JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, A08224, doi:10.1029/2008JA013048, 2008

Effect of geomagnetic disturbances and solar wind density on relativistic electrons at geostationary orbit

Wladislaw Lyatsky[1] and George V. Khazanov[1]

Received 20 January 2008; revised 14 May 2008; accepted 23 May 2008; published 23 August 2008.

[1] It is well known that fluxes of relativistic electrons in the Earth's magnetosphere well correlate with solar wind speed but surprisingly they show a weaker correlation with geomagnetic activity indices. For a long time, this result seemed puzzling since geomagnetic disturbances, measured by geomagnetic activity indices, are associated with strong electric fields and low-frequency waves, which should significantly affect (directly or indirectly) the particle acceleration to high energies. To understand why the relativistic electron fluxes show the relatively weak correlation with geomagnetic disturbances, we investigated statistically the data of relativistic electrons at geostationary orbit for 6 years (1997–2002) and compared these data with solar wind parameters and geomagnetic activity indices. We found that, for the generation of the strong electron fluxes, the combination of two factors is needed: (1) strong geomagnetic disturbances about two days before the following increases in electron fluxes and (2) low solar wind density within these 2-day intervals between the geomagnetic disturbances and following increases in the electron fluxes. By these conditions, the correlation between the electron fluxes and geomagnetic indices is improved and becomes higher than the correlation between the electron fluxes and solar wind speed. A large majority of the strongest relativistic electron events occurred just during these conditions. This allows us to suggest that not solar wind speed alone but rather geomagnetic activity combined with low solar wind density conditions may be a primary cause for the generation of relativistic electrons.

Citation: Lyatsky, W., and G. V. Khazanov (2008), Effect of geomagnetic disturbances and solar wind density on relativistic electrons at geostationary orbit, *J. Geophys. Res.*, *113*, A08224, doi:10.1029/2008JA013048.

1. Introduction

[2] Relativistic electrons in the Earth's magnetosphere are one of most hazardous phenomena in geospace environment. Understanding the cause of this phenomenon is an important area of research. However, despite extensive studies by many researchers, the behavior of relativistic electrons is yet not well clear.

[3] The results of statistical analysis showed (*Paulikas and Blake* [1979], *Baker et al.* [1998], *O'Brien et al.* [2001], *Li and Temerin* [2001], *Li et al.* [2005], and many others) that the relativistic electron fluxes well correlate with solar wind speed but show a weaker correlation with geomagnetic activity indices. Enhancements of electron fluxes occur after increasing the solar wind speed or geomagnetic activity with a time delay that increases with energy [*Li et al.*, 2005]. For relativistic (>2 MeV) electrons at geostationary orbit, the time delay is about 2 days [*O'Brien et al.*, 2001; *Li et al.*, 2005; *Lyatsky and Khazanov*, 2008].

[4] It is commonly suggested [e.g., *Baker et al.*, 1998; *Meredith et al.*, 2002, 2003; *Horne et al.*, 2005; *Li et al.*, 2005] that electron acceleration to high energies includes two stages: first, plasma sheet electrons are accelerated in the auroral zone during magnetospheric substorms and then they are accelerated in the inner magnetosphere by low-frequency waves, so that the total acceleration to relativistic energies may take some days. The good correlation of relativistic electrons with solar wind speed led to the suggestion that a dominant role in the generation of these electrons is played by low-frequency waves, generated by high-speed solar wind. *Rostoker et al.* [1998], *Baker et al.* [1998], *Elkington et al.* [1999], *O'Brien et al.* [2001], *Li et al.* [2005], and others suggested that primarily accelerated electrons with energy of about 100 keV undergo additional acceleration by ULF waves, driven by high-speed solar wind due to the Kelvin-Helmholtz instability on magnetopause flunks or random compressions-decompressions of dayside magnetosphere. On the other hand, *Meredith et al.* [2002, 2003], *Horne et al.* [2005], *Summers et al.* [2007] and other researchers investigated electron energization due to resonant interaction with the very-low-frequency (VLF) "chorus" waves, driven by magnetospheric substorms.

