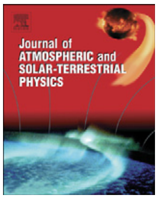
Journal of Atmospheric and Solar-Terrestrial Physics 70 (2008) 1745–1759

Contents lists available at ScienceDirect

Journal of
Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp



Characterization of relativistic electron flux rise times during the recovery phase of geomagnetic storms as measured by the NS41 GPS satellite

Athina Varotsou [a,*], Reiner H. Friedel [a], Geoff D. Reeves [a], Benoit Lavraud [a], Ruth M. Skoug [a], Tom E. Cayton [a], Sebastien Bourdarie [b]

[a] *Space Science and Applications, Los Alamos National Laboratory, MS D466, Los Alamos, NM 87545, USA*
[b] *Office National d'Etudes et Recherches Aérospatiales, 2, av. Edouard Belin, BP 74025-31055 Toulouse Cedex 4, France*

ARTICLE INFO

Article history:
Accepted 29 January 2008
Available online 13 February 2008

Keywords:
Radiation belt dynamics
Relativistic electrons
Geomagnetic storms
Satellite data

ABSTRACT

Intense relativistic electron enhancements in the Earth's radiation belts are observed during periods of enhanced geomagnetic activity. Different physical processes—identified as being responsible for these enhancements—would lead to different characteristic rise times of the electron fluxes. Here we present for the first time MeV electron flux rise times near the equator as estimated from $5\frac{1}{2}$ years of data from the NS41 Global Positioning System (GPS) satellite, in an effort to relate measured electron flux rise timescales with those predicted by theory. The GPS orbit crosses the heart of the radiation belts, covering the $L>4$ region and measuring equatorial fluxes at $L\sim4.2$. We have calculated L^* values using the Tsyganenko 2001 storm magnetic field model and have limited our study to the equator by imposing $L^* = 4$–4.5. Forty events, for which fluxes rise by a factor of 5 or more after the storm main phase, were selected from the analysis of the >1.22 MeV electron channel. The main results of our study are as follows: (1) the electron flux rise time distribution is very large indicating that there are a large variety of events observed at GPS orbit, similar to that observed at GEO, (2) fluxes rise in two phases, an initial fast rise is observed where most of the flux increase takes place, followed by a slower increase to the maximum flux, (3) fluxes gain 1–2 orders of magnitude on a timescale of 1–2 days, on average, in good agreement with timescales predicted by electron-chorus resonant interaction in quasi-linear theory using average wave characteristics for AE$>$500 nT, and (4) the direction of the IMF Bz could be an important parameter in determining the behavior of the flux of relativistic electrons during the recovery phase.

1. Introduction

Radiation belt studies in the last 10 years have been focusing on source, loss and transport processes acting on the trapped relativistic electron population. Identifying these processes and the region and time that they occur, are the subject of ongoing studies (see reviews by Li and Temerin, 2001; Friedel et al., 2002; Horne, 2002).

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). Radial transport across magnetic field lines conserving the particle's first and second adiabatic invariants has been identified very early as a key mechanism for the trapped electron dynamics (Schulz and Lanzerotti, 1974). Radial

---

* Corresponding author. Tel.: +1 505 667 6608; fax: +1 505 665 7395.
E-mail addresses: athina@lanl.gov (A. Varotsou), friedel@lanl.gov (R.H. Friedel), reeves@lanl.gov (G.D. Reeves), lavraud@lanl.gov (B. Lavraud), rskoug@lanl.gov (R.M. Skoug), tcayton@lanl.gov (T.E. Cayton), sebastien.bourdarie@onecert.fr (S. Bourdarie).

1364-6826/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2008.01.020

diffusion could be sufficient to explain the electron radiation belt dynamics if we consider adiabatic effects to be responsible for the main phase flux decrease during a storm (Kim and Chan, 1997) and higher post-storm fluxes to be due to enhanced storm-time radial diffusion transporting particles to the inner magnetosphere from an external source and energizing them at the same time.

However, recent observational studies have shown that radial transport alone cannot explain all observed features (Brautigam and Albert, 2000; Horne et al., 2003a, b; Miyoshi et al., 2003; Green and Kivelson, 2004; Shprits and Thorne, 2004; Chen et al., 2006; Fox et al., 2006; Iles et al., 2006). There are various loss, source and transport mechanisms acting on the trapped MeV electron population, which are enhanced during active magnetospheric conditions.

