Advances in Physics Theories and Applications
ISSN 2224-719X (Paper) ISSN 2225-0638 (Online)
Vol.32, 2014
www.iiste.org

Relativistic Electron Enhancement (REE) Behavior during the Recovery Phase of Solar Cycle 23

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Abstract

To quantify the relationship between geomagnetic storms and relativistic electron enhancement (REE) at geosynchronous orbit and magnetic storms, a full solar cycle (1996–2006) of data has been examined. The relativistic electron fluxes of the earth's outer belt are subjected to strong temporal variations. The most prominent changes are initiated by the fast solar wind streams which often also caused enhanced substorm activity and magnetic storms. We considered the weak, moderate and intense geomagnetic storms using the index for 313 storms that occurred during Solar Cycle 23 (in the interval from January 1996 to December 2006). The relativistic electron fluence data were based on fluxes observed by the GOES geosynchronous satellites.

In the present study, we analyzed 313 Intense, Moderate and Weak storms observed at three different latitudes. A statistical study has been performed to quantify the REE behavior before and after the recovery phase of magnetic storms. Every relativistic electron event was associated with a magnetic storm, but, magnetic storms could occur without appreciable enhancement of the relativistic electron fluxes. More input parameters such as; solar wind velocity, dynamic pressure, and density, were thus used to make a cross-correlation analysis to determine what parameters might influence the flux of relativistic electrons.

Keywords: Geomagnetic storms, Geosynchronous orbit, Dst index, Relativistic Electron Enhancement.

1. Introduction

Active sun is characterized by powerful solar transient eruptions, like solar flares, coronal mass ejections (CMEs) and fast solar wind streams that are accompanied by enormous energy and mass. Impact of these disruptive solar emissions on the earth's magnetosphere leads to sudden disturbances in the geomagnetic field, known as Geomagnetic storms, can cause serious problems for many radio applications such as navigation systems, communication systems, and radio astronomy, *etc.* (Rawat *et al.* 2007).

Large-scale dynamical processes are set-in due to heating at high latitudes. The solar wind energy dissipation at high latitudes causes a temperature increase, which in turn leads to expansion of atmospheric gases. This expansion produces vertical winds, which transport mass and energy to higher altitudes. A bulge in the density and temperature occurs above the region, where the energy was initially deposited, and sets up pressure gradients (Eranna 2008).

Geomagnetic storms are major disturbances of the Earth's magnetosphere that occur when the interplanetary magnetic field turns southward and remains southward for a prolonged period of time.

The geomagnetic activity can be expressed by several magnetic indices. For low latitudes, the most accepted index is the disturbance storm time (Dst) derived by Sugiura (1964). Storms are typically divided into three distinct phases according to the signatures in Dst; Initial phase, Main phase, and Recovery phase. The Dst index or Disturbance Storm Time index which is a measure of the ring current at low latitudes, is taken as an index of geomagnetic activity in the present analysis. Dst is used to assess the severity of magnetic storms.

The relativistic electrons are very dangerous for spacecraft for huge changes of their fluxes, since relativistic electrons have enough energy to penetrate the outer skin of spacecraft and cause internal charging. They can cause spacecraft anomalies or destroy a spacecraft completely when the solar wind-magnetospheric interactions are enhanced (Wrenn 1995).

Relativistic electron fluxes usually decrease during the main phase of a storm and then either increase or stay low during the recovery phase (Reeves *et al.* 2003).

The present research work seeks to identify the most likely effective parameter of REE and to provide means of anticipating their response. The present work improves upon earlier investigations by using a longer database and higher time resolution, comparing multiple solar wind and magnetospheric parameters that may be associated with the relativistic electrons.

Only the subsets of parameters that seem to be most relevant to REE were presented in detail. While Dst in itself is not a good proxy, it is the most widely used indicator of storm activity and is used here to define the main phase, and recovery phase of a storm.

2. Data Description

The Dst index (nT) final values from the World Data Center for Geomagnetism, Kyoto, Japan, are used. The interplanetary magnetic field B (unit: nT), IMF Bz (nT), solar wind speed VSW ($km.s^{-1}$) come from the OMNI database. The fluxes of the geomagnetic high-energy electrons come from three geosynchronous satellites, GOES10.

As a general measure of storm intensity, we used the 1-hour resolution Dst index for 1996 through 2006. For solar wind velocity we used 1-hour values from the OMNI database.

In order to find the relativistic electron events occurring at geosynchronous orbit, we analyzed the 5-minute average electron fluxes of E > 2MeV measured by the GOES 10 satellite. The electron fluxes are taken from the CDA (Coordinated Data Analysis) web data service located by the URL http://cdaweb.gsfc.nasa.gov/.