[5] The relatively weak correlation of relativistic electron fluxes with geomagnetic activity indices seems puzzling [e.g., *Li and Temerin*, 2001; *Li et al.*, 2001]. Varying electric fields of large-scale geomagnetic disturbances, such as magnetospheric substorms, are much stronger than electric

[1]NASA/Marshall Space Flight Center, Huntsville, Alabama, USA.

0148-0227/08/2008JA013048

fields of ULF waves. As to another candidate, the VLF "chorus" waves, they occur during substorms and their occurrence well correlate with substorm activity. Why almost all other phenomena in the magnetosphere and ionosphere well correlate with geomagnetic activity indices but relativistic electrons better correlate with solar wind speed?

[6] In our previous paper [*Lyatsky and Khazanov*, 2008], we examined the relationship between relativistic electron fluxes at geostationary orbit and two solar wind parameters, the speed and density. We found that solar wind density plays an important role in the decay of relativistic electrons. In the present paper, we are investigating the effect of geomagnetic disturbances on relativistic electrons. One of the purposes of this paper is to answer on the question: why relativistic electron fluxes correlate with solar wind speed better than they correlate with geomagnetic activity?

2. Data Used for Analysis

[7] We used for the analysis the data of relativistic (>2 MeV) electron fluxes measured with the Goes-8 and Goes-10 satellites, upstream solar wind data, and geomagnetic activity indices for six years from 1997 through 2002. The data of relativistic electron fluxes are available from the NOAA web site at http://spidr.ngdc.noaa.gov; we note that the data from Goes-10 are available only from July 1998 through 2002. The solar wind data and Kp geomagnetic activity indices were obtained from OMNI data set (ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni). The auroral electrojet *AL* indices were obtained from the Kyoto World Data Center (http://swdcdb.kugi.kyoto-u.ac.jp).

3. Results of Analysis

[8] In this study, we examined the relationship between relativistic electron fluxes at geostationary orbit and four quantities: solar wind speed and density, and two geomagnetic activity indices: the auroral electrojet *AL* index, and *Kp* index. The auroral electrojet *AL* index shows activity of magnetospheric substorms which are the strongest disturbances at high latitudes, while the *Kp* index shows geomagnetic activity at subauroral and middle latitudes. We examined the correlation of the electron fluxes with the square root of the *AL* index, which improves the correlation. Since the *AL* index is usually negative, we took the root square of the absolute value of this index.

[9] We used for the analysis the daily mean values of the relativistic (>2 MeV) electron fluxes, the solar wind speed, and geomagnetic activity indices. Since measurements of small values of relativistic electron fluxes and solar wind density, n, may contain large errors, we examined events for log $F_e > 0$ and the solar wind density $n > 2$ cm^{-3}. While investigating the correlation of the electron fluxes with solar wind speed and geomagnetic activity, we found that the responses in relativistic (>2 MeV) electron fluxes follow the variations in solar wind speed and geomagnetic activity indices with a significant time delay of about 2 days, which is consistent with results by *O'Brien et al.* [2001] and *Li et al.* [2005]. Therefore for the analysis we used the 2-day delay in data of relativistic electron fluxes while correlating them with solar wind speed and geomagnetic activity indices.

