

Dynamic modeling of geomagnetic cutoff for the 23–24 November 2001 solar energetic particle event

B. T. Kress,¹ M. K. Hudson,¹ K. L. Perry,¹ and P. L. Slocum²

Received 10 September 2003; revised 21 October 2003; accepted 18 December 2003; published 25 February 2004.

[1] We investigate numerically the time variations of geomagnetic cutoffs of solar energetic particles. As a test case, the geomagnetic cutoff of 25 MeV protons is modeled for the 23–24 November 2001 solar energetic particle (SEP) event. Following *Smart and Shea* [2001], solar energetic particle access is determined by computing the reverse particle trajectories. Magnetospheric fields are obtained from the Lyon-Feder-Mobarry (LFM) global MHD model, which is driven by measured solar wind parameters at the sunward boundary. We find well-defined surfaces of constant cutoff that exhibit dynamic behavior in response to solar wind conditions. We show that dynamic modeling of cutoff surfaces may be used as a tool to investigate SEP access to the inner magnetosphere. The numerical results are compared with proton observations from a highly elliptical orbit (HEO) satellite. The results suggest that an enhancement in the solar wind dynamic pressure plays a role in the observed ion injection. **INDEX TERMS:** 2720 Magnetospheric Physics: Energetic particles, trapped; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2753 Magnetospheric Physics: Numerical modeling; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions. **Citation:** Kress, B. T., M. K. Hudson, K. L. Perry, and P. L. Slocum (2004), Dynamic modeling of geomagnetic cutoff for the 23–24 November 2001 solar energetic particle event, *Geophys. Res. Lett.*, 31, L04808, doi:10.1029/2003GL018599.

1. Introduction

[2] Ion injections, transport and trapping in the inner magnetosphere have been observed to occur in conjunction with SEP events and geomagnetic storms. A summary of 13 previously reported and 4 additional observations of MeV ion injections during storms, occurring between November 1960 and July 2000, is given by *Lorentzen et al.* [2002]. Occasionally, large variations in radiation belt proton populations result in the formation of distinct new radiation belts [*Blake et al.*, 1992]. *Slocum et al.* [2002] reported 11 SEP events occurring between 4 April 2000 and 31 May 2002, associated with the formation of new radiation belts at $2.0 \lesssim L \lesssim 3.5$. In particular, they study the 24 Nov 2001 storm, which is distinguished by the appearance of a new radiation belt at $L \sim 2.5$ that still persisted through the end

of June 2002, merging with inner zone cosmic ray albedo neutron decay (CRAND) source protons.

[3] Figure 1 shows the omnidirectional flux of $E > 25$ MeV protons from the HEO 1997-068 spacecraft for the month of Nov 2001 (See *Blake et al.* [1997] for HEO orbit). The time resolution of the HEO data is approximately 4 bins per day. However, flux measurements in the inner magnetosphere are only available at ~ 9 hour intervals due to the large portion of orbital time spent near apogee. In this paper we focus on the latter of the two large SEP events appearing in the HEO data. The bin indicated by the arrow corresponds to an inward bound portion of the HEO orbit occurring between 6:30 UT and 9:30 UT on 24 Nov. Significantly enhanced flux levels at $L \leq 4$ are first measured at $\sim 8:00$ UT 24 Nov, although the initial injection may have occurred at any time 0–9 hours earlier. On 23 Nov, after the solar event but before the solar wind disturbance reaches the magnetosphere, 25 MeV solar proton access appears to be limited to L shells above $L \sim 4$.

[4] The processes by which solar ions gain access to the inner magnetosphere, producing long lived stably trapped populations, are not well understood. In each case reported by *Lorentzen et al.* [2002] the measured proton cutoff location is well above the newly formed proton belt, indicating that the protons do not have Stormer orbit access to this region. A number of mechanisms for variations in radiation belt distributions have been suggested. Simulations by *Li et al.* [1993] showed that a large electric field pulse associated with the storm sudden commencement (SSC) could create a new electron belt on a time scale of minutes. This type of shock induced transport has also been used to model the formation of a new proton belt, both in an analytic field model [*Hudson et al.*, 1995] and in fields from an MHD storm simulation [*Hudson et al.*, 1997]. Additionally, enhanced radial diffusion by drift resonance with ULF waves has been suggested as a possible mechanism for radial transport [*Perry et al.*, 2000].