The hourly data for interplanetary parameters were obtained from the following sites:

- http://spidr.ngdc.noaa.gov (Dst index and REE).
- http://ottawa.intermagnet.org (geomagnetic data from observatories: GUA, KAK, and VIC).
- http://spdf.gsfc.nasa.gov/index.html (solar winds parameters such as velocity, density, dynamic pressure and the IMF Bz).

2.1 Selection of events

The selection of the magnetic storm events was mainly based on the flux of the relativistic electrons, which increases during the recovery phase of the storms, provided that fluxes should have reached their maximum value before another magnetic storm takes place. This last criterion is satisfied if fluxes start decreasing or if they stay constant for a day before another storm occurs. Events that occurred while Dst was still recovering from an earlier storm were not included in this analysis because the combined Dst produced by a new ring current injection added to a pre-existing ring current does not accurately define the solar wind energy input. Relativistic electron events with multiple peaks were also counted as a single event.

3. Data Analysis

In this paper, we conducted a similar study as Reeves (1998). Reeves (*op. cit.*) examined the relationship between relativistic electron enhancements at geosynchronous orbit and the magnetic storms measured by the Dst index using LANL geostationary satellite data. We adopted a statistical approach using GOES 10 satellite data.

To investigate the relationship between the magnitudes of the events as measured by Dst and relativistic electron fluxes, we assembled 313 weak, moderate and intense geomagnetic storms spanning the 11 years from 1996 through 2006. We found that the geomagnetic storms can either increase or decrease the fluxes of relativistic electrons in the radiation belts.

Throughout the analysis of relativistic electrons to the 313 weak, moderate and intense geomagnetic storms, we started by identifying geomagnetic storms and then investigating the relativistic electrons response. We used a fixed definition of geomagnetic storms as distinct intervals during which the minimum value of the Dst index is less than -50 nT. Gonzalez *et al.* (1994) defined these storms as moderate (Dst < -50 nT) or intense (Dst < -100 nT).

Only negative Dst values are included because positive Dst values distort the results. Positive Dst values are caused by magnetopause compressions and are unrelated to the energy content in the ring current Reeves (1998).

By correlating the maximum electron flux in each event with the minimum Dst value, it was found that the correlation between the strength of a magnetic storm and the strength of the relativistic electron event is relatively low and the relativistic electron events were only observed during the magnetic storms. It is noted that our technique of selecting maximum electron fluxes and minimum Dst values compares events with a variety of lag times. A variety of lags between Dst and relativistic electron fluxes are in fact observed. Figure 1 shows the statistical relationship between the maximum flux of > 2 MeV electrons for each event and the minimum Dst value reached during the event. 39 intense events from (1996-2006) fall within the smaller observed Dst values ≤ - 100 nT. The plot indicates a rough correlation between the strength of the ring current (more negative Dst) and the peak relativistic electron flux. The scatter in the distribution of points is large. The plot should not be used to determine expected flux levels for a given Dst because events were selected based on electron flux not Dst minima. Therefore, storms with no relativistic electrons are not included.

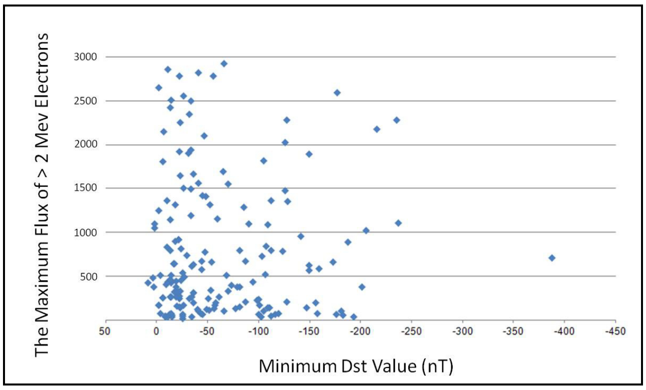

Figure 1. All events (1996-2006) statistics.

The number of Intense Storms for which the flux was enhanced was 55 which represent 59% of the available 85 Intense Storms in this eleven-year period. The number of Moderate Storms for which the flux was enhanced was 41 which represent 54.5% of the available 75 Moderate Storms in this eleven-year period. The number of Weak Storms for which the flux was enhanced was 79 which represent 51.5% of the available 153 Weak Storms in this eleven-year period.

Again, the events were chosen based on (1) a clear flux of the relativistic electrons (2) a clear Dst signature with a recovery to near zero and (3) fluxes have reached their maximum value before another magnetic storm takes place. Events that occurred during the recovery of an earlier storm were not included. Most chosen events met our criteria and had a clear and complete recovery.