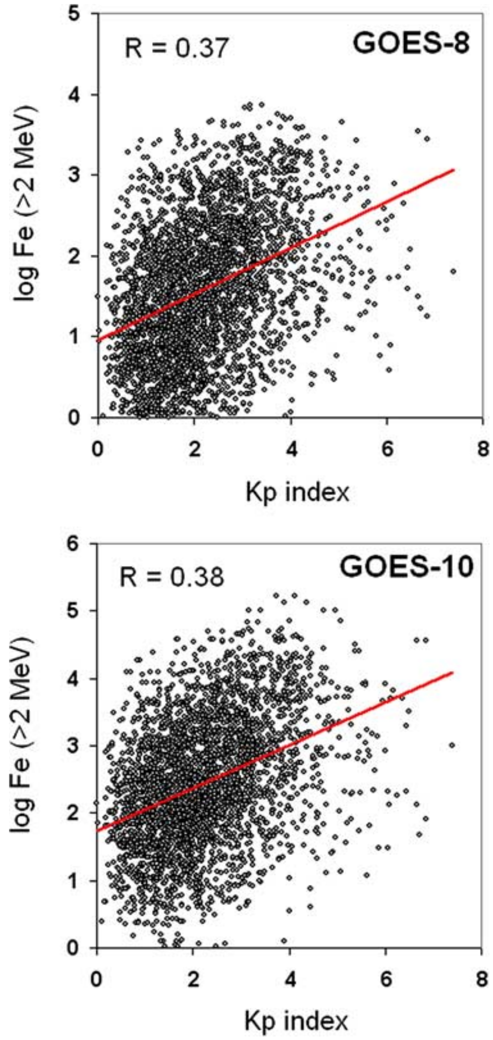

Figure 1. Correlation patterns for daily mean values of log F_e, where F_e is the relativistic electron fluxes in counts/cm^2·s·sr versus daily mean values of geomagnetic activity *Kp* index for Goes-8 and Goes-10 data for 1997–2002. The time delay of F_e with respect to solar wind speed and *Kp* index is 2 days. Trend lines and the Pearson correlation coefficients, R, are shown.

[10] Figure 1 shows the correlation between the geomagnetic activity *Kp* index and log F_e, where F_e is relativistic electron fluxes as measured with Goes-8 and Goes-10 spacecraft, for 6 years: 1997–2002. One can see that the correlation is not high: the correlation coefficient is ~0.37–0.38 only. Increasing in the time-delay to 2.5–3 days insignificantly affects the correlation. This correlation between the *Kp* index and log F_e is significantly worse than that between solar wind speed and log F_e (see e.g., *Lyatsky and Khazanov* [2008], where the correlation coefficient for the correlation between solar wind speed and log F_e was found to be ~0.54–57 for the same time period, which is consistent with results by *Paulikas and Blake* [1979], *O'Brien et al.* [2001], *Li et al.* [2005], and others).

