Why are relativistic electrons persistently quiet at geosynchronous orbit in 2009?

Ryuho Kataoka[1] and Yoshizumi Miyoshi[2]

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[1] Relativistic electrons at geosynchronous orbit (GEO) were persistently quiet in 2009 for almost a whole year. The solar wind speed, which has been known as a primary parameter controlling the outer belt electrons, was very slow in 2009 as expected and at a comparably low level as of 1997 when we did not observe such a persistently quiet condition. Since the interplanetary magnetic field (IMF) was quite different between 1997 and 2009, the difference in IMF is a possible cause of the difference in the electron flux levels, providing an important clue to understand the complex source and loss process of relativistic electrons at GEO. We suggest that the extremely weak IMF of the very slow solar wind plays an essential role in diminishing the source processes themselves associated with magnetic storms and substorms, and in turn to suppress the relativistic electron flux at GEO over the time scale of a year, as an inevitable consequence of extremely weak open magnetic field of the Sun associated with the extremely weak current solar minimum.

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1. Introduction

[2] Understanding the fundamental mechanisms controlling the trapped energetic electrons in the Earth's radiation belts has been a key topic in space weather research, since the large flux enhancement can damage satellite services in modern life [*Lanzerotti*, 2001]. The large flux enhancement of relativistic electrons at geosynchronous orbit (GEO), typically corresponding to the outer part of the outer radiation belt, has been therefore investigated in detail based on solar, solar wind, and geomagnetic observations in a few decades and it is now even possible to operate the space weather probabilistic forecast of the large flux enhancement a week in advance [*Kataoka and Miyoshi*, 2006; *Miyoshi and Kataoka*, 2008b]. In 2009, even though we observed very slow solar wind, we expected some minor flux enhancements of relativistic electrons at GEO, according to the forecast scheme considering the seasons and the sector polarity of interplanetary magnetic field (IMF), i.e., the Russell-McPherron effect [*Russell and McPherron*, 1973]. The relativistic electrons at GEO in 2009, however, was persistently quiet for the time interval of about a whole year, motivating us to investigate the cause(s) in detail to achieve more reliable forecasting of extreme and/or unexpected radiation belt conditions.

[1]Interactive Research Center of Science, Tokyo Institute of Technology, Tokyo, Japan.

[2]Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Japan.

[3] The current solar minimum is unusual, as readily recognized by the record number of zero sunspot days. The solar magnetograph observations indicated that the polar field strength of the current solar minimum is ~40% weaker than that of the previous two minima [*Wang et al.*, 2009]. Also, polar coronal holes appeared smaller in the current solar minimum relative to the previous solar minimum [*Kirk et al.*, 2009]. More recently, some research teams involved with the Ulysses mission reported the lowest solar wind density ever observed [*McComas et al.*, 2008; *Issautier et al.*, 2008]. In addition, the IMF strength was found to be lower than in the previous solar minimum [*Smith and Balogh*, 2008]. As a consequence of the weak solar magnetic activities, extreme flux enhancements are observed in cosmic rays in space [*Heber et al.*, 2009] and at ground (http://cosmicrays.oulu.fi/).

[4] Almost identical data sets of solar, solar wind, GEO, and geomagnetic activity indices are now continuously available for both the current and previous solar minima for the first time. In this paper we examine why the activity of relativistic electrons at GEO in 2009 was persistently quiet, by comparing the occurrence probability of solar wind parameters and geomagnetic activity indices between 1997 and 2009. The main reason why we compare these two years is that the persistently quiet condition did occur in 2009 and did not occur in 1997 under similar conditions of very low solar wind speed. The solar wind speed has been known as the primary controlling parameter of relativistic electron flux at GEO [e.g., *Paulikas and Blake*, 1979; *Li et al.*, 2006]. It is found that the IMF strength