Typically the minimum Dst occurred near the onset of, or prior to, the intensification of the relativistic electrons. This is to be expected since the relativistic electrons are known to peak several days after the onset of geomagnetic activity (Paulikas & Blake 1979; Nagai 1988).

Our statistical study showed that more than 159 of the total events occurred were associated with weak (or sometimes virtually no) magnetic storms. Only 98 of the events took place were accompanied by a strong magnetic storm of Dst (nT).

The analyzed observational data exhibit some relativistic electron event occurred without accompanying geomagnetic storms. It indicates that a relativistic electron event does not necessarily occur associated with a geomagnetic storm, which is inconsistent with Reeves (1998). We also found no obvious correlation between the maximum electron flux of an event and the size of geomagnetic storm similar to Reeves (op. cit.). Therefore, it is conceivable that the role of a geomagnetic disturbance for the relativistic electron enhancements at geosynchronous could be less essential than commonly presumed.

4. Discussion and Conclusion

For assessing the role of interplanetary conditions in guiding the dynamics associated with geomagnetic field variations, several storm events are studied. The full set of geomagnetic storms that occurred during Solar Cycle-23 has been analyzed in search of their solar and interplanetary origin. Solar cycle-23 evidenced many geomagnetic storms during maximum and descending phase. Solar wind conditions are necessary to generate a strong relativistic electron response.

We examined over 11 years (1996–2006) of solar wind and geosynchronous electron data in order to understand, in more detail, the relationship between solar wind driving and radiation belt response. In particular we examined the correlation between disturbance storm time (Dst), solar wind velocity, dynamic Pressure, density, and the IMF Bz, and > 2 MeV electron flux. As an example, figure 2 represents a correlation of selected solar wind parameters for a four-day period, starting on 17 February 1998. In doing so, we would be able to suggest some additional factors, either in the solar wind or in the magnetosphere, that determine whether a given storm will produce relativistic electrons or not and how strong that response will be.

4.1 Electron Flux

By correlating the maximum electron flux in each event with the minimum Dst value, there is no clear correlation between the maximum electron flux of an event and the associated minimum of Dst. This result suggests that large geomagnetic storms may not be crucial for the occurrence of a relativistic event at geosynchronous orbit. Therefore, any study on the physical mechanism(s) accounting for the relativistic events should take into account that strong magnetic storms may not be necessarily required for the occurrence of a relativistic electron event at geosynchronous orbit.

4.2 Solar Wind Velocities

In the present study, we have considered the isolated effects of solar wind density and velocity on the electron flux level. The highest-flux days were observed across the full distribution of solar wind velocities, as it is noticeable in figure 2. Higher solar wind velocities do give a higher probability for observing the most intense fluxes but, for example, a Vsw of 400 km/s is just as likely to produce flux >3.98 $(cm^2\text{-s-sr-keV})^{-1}$ as a Vsw of 480 km/s. While it is confirmed that solar wind velocity is a critical parameter for determining radiation belt electron flux, the relationship is far from simple. It is found that the correlation between solar wind velocity and the geosynchronous MeV electron flux is actually quite low and far from linear.

4.3 Dynamic Pressure

The dynamic pressure is dependent on (a) V and (b) Bz during storm onset for all storms (Adebesin *et al.* 2012). The dynamic pressure is responsible for generation of ULF waves and acceleration of lower energy particles, then a correlation between the relativistic electron flux and solar wind density is a must. The correlation between dynamic pressure and the geosynchronous MeV electron flux does not actually exist.

4.4 Density

The density may be considered as a proxy for solar wind dynamic pressure. In the current study, it has been shown that different results are obtained by conducting a parameter sensitivity analysis, and thus, that the Vsw-density relationship needs to be taken into account in the analysis. This may account for the discrepancy between studies promoting density as the primary driver of relativistic flux variance, to those which have promoted Vsw as the primary driver.

An anti-correlation was observed between the density and flux value in Figure 2. Elevated solar wind density does not only result in radial diffusion of particles, but statistically produces significant loss of relativistic electrons.

4.5 The IMF Bz

Many authors have studied the effect of IMF Bz on the solar wind conditions and the Earth's magnetosphere. Gosling & McComas (1987) proposed that the generation of IMF Bz may occur as a result of compression of the horizontal ambient IMF about the CME body. Also, Gosling *et al.* (1991) and Gosling & Bame (1993) mentioned that the strong IMF Bz is the main cause in the generation of geomagnetic storms.