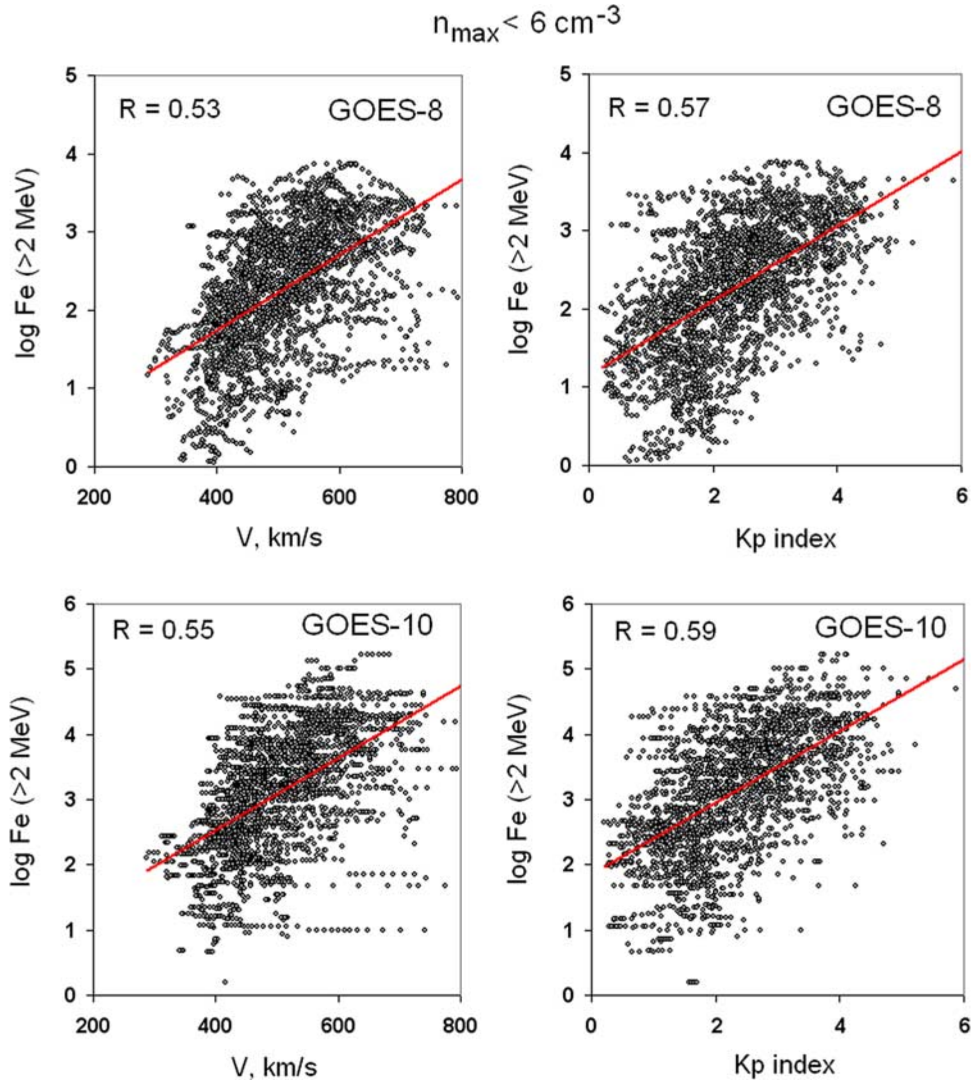

Figure 2. Correlation patterns for daily mean values of log F_e, where F_e is the relativistic electron flux in counts/cm^2·s·sr versus daily mean values of solar wind speed, *V*, and *Kp* index for Goes-8 and Goes-10 data for 1997–2002, for events when solar wind density, *n*, did not exceed 6 cm^{-3} within 2-day intervals before measured fluxes of relativistic electrons. The time delay of F_e with respect to solar wind speed and *Kp* index is 2 days.

[11] For understanding the cause for the relatively low correlation between geomagnetic activity indices and the electron fluxes, we accounted additionally for the effect of the solar wind density. It is well known that solar wind speed and density tend to anti-correlate: high-speed solar wind is often related to low density, and vice versa. The anti-correlation, however, is not very strong, so that these parameters are partially independent. In our previous work [*Lyatsky and Khazanov*, 2008], we showed that solar wind density may significantly affect the relativistic electron fluxes. Therefore we suggested that a joint effect of geomagnetic activity and solar wind density may provide a better correlation with the electron fluxes.

[12] Indeed, we found that the correlation between geomagnetic activity and relativistic electron fluxes increases significantly with decreasing solar wind density within the 2-day intervals between geomagnetic disturbances and following variations in the electron fluxes, and this effect becomes even stronger while considering not the average but maximal values of solar wind density within these time intervals. The results of this analysis are presented in Figures 2 and 3.

[13] Figure 2 shows the correlation of running daily averages of log F_e versus solar wind speed, *V*, and *Kp* index for events when 3-hour values of solar wind density, *n*, within the 2-day time intervals before measured values of relativistic electron fluxes did not exceed n_{max} = 6 cm^{-3}. This figure demonstrates significant improving the correlation between log F_e and *Kp* index while the correlation between log F_e and solar wind speed varies insignificantly. Correlation coefficients, *R*, for log F_e versus *Kp* index in this figure increased to 0.57–0.59 and exceeds the correlation coefficients for log F_e versus solar wind speed. More rigid restriction of solar wind density leads to further improving the correlation between geomagnetic indices and log F_e, so that the correlation coefficients increase up