[5] A charged particle's ability to penetrate a magnetic field is determined by its magnetic rigidity, which is defined as its momentum per unit charge. The earth's magnetic field usually shields the inner magnetosphere from direct penetration by MeV solar protons. The degree of geomagnetic shielding is quantified in terms of geomagnetic cutoff. Cutoff refers to a cutoff rigidity, below which particle fluxes are cut off due to magnetic shielding. Each geographic position has a corresponding cutoff rigidity. Previously, effort has been directed at calculating world grids of cutoff rigidities for space dosimetry applications, e.g., *Smart and Shea* [2001] calculate vertical cutoff rigidities using the Tsyganeko magnetospheric model [*Tsyganenko*, 1989]. To our knowledge, this is the first work where geomagnetic cutoffs have been calculated using a dynamic magneto-

¹Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire, USA.

²Space Science Applications Laboratory, The Aerospace Corporation, Los Angeles, California, USA.

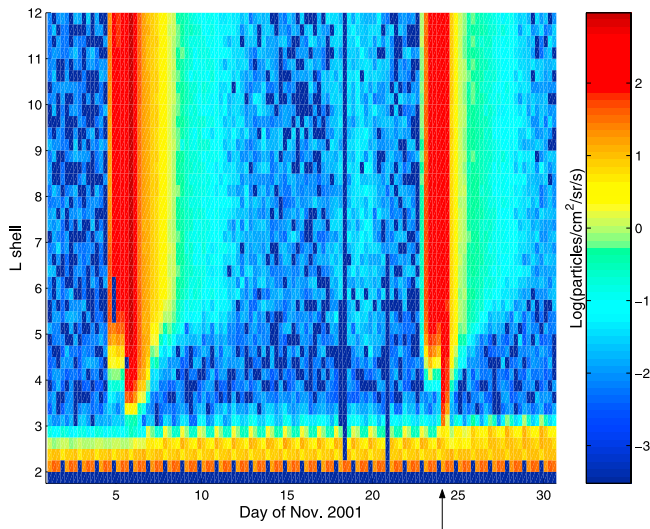


Figure 1. Proton fluxes with $E > 25$ MeV from the HEO 1997–068 spacecraft for the month of Nov 2001. The time resolution of the data is approximately 4 bins per day. The bin indicated by the arrow corresponds to an inward bound portion of the HEO orbit occurring between 6:30 UT and 9:30 UT on 24 Nov [Slocum *et al.*, 2002].

spheric model, except for some preliminary cutoff calculations discussed by Freeman and Orloff [2001]. In this paper, we consider a surface of constant cutoff that shields particles of a given rigidity. Our goal is to study how direct SEP access to the inner magnetosphere is modified by storm conditions.

2. Theory

[6] The equation of motion of a particle with charge q and mass m is

$$\frac{d(\gamma\mathbf{v})}{dt} = \frac{q}{m}(\mathbf{E} + (\mathbf{v} \times \mathbf{B})/c), \quad (1)$$

with CGS units used. $\gamma = 1/\sqrt{1 - v^2/c^2}$ is the relativistic factor, v is the particle velocity, and c is the speed of light. In a pure dipole magnetic field geometry, no closed form solution of (1) has been found except for a few special cases. However, Störmer [1955] showed the existence of an inner forbidden region that an incident particle of a given rigidity can not access. The boundary of this region is defined by the equation

$$r = \sqrt{\frac{Mq}{mvc} \frac{\cos^2 \lambda}{1 + \sqrt{(1 + \cos^3 \lambda)}}}, \quad (2)$$

where M is the dipole moment, λ is the latitude and r is the radial distance from the center of the dipole. From (2) we see that, in a constant dipole magnetic field, a given cutoff surface is defined by the rigidity of the particle. As an example, the red line plot in Figure 2 shows the cross section of a cutoff surface for a 25 MeV proton in a magnetic dipole oriented in the \hat{z} direction, with $M = 8.06 \times 10^{25}$ gauss-cm³. In what follows we will discuss the geomagnetic cutoff in terms of proton energy instead of rigidity. A 25 MeV proton