Electron–wave interactions are believed to be one of the predominant physical mechanisms acting both as a loss and a source for MeV radiation belt electrons (Thorne et al., 2005; Horne et al., 2006). Different waves are present in different regions of the inner magnetosphere and they act on different timescales (e.g., Horne et al., 2005a; Shprits et al., 2006a). Plasmaspheric hiss is believed to be responsible for relativistic electron losses due to pitch angle scattering on timescales of 5–10 days inside the plasmasphere, where the plasma density is high (Lyons et al., 1972; Abel and Thorne, 1998; Meredith et al., 2006). EMIC waves are also present in this high-density environment, especially in plasmaspheric plumes formed during the storm's main phase (e.g., Erlandson and Ukhorskiy, 2001). They are believed to cause important MeV electron losses, by pitch angle scattering near the loss cone, in high-density regions, during the main phase on timescales of hours (Thorne and Kennel, 1971; Albert, 2003; Meredith et al., 2003c; Summers and Thorne, 2003). Whistler-mode chorus waves interact with electrons principally outside the plasmapause in a low-density plasma environment (Meredith et al., 2003a). These waves can act as an important local source (by energy diffusion) and loss (by pitch angle scattering) mechanism for relativistic electrons on timescales of the order of several hours to a day (Horne and Thorne, 1998; Summers et al., 1998, 2002, 2007; Horne et al., 2003a, 2005a, b; Glauert and Horne, 2005).

In addition to these processes, we should consider losses to the Earth's magnetopause, which have been found to contribute to rapid outer radiation belt depletions on the timescale of hours (Desorgher et al., 2000; Green et al., 2004; Shprits et al., 2006b). These losses can be very important in the case of intense storms where the Earth's magnetosphere is greatly compressed and drift paths are very distorted (Ukhorskiy et al., 2006).

Bortnik et al. (2006) investigated loss mechanisms during the November 20, 2003 radiation belt dropout event using various spacecraft data. They suggested that for electrons of energy greater than 0.5 MeV the dropout was due to losses to the magnetopause in the high L-shell region ($L>5$) and due to losses from EMIC wave pitch angle scattering at lower L-shells ($L<5$).

In an effort to understand (and perhaps predict) the dynamics of the Earth's radiation environment, we need to take all these physical processes into account. Theoretical predictions may be tested using in situ measurements. The motivation to study MeV electron flux rise times during the recovery phase of magnetic storms comes from the realization that different processes act on different timescales and that the occurrence of some of them is limited to a certain region inside the radiation belts.

Timescales for relativistic electron enhancements during the recovery phase of storms have been reported previously. Baker et al. (1994) used SAMPEX low-altitude data to show that MeV electron fluxes rise fast, on a timescale of 1–2 days or less, for $2.5\leqslant L\leqslant 5$. They found that low L-shells would have such a prominent response remarkable and tried to explain this rapid increase by associating it to high solar wind speed streams observed during these events. However, low-altitude measurements are limited by the fact that the main population, located at the equator, cannot be sampled.

More recent studies have used CRRES near-equatorial particle and wave data to show that relativistic electron enhancements coincide with enhanced whistler-mode chorus wave activity (Meredith et al., 2002a, b, 2003b). More evidence has been provided by theoretical work estimating MeV electron flux rise times due to energization of lower-energy electrons from whistler-mode chorus waves (i.e., that matched observed flux rise times). Horne et al. (2005a) used chorus wave spatial distributions measured by CRRES and estimated—by applying wave–particle quasi-linear theory—that the timescale for an order of magnitude increase of the electron flux at 1 MeV is about 24 h at $L=4.5$. Timescales of the same order have been observed for MeV electron fluxes measured by CRRES (Meredith et al., 2002a, b). These theoretical calculations set the lower limit of expected electron flux rise timescales in this region of space—since radial diffusion is slower than that found here.

Relativistic electron fluxes near geosynchronous orbit have been seen to rise on timescales of the order of 2–3 days and these rises are shown to be well correlated with high solar wind speed (O'Brien et al., 2001; Iles et al., 2002; Dmitriev et al., 2005; Kataoka and Miyoshi, 2006; Vassiliadis et al., 2005). At the geosynchronous orbit ($L=6.6$) radial diffusion—enhanced by ULF wave activity (Elkington et al., 1999; Mathie and Mann, 2000)—is expected to have an important effect on radiation belt electron dynamics (O'Brien et al., 2001). But as we move inwards towards the Earth, in regions where the effect of radial diffusion becomes weaker, we should be able to differentiate better between source mechanisms.

Almost all in-situ energetic particle studies performed in the equatorial $L=4$–6 region have been based on data from CRRES obtained during $\sim$1 year. Equatorial measurements are of interest because it is the region where the whole particle distribution can be observed and studied. Results from these studies have shown that this region is of great importance to radiation belt dynamics as a whole, since it is where various source, loss and transport mechanisms are acting. The Global Positioning System (GPS) orbit is covering this region but not many studies have been published where energetic electron dynamics