There is a dependence of IMF Bz on the solar wind velocity. For ‘intense’ conditions, IMF Bz is the most important factor to be considered during storm onset, whereas the flow speed is the most considered factor with regards to ‘very intense’ storms; when considering their dependency with the dynamic pressure (Adebesin *et al.* 2012). It seems that IMF Bz plays no clear rule in relativistic electron enhancement.

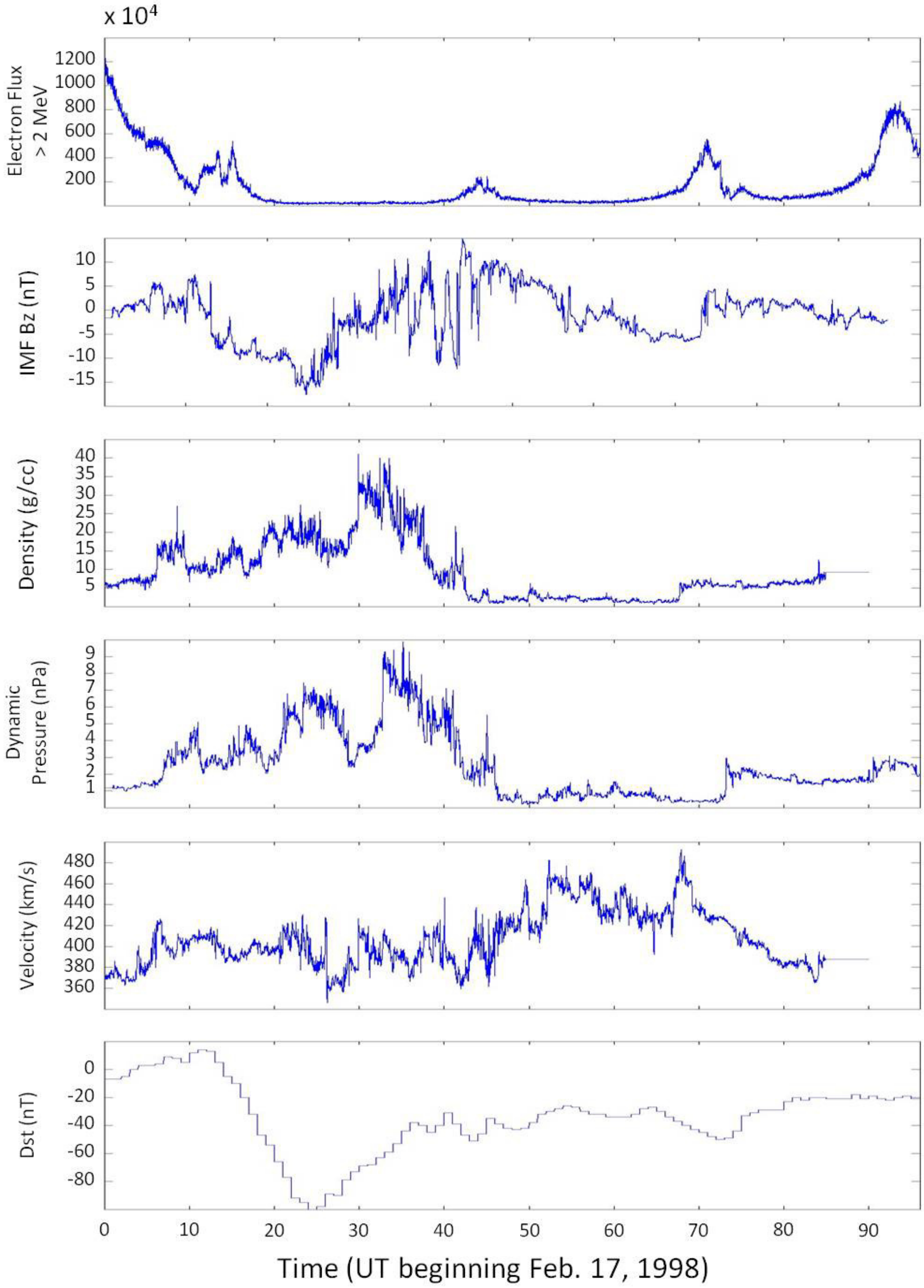

Figure 2. The correlation between disturbance storm time (Dst), solar wind velocity, dynamic pressure, density, and the IMF Bz, and > 2 MeV electron flux.

4.6 Conclusion

We can conclude that the relativistic electron events at geosynchronous orbit do not always occur associated with strong geomagnetic storms. The relativistic electron enhancement is directly driven by the solar wind conditions and the pre-existing source population. These results are consistent with Reeves (1998).

Despite many years of study, there remain several unanswered questions about this important topic. In particular, why do some geomagnetic storms lead to Relativistic Electron Enhancements while others do not? and what are the mechanisms for enhancement?, remain unresolved.

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