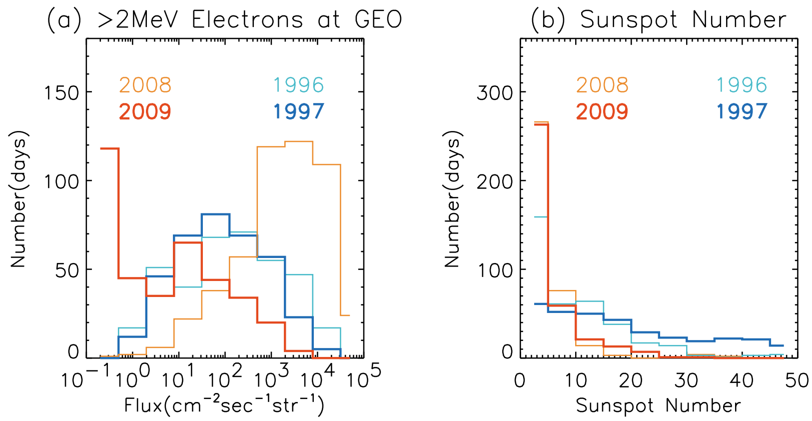

Figure 1. The occurrence distributions of (a) the daily averaged GOES > 2 MeV electron flux at 10–14 MLT, and (b) sunspot number during the years of current and previous solar minima.

is quite different between these two years, and we discuss the possibility of an important role of IMF in the persistently quiet condition of relativistic electrons at GEO.

2. Results

[5] First of all, we show the persistently quiet condition in 2009 in Figure 1a by the occurrence distributions of relativistic electron flux. The histogram is constructed from the daily averaged GOES > 2 MeV electron flux at 10–14 MLT, where the data contaminated from energetic protons are removed from the onboard proton sensor. The years 1996, 1997, 2008, and 2009 around the current and previous solar minima are selected for the histogram analysis for comparison. As shown in Figure 1b, the occurrence distributions of the sunspot number in 2008 and 2009 are very different from in 1996 and 1997. The numbers of spotless days are 159, 61, 266, and 263 in 1996, 1997, 2008 and 2009, respectively. Interestingly, the occurrence distributions of electron flux in 2008 are very different from in 2009, in contrast to the very similar occurrence distributions of sunspot number. The following analyses resolve the mechanisms hidden behind the relationship between Figures 1a and 1b.

[6] Second, we show the time series to see how the solar and solar wind conditions are unusual in 2009. Figures 2a and 2b show the Sun's polar magnetic field and sunspot number, respectively. The average polar magnetic field data is obtained from the Website of Wilcox Solar Observatory (http://wso.stanford.edu/Polar.html) [*Hoeksema*, 1995; *Svalgaard et al.*, 1978]. Thick and thin lines are from north and south poles of the Sun, respectively. It is apparent from Figure 2a that the polar magnetic field strength remained in the range 0.8–1.5 G during previous solar minima, but fell to only ~0.5 G during the current solar minimum.

[7] Figures 2c, 2d, and 2e show the IMF strength, solar wind density, and solar wind speed, respectively, as obtained from 27 day averaged OMNI-2 database. From the visual inspection, it is apparent that the IMF strength (Figure 2c) is the best correlated parameter with the sunspot solar cycles (Figure 2b), while other parameters are not simply correlated with sunspots and show relatively complex variability. The IMF strength remained in the range of 5–7 nT during previous solar minima, but fell to only ~4 nT during the current solar minimum, which is a consistent variation based on the theoretical estimation from the Sun's open magnetic field [*Wang et al.*, 2009]. It is also found that both the IMF strength and solar wind speed in 2009 reach at the lowest level ever observed. The annual average of the solar wind speed in 2009 is 363 km/s, showing ~5% decrease compared with the average speed of 379 km/s in 1997. The solar wind density dropped off at the lowest level in 2008, although similar decreases occurred not only in the solar minimum but also in the solar declining phases, e.g., in 1994 and 2003.