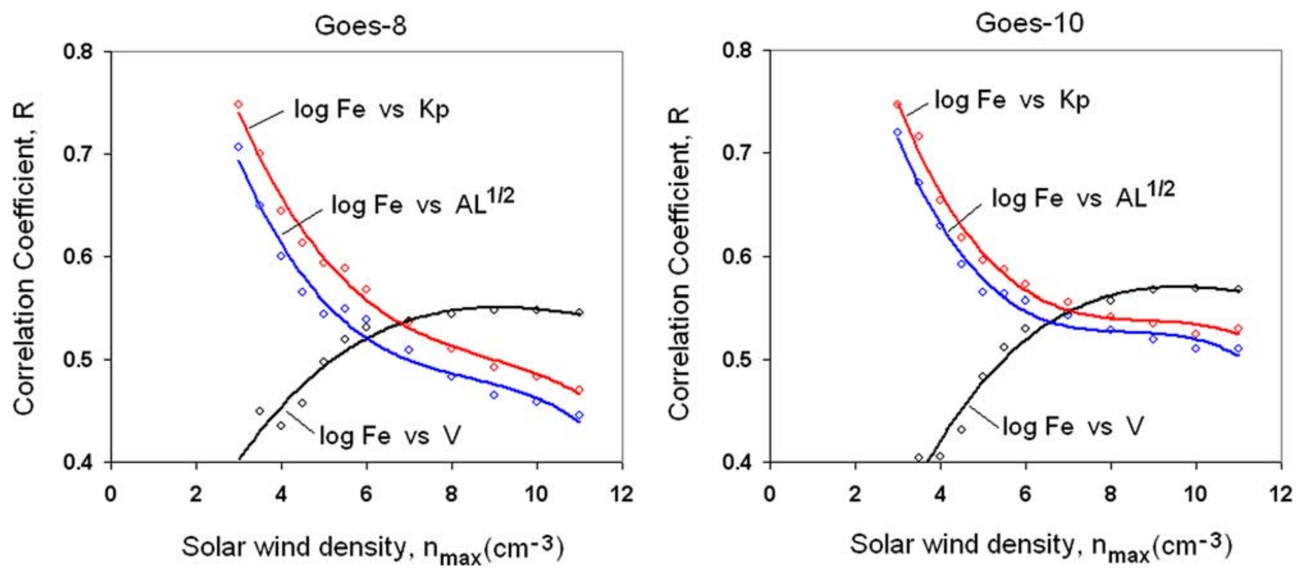

Figure 3. Correlation coefficients for the correlation between daily mean values of log F_e and three parameters (solar wind speed, *V*, the *Kp* index, and the square root of the auroral electrojet *AL* index) as functions of maximal values of solar wind density inside 2-day intervals between values of these parameters and responses in the electron fluxes.

to 0.75 and even more. We note that despite the rigid restriction in the solar wind density and, as a result, in the number of events, the large majority (from 62 to 68 per cent) of strong relativistic electron events, related to log $F_e > 3$ in Goes-8 data, and log $F_e > 4$ in Goes-10 data, were observed during the intervals of low-density solar wind conditions.

[14] Figure 3 shows the correlation coefficients for the correlation between log F_e and the three quantities (the solar wind speed, *Kp* index, and square root of the *AL* index) as a function of maximal magnitudes of solar wind density, $n_{\max}$, within the 2-day intervals between measured geomagnetic indices and following responses in electron fluxes. The two upper curves in this figure are related to the correlation of log F_e versus *Kp* index and the square root of the *AL* index, while the lowest curve is related to the correlation of log F_e versus solar wind speed. One can see a strong increase in the correlation of log F_e versus $AL^{1/2}$ and *Kp* indices for low-density solar wind while the correlation between log F_e and solar wind speed becomes worse.

[15] Thus Figures 2 and 3 show a very important role played by geomagnetic activity in the generation of relativistic electrons during low-density solar wind conditions. The decrease in relativistic electron fluxes at geostationary orbit during high-density solar wind conditions may be caused by enhanced losses of these electrons due to their spread on EMIC and VLF waves, which are better generated in the regions with enhanced plasma density [*Meredith et al.*, 2002, 2003; *Thorne et al.*, 2005; *Summers et al.*, 2007; *Onsager et al.*, 2007]. Figures 2 and 3 clarify when and why the correlation between the electron fluxes and geomagnetic indices may be low or high. The correlation is low for all solar wind conditions, since geomagnetic disturbances during high-density solar wind conditions are not able to provide a significant increase in relativistic electron fluxes because of a strong decay of relativistic electrons. However, the correlation between geomagnetic disturbances and following variations in relativistic electron fluxes is strongly improved for low-density solar wind conditions.

4. Discussion and Conclusion

[16] The results of this study showed that two factors are needed for the generation of strong relativistic electron fluxes at geostationary orbit: high geomagnetic activity two days before the following responses in relativistic electron fluxes, and low-density solar wind within the time interval between geomagnetic disturbances and the increases in the electron fluxes. Geomagnetic disturbances, followed by high-density solar wind conditions, do not contribute significantly to relativistic electron population. This explains a weak correlation between geomagnetic activity indices and relativistic electron fluxes for all solar wind conditions. However, the correlation is strongly improved for low-density solar wind conditions. The effect of solar wind density on relativistic electrons is consistent with recent results by *Lyons et al.* [2005], *Onsager et al.* [2007], and *Lyatsky and Khazanov* [2008] who found that strong relativistic electron events tend to occur in times of low-density solar wind conditions, though they have not investigated a combine effect of geomagnetic activity and solar wind density on relativistic electrons and did not report the strong increase in the correlation between geomagnetic disturbances and following electron fluxes during these events.

