominant and it was during a time of unusually high solar wind density ($n = 39$ cm$^{-3}$). Our crude characterization of the dayside reconnection rate are functions of only the IMF direction and neither $n$ nor $B_y$; if our characterization of the reconnection rate were to take these additional variables into account, this occurrence would probably not remain in the weak reconnection category. The correlation of bright polar rain with southward IMF $B_y$ was found to deteriorate immediately when the monitor exceeded $12 R_E$ from Earth–Sun line. The strong dependence of our result on the position of IMF 8 suggests that there is an error built into statistical results (roughly one in five events) that do not necessarily restrict the location of their solar wind monitor. This conclusion holds for a monitor at IMP 8 distances and probably should not be applied to monitors further upstream except possibly as a lower limit.

When the solar wind monitor is within $10 R_E$ of the Earth–Sun line and IMF $B_z$ is not dominant, we find that bright polar rain occurs 95% of the time for clearly southward IMF relative to clearly northward IMF. These are conditions of rapid and slow dayside merging, respectively. This supports the contention that bright polar rain occurs only on recently merged field lines that thread the magnetopause much closer to Earth than the open field lines which predominate during times of slow reconnection and hence have little or no polar rain on them.

A striking feature of Table 1 is that, as the admittedly crude characterizations of the dayside reconnection rate are improved, our result becomes stronger. Ideally, a high-resolution time series of IMF, $v_{SW}$, and $n$, measured on the Earth–Sun line, would be used with a formula for the reconnection rate that is known to be accurate. These ideal conditions have not yet been achieved, but we do observe that our result becomes stronger as they are approached. This limiting behavior is a good indication that bright polar rain occurs only on recently merged field lines, even though we have only explicitly demonstrated that this holds 95% of the time. We conclude that observation of bright polar rain is a more reliable indication that dayside merging has recently been active than is a solar wind monitor off the Earth–Sun line, although it is a sufficient but not necessary diagnostic for reaching that conclusion. Indeed, since our interpretation is that bright polar rain is a direct result of rapid dayside merging, it may even be more reliable than a monitor on the Earth–Sun line since propagation of solar wind conditions to the magnetopause invokes simplifying assumptions.

We have been studying only the clearest IMF conditions, not necessarily the most common. Under the same conditions used to generate Table 1, bright polar rain was found to be associated with intervals containing at least 5 min of southward IMF in 626 instances (16 with IMP 8 within $10 R_E$ of the Earth–Sun line). These large numbers (compare with Table 1) are no surprise since 2/3 of the 30-min solar wind intervals that were surveyed independent of the presence of polar rain contained at least

| Table 1. Frequency of Bright Polar Rain for Various IMF Conditions and Monitor Positions |
|---------------------------------|--------|--------|----------------|
| IMF 8 position     | $\langle B_z \rangle$ | Clearly N/S | $|B_y| < 2.5|B_z|$ |
| Number south       | 536    | 314    | 225            |
| Percentage south   | 285    | 116    | 65             |
| Number north       | 65%    | 73%    | 78%            |
| Percentage south   | 31     | 20     | 18             |
| Number north       | 10     | 6      | 1              |
| Percentage south   | 76%    | 77%    | 95%            |
5 min of southward IMF (2/3 also contained at least 5 min of northward IMF).

5. Conclusion

The relationship between the presence of polar rain in the polar cap and the IMF conditions preceding its observation was studied. It was found that bright polar rain occurs almost exclusively during times of rapid dayside merging. This implies that open field lines have a distinctly different character for northward IMF, threading the magnetopause much farther downtail than during southward IMF. It also suggests the idea that open field lines can be partially decoupled from the solar wind electric field. Finally, the dependence of our result on the distance between the solar wind monitor and the Earth–Sun line suggests that when the IMF is monitored more than ~10 RE from the Earth–Sun line, there is an approximately one in five chance of seeing a significantly different field than is impinging on the Earth’s magnetosphere.

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