[8] Figure 2f shows the GOES observations of monthly averaged >2 MeV electron flux at GEO. Multiple GOES satellite data are compiled, limiting the satellites' geographic longitude of 75W (thick line) and 135W (thin line) degrees for the last 15 year when the data at both longitudes are mostly available. The electron flux at GEO at 135W is typically higher than the simultaneous flux at 75W due to the difference in geomagnetic latitudes. A good correlation between the relativistic electron flux at GEO and solar wind speed is found over solar cycles. It is found that the electron flux at GEO in 2009 has been mostly less than 20 cm^{-2} sec^{-1} str^{-1} and never increased to a higher level for a whole year. The persistently quiet condition is remarkable, for example, inconsistent with the typical behavior that can be seen during magnetic storms: the electron flux transiently drops at the beginning of the main phase and usually starts to recover during the recovery phase [e.g., *Reeves et al.*, 2003; *Miyoshi and Kataoka*, 2005]. *Li et al.* [2001] and *Miyoshi et al.* [2004] reported that the outer belt nearly disappeared around summer solstice of 1996. The disappearing event in 1996 can also be seen in Figure 2f, and similar disappearing events were found

triple times around January, June, and September/October in 2009. The quiet condition in 2009 is therefore different from the 1996 event particularly in terms of the persistency. It is important to note here that there was no disappearing event in 1997 when the solar wind speed was significantly lower than in 1996. It is therefore difficult to explain the mechanisms by the solar wind speed dependence alone, and we need to seek the other causes as shown below.

[9] In order to investigate the difference between the current and previous minima in more detail, histogram analysis is performed for solar wind parameters and geomagnetic activity indices. The time intervals for the histogram analysis are shown by vertical dashed lines in Figure 2. Figure 3 shows the occurrence distributions of the IMF strength, solar wind speed and density, and the Kp, Dst, and AE indices, as constructed from hourly averaged OMNI-2 database. Since the Kp index basically represents integrated geomagnetic activities of both magnetic storms and substorms, the Dst and AE indices are also included in the following analysis to better represent storms and substorms, respectively. A part of the Dst and AE indices used in this study still include provisional (2004–2006 for Dst, 1989–1995 and 2000–2009 for AE) and quick-look (2007–2009 for Dst, 1997–1999 for AE) values. Before constructing the histograms, we took logarithm of the solar wind parameters since the lognormal distribution has been known as a good model for the IMF strength [*Burlaga and Ness*, 1998] and for the solar wind plasma parameters [*Burlaga and Lazarus*, 2000].

[10] From Figure 3, it is found that the solar wind parameters show significant variations in the occurrence distribution around the solar minimum from year to year. As shown in Figure 3b, the histograms of the solar wind speed are very similar in 1997 and 2009. Again, it is therefore essential to compare these two years to understand the real cause of the persistently quiet condition, even though there is a good correlation between the solar wind speed and electron fluxes over solar cycles (Figures 2e and 2f). The double-peaked solar wind speed distribution in 2008 (Figure 3b) was investigated in detail by *Tokumaru et al.* [2009], and the higher speed component was associated to be originated from equatorial coronal holes. The extremely low density in 2008 (Figure 3c) was also investigated in detail by *McComas et al.* [2008] and *Issautier et al.* [2008], using Ulysses observations, and relate the low density with unusually low polar magnetic field activities of the Sun as shown in Figure 2a. *Burlaga and Lazarus* [2000] reported somewhat similar double-peaked distributions of the solar wind speed and density using the solar wind data in 1995, and associated with the double peak structures to corotating streams.

3. Discussions

[11] The variation of the radiation belt electrons is a result of a dynamic balance between sources and losses [e.g., *Reeves et al.*, 2003]. There are many different types of possible causes that the solar wind parameters control the relativistic electrons at GEO, and we need to discuss the source and loss processes that we learned from the extreme conditions in more detail. First we discuss a possibly important density effect to suppress the loss process. Second, we discuss the quiet geomagnetic conditions as a lack of a source process. Third, we suggest that the persistently quiet electrons at GEO may be an inevitable consequence of extremely weak open magnetic field of the Sun associated with the extremely weak current solar minimum.