[17] A possible cause for the effects of geomagnetic activity and solar wind density on relativistic electrons may be described in the following way. The magnitude of the relativistic electron flux in the radiation belt is a result of the balance between the sources, responsible for acceleration of electrons to relativistic energies, and their losses. The sources are the electric fields generated during geomagnetic disturbances, including the electric fields of the VLF ''chorus'' waves. The chorus waves, according to many

researchers, are tightly associated with geomagnetic activity and able to accelerate electrons to high energies [e.g., *Meredith et al.*, 2003; *Horne et al.*, 2005; *Thorne et al.*, 2005; *Summers et al.*, 2007]. This explains an increase in intensity of electron fluxes with geomagnetic activity by conditions when losses of these electrons are low. The losses of relativistic electrons are caused by their pitch-angle spread on ion- and electron-cyclotron waves and precipitation into the ionosphere [e.g., *Kennel and Petschek*, 1966; *Summers et al.*, 2007]. The growth rate of the ion/electron-cyclotron waves and losses of relativistic electrons from the radiation belt increase with decreasing the Alfven velocity, which is inversely proportional to the square root of the plasma density. Penetrating the solar wind plasma into the plasma sheet affects the plasma sheet density [e.g., *Borovsky et al.*, 1998], which makes the solar wind density an important factor affecting the losses of relativistic electrons. This possible explanation does not pretend to answer all questions. A detailed consideration of the mechanisms responsible for the observed correlation relativistic electrons with geomagnetic activity and solar wind density is beyond the scope of the present paper.

[18] Thus in this study we found that for the generation of strong electron fluxes, the combination of two factors is needed: (1) strong geomagnetic disturbances about two days before the following increases in electron fluxes and (2) low solar wind density within these 2-day intervals between the geomagnetic disturbances and following increases in the electron fluxes. By these conditions, the correlation between the electron fluxes and geomagnetic indices is significantly improved and becomes higher than the correlation between the electron fluxes and solar wind speed. A large majority of strongest relativistic electron events occurred just during these conditions, which allows us to suggest that not solar wind speed alone but rather geomagnetic disturbances in combination with low-density solar wind conditions may be a primary source of strong relativistic electron fluxes in the Earth's magnetosphere.

[19] **Acknowledgments.** We gratefully acknowledge efforts of the NOAA staff in providing data on relativistic electron fluxes from the geostationary spacecraft, and the Goddard Space Flight Center and World Data Center for Geomagnetism in Kyoto, Japan, in providing solar wind data and geomagnetic activity indices. We are grateful to Robert Sheldon for useful discussions. This research was performed while Wladislaw Lyatsky held a NASA Senior Postdoctoral Program appointment at NASA/MSFC. Funding in support of this study was provided by NASA HQ POLAR Project and NASA LWS Program. Wladislaw Lyatsky is a fellow of Oak Ridge Associated Universities, Oak Ridge, Tennessee.

[20] Wolfgang Baumjohann thanks the reviewers for their assistance in evaluating this paper.

References

Baker, D. N., X. Li, J. B. Blake, and S. Kanekal (1998), Strong electron acceleration in the Earth's magnetosphere, *Adv. Space Res.*, *21*, 609–613.

Borovsky, J. E., M. F. Thomsen, and R. C. Elphic (1998), The driving of the plasma sheet by the solar wind, *J. Geophys. Res.*, *103*(A8), 17,617–17,640.

Elkington, S. R., M. K. Hudson, and A. A. Chan (1999), Acceleration of relativistic electrons via drift-resonant interaction with toroidal-mode Pc-5 ULF oscillations, *Geophys. Res. Lett.*, *26*(21), 3273–3276.