[12] First, we discuss the possibly important density effect to suppress the loss process. As shown in Figure 3c, the solar wind density in 2008 is typically lower than in 2009. Recent studies have shown that low solar wind densities lead to suppress the loss rate of relativistic electrons, and thus in turn even enhance the radiation belt flux at GEO [*Kataoka and Miyoshi*, 2008a, 2008b]. In this reason, the loss rate should be lower in 2008 than in 2009. *Gibson et al.* [2009] reported that the relativistic electron flux at GEO in 2008 was still at unexpectedly high level even in the solar minimum. The relatively high flux in 2008 can be interpreted as a result of high speed solar wind streams emanating from equatorial coronal holes, likely due to the extremely small densities (cf., Y. Miyoshi and R. Kataoka, Solar cycle variations of outer radiation belt and solar wind structures, submitted to *Journal of Atmospheric and Solar-Terrestrial Physics*, 2009). However, considering the fact that the solar wind density in 2009 is typically lower than in 1997, the loss rate associated with the density effect should be lower in 2009 than in 1997. It is therefore suggested that the loss process associated with the low solar wind density in 2009 is not responsible for the quiet relativistic electron condition in 2009.

[13] Second, we discuss the quiet geomagnetic conditions as a lack of a source process. The extremely weak IMF strength as shown in Figure 3a results in an extremely small amount of the Alfvénic [e.g., *Kataoka et al.*, 2005] southward IMF, and consequently all of the geomagnetic activities such as storms and substorms become weak as shown in Figures 3e and 3f, respectively. Many observations indicate that the most important driver to enhance the radiation belt is the solar wind speed, but for a strong radiation belt enhancement to develop, the high-speed solar wind must be accompanied by the southward IMF during the recovery phase of storms [*Miyoshi and Kataoka*, 2005, 2008a]. The Alfvénic southward IMF is also essential for producing seed electrons associated with High Intensity Long Duration and Continuous AE Activities (HILDCAAs) [*Tsurutani and Gonzalez*, 1987], which are then accelerated to relativistic energies through wave-particle interactions [*Iles et al.*, 2002; *Miyoshi et al.*, 2007]. In fact the HILDCAAs and relativistic electron flux at outer belt are modulated by the Russell-McPherron effect [*Miyoshi and Kataoka*, 2008a; *McPherron et al.*, 2009]. As shown in Figures 3d and 3f, the Kp and AE index are extremely low in 2009, and it is expected that both injections of sub-relativistic electrons and magnetospheric convection are very weak in 2009, associated with the low substorm activities. We therefore

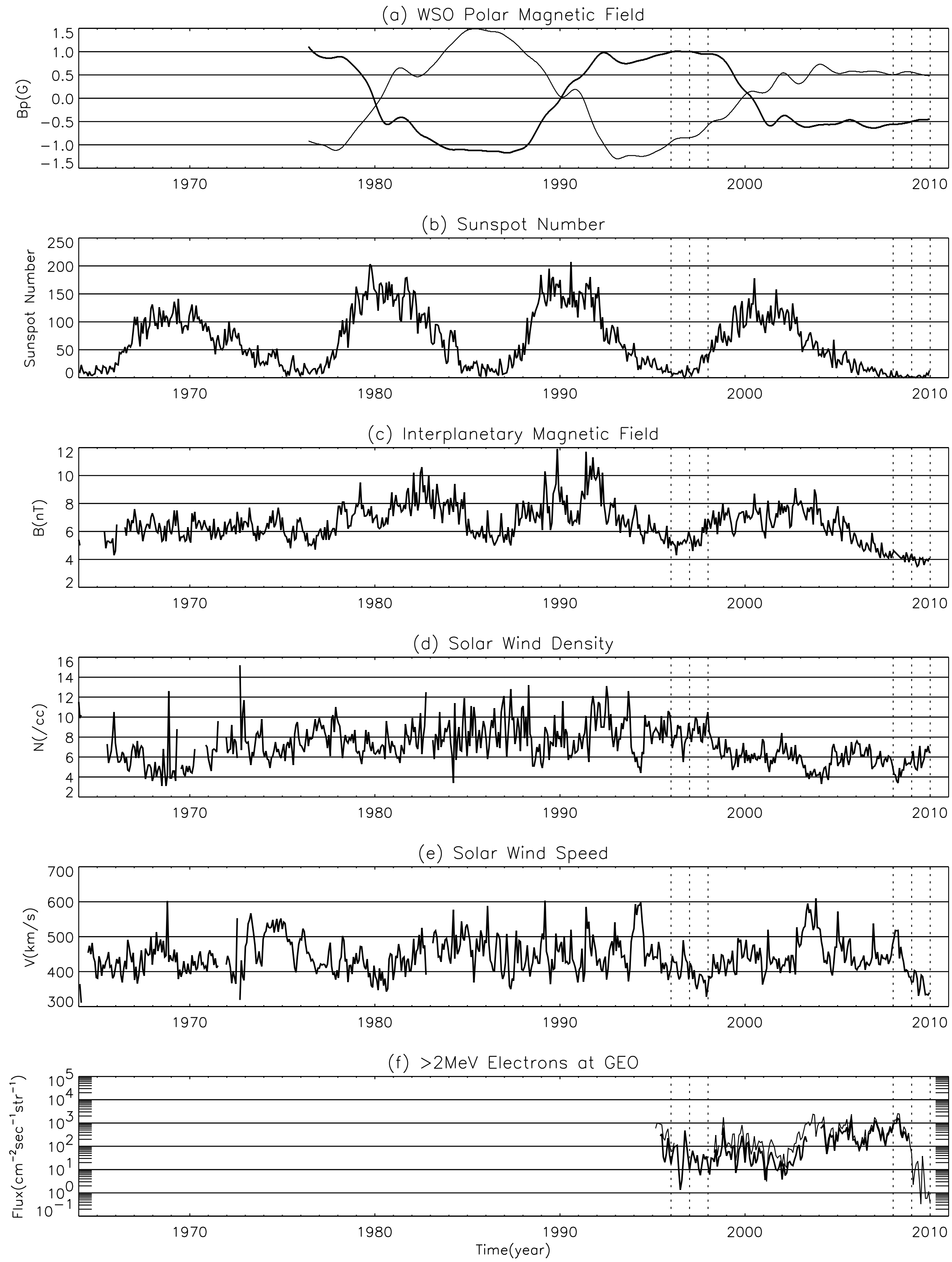

Figure 2. Solar cycle variations of 27 day averaged (a) WSO polar magnetic field of north (thick) and south (thin) poles of the Sun, (b) sunspot number, (c) IMF strength, (d) solar wind density, (e) solar wind speed, and (f) GOES > 2 MeV electron flux at 135W (thin) and 75W (thick).