Horne, R. B., R. M. Thorne, S. A. Glauert, J. M. Albert, N. P. Meredith, and R. R. Anderson (2005), Timescale for radiation belt electron acceleration by whistler mode chorus waves, *J. Geophys. Res.*, *110*, A03225, doi:10.1029/2004JA010811.

Kennel, C. F., and H. E. Petschek (1966), Limit on stably trapped particle fluxes, *J. Geophys. Res.*, *71*(1), 1–28.

Li, X., and M. A. Temerin (2001), The electron radiation belt, *Space Sci. Rev.*, *95*, 569–580.

Li, X., M. Temerin, D. N. Baker, G. D. Reeves, and D. Larson (2001), Quantitative prediction of radiation belt electrons at geostationary orbit based on solar wind measurements, *Geophys. Res. Lett.*, *28*(9), 1887–1890.

Li, X., D. N. Baker, M. Temerin, G. Reeves, R. Friedel, and C. Shen (2005), Energetic electrons, 50 keV to 6 MeV, at geosynchronous orbit: Their responses to solar wind variations, *Space Weather*, *3*, S04001, doi:10.1029/2004SW000105.

Lyatsky, W., and G. V. Khazanov (2008), Effect of solar wind density on relativistic electrons at geosynchronous orbit, *Geophys. Res. Lett.*, *35*, L03109, doi:10.1029/2007GL032524.

Lyons, L. R., D.-Y. Lee, R. M. Thorne, R. B. Horne, and A. J. Smith (2005), Solar wind-magnetosphere coupling leading to relativistic electron energization during high-speed streams, *J. Geophys. Res.*, *110*, A11202, doi:10.1029/2005JA011254.

Meredith, N. P., R. B. Horne, R. H. A. Iles, R. M. Thorne, D. Heynderickx, and R. R. Anderson (2002), Outer zone relativistic electron acceleration associated with substorm-enhanced whistler mode chorus, *J. Geophys. Res.*, *107*(A7), 1144, doi:10.1029/2001JA900146.

Meredith, N. P., M. Cain, R. B. Horne, R. M. Thorne, D. Summers, and R. R. Anderson (2003), Evidence for chorus-driven electron acceleration to relativistic energies from a survey of geomagnetically disturbed periods, *J. Geophys. Res.*, *108*(A6), 1248, doi:10.1029/2002JA009764.

Onsager, T. G., J. C. Green, G. D. Reeves, and H. J. Singer (2007), Solar wind and magnetospheric conditions leading to the abrupt loss of outer radiation belt electrons, *J. Geophys. Res.*, *112*, A01202, doi:10.1029/2006JA011708.

O'Brien, T. P., R. L. McPherron, D. Sornette, G. D. Reeves, R. Friedel, and H. J. Singer (2001), Which magnetic storms produce relativistic electrons at geosynchronous orbit, *J. Geophys. Res.*, *106*(A8), 15,533–15,544.

Paulikas, G. A., and J. B. Blake (1979), Effect of the solar wind on magnetospheric dynamics: Relativistic electrons at the synchronous orbit, in *Quantitative Modeling of Magnetospheric Processes*, *Geophys. Monogr. Ser.*, vol. 21, edited by W. P. Olsen, p. 180, AGU, Washington, D. C.

Rostoker, G., S. Skone, and D. N. Baker (1998), On the origin of relativistic electrons in the magnetosphere associated with some geomagnetic storms, *Geophys. Res. Lett.*, *25*(19), 3701–3704.

Summers, D., B. Ni, and N. P. Meredith (2007), Timescales for radiation belt electron acceleration and loss due to resonant wave-particle interactions: 2. Evaluation for VLF chorus, ELF hiss, and electromagnetic ion cyclotron waves, *J. Geophys. Res.*, *112*, A04207, doi:10.1029/2006JA011993.

Thorne, R. M., T. P. O'Brien, Y. Y. Shprits, D. Summers, and R. B. Horne (2005), Timescale for MeV electron microburst loss during geomagnetic storms, *J. Geophys. Res.*, *110*, A09202, doi:10.1029/2004JA010882.

G. V. Khazanov and W. Lyatsky, NASA/Marshall Space Flight Center, Space Plasma Group, 320 Sparkman Drive, Huntsville, AL 35805, USA. (lyatsky@cspar.uah.edu)