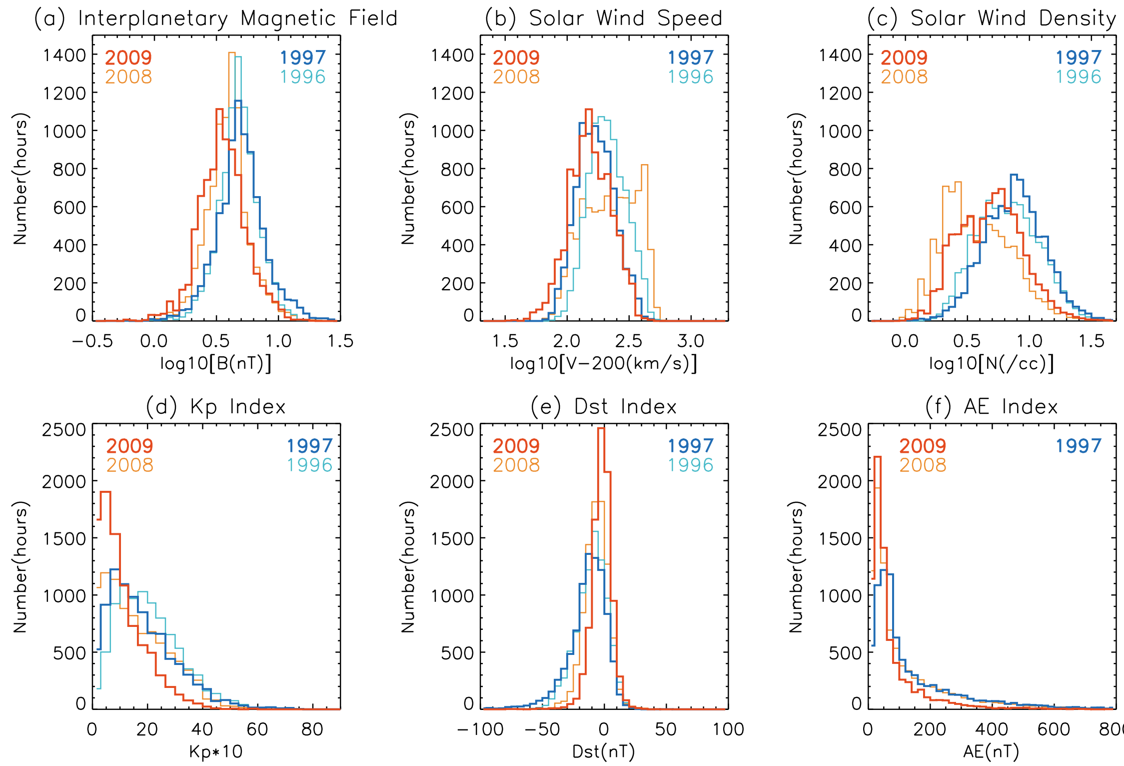

Figure 3. Occurrence distributions of the hourly averaged (a) IMF strength, (b) solar wind speed, (c) solar wind density and (d) Kp, (e) Dst, and (f) AE indices during the years of current and previous solar minima.

suggest that the extremely weak IMF played an essential role in diminishing the sources for building the outer belt in 2009.

[14] To summarize, combining the discussions above, the persistently quiet condition in 2009 can be understood by the lack of necessary constituents of the sources for building up the outer radiation belt electrons at GEO, rather than enhancement of the losses. The extremely weak IMF contains only small amount of southward IMF, and cannot enhance the essential source processes associated with storms and substorms. The very slow solar wind speed is also a necessary condition for further suppressing the geomagnetic activities.

[15] Third, we suggest that the persistently weak condition seems to be an inevitable radiation belt response associated with the extremely weak solar minimum. The very weak solar magnetic fields are not only the origin of the very weak IMF, but also the possible origin of slow solar wind speed. *Suzuki and Inutsuka* [2006] showed that both fast and slow solar wind can be explained by a single process of the dissipation of the low-frequency Alfvén waves, with different sets of the Alfvén wave strength, the ratio of photospheric magnetic field strength, and the radial expansion of the cross section. Based on their theory, slower solar wind is naturally originated from the weaker open field region. *McComas et al.* [2008] also discussed that globally weaker solar wind is likely related to the lower average strength of the open field of the Sun, based on the theory of *Schwadron et al.* [2006] and *Schwadron and McComas* [2008].

[16] We are entering a new phase of the geospace activities that we have not experienced yet, and what we learned from the persistently quiet condition is that the physics-based modeling becomes very important in a practical sense to accurate and reliable forecasting of both typical and extreme radiation belt conditions. A challenge posing for radiation belt and magnetospheric modelers is therefore to extend the dynamic range of their controlling parameters for such unexpected solar wind and IMF conditions, e.g., with the IMF strength ranging from 0.1 nT to 100 nT.

4. Conclusions

[17] The reason why relativistic electrons at GEO in 2009 were persistently quiet is essentially the lack of source processes associated with storms and substorms due to the extremely weak IMF of the very slow solar wind. The persistently quiet response of outer belt electrons at GEO seems to be an inevitable consequence of the extremely weak open magnetic field of the Sun associated with the extremely weak solar minimum.

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R. Kataoka, Interactive Research Center of Science, Tokyo Institute of Technology, Tokyo, 152-8551, Japan. (ryuho@geo.titech.ac.jp)

Y. Miyoshi, Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, 464-8601, Japan.