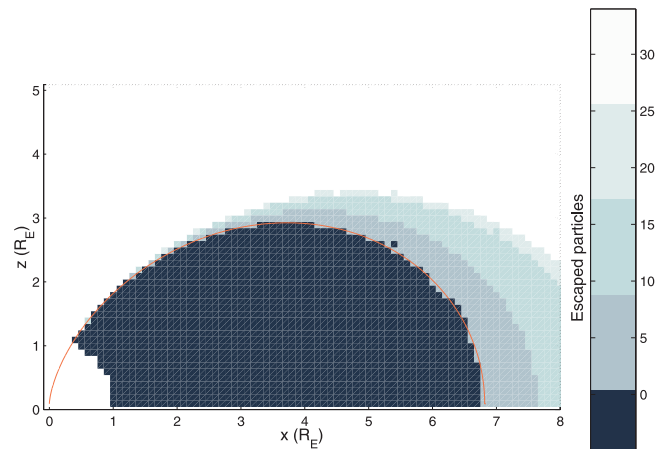


Figure 2. Numerical and analytic cutoff results for a 25 MeV proton in a pure dipole magnetic field oriented in the \hat{z} direction with $M = 8.06 \times 10^{25}$ gauss-cm³. The black shaded area shows the region from which zero particles escape, i.e., there is no direct Störmer orbit access. The red line plot is Störmer's analytic result given by equation (2). No particles were launched from points with $r < 1 R_E$.

corresponds to a rigidity of 0.22 GV. All distances are expressed in units of earth radii (R_E).

3. Computational Method

[7] Equation (1) is solved using a 4th order Runge-Kutta integrator with the step size adjusted at each step to be 1% of the instantaneous gyro period of the particle. The magnetospheric fields are generated by the LFM global MHD model. The 24 Nov 2001 solar wind parameters used to drive the LFM code are shown in Figure 3. In this work we follow the proton trajectories in static fields, without interpolation between MHD time steps. Note that, a 25 MeV

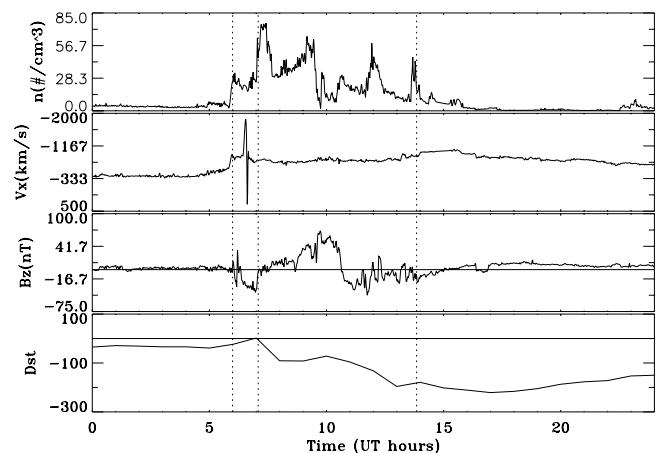


Figure 3. Nov 2001 Wind satellite data given in SM coordinates used to drive the LFM magnetospheric model. Measured values for the other magnetic and velocity field components and plasma temperature are also used but not shown here. Also shown is the Dst index from the WDC-C2 KYOTO Dst index service.

proton traverses $\sim 1/4$ of the computational domain in a single MHD time step of 0.25 seconds. Here, we do not include effects of diffusion or scattering processes, but only consider direct Störmer orbit access. As will be shown, the change in the geomagnetic field configuration over the course of a storm substantially changes the direct access of protons to the inner magnetosphere in a dynamic model.

[8] SEP access is determined by launching a particle and following its trajectory backwards in time. If the particle escapes the magnetosphere then the trajectory is considered viable, indicating SEP access to the point from which it was launched. In this work we define an escaped particle as one that exits $15 R_E$ before its total trajectory path length exceeds $1000 R_E$. The cutoff is located by launching particles from points on a spatial grid with their velocities uniformly distributed over all directions. No attempt is made to distribute the velocities in directions where access is most likely, although this refinement would be one way to make the method more efficient. An additional modification that will greatly improve efficiency is to locate the cutoff surface with a suitable search algorithm, rather than launching particles from a uniform grid.

[9] As a test, 25 MeV particles were launched in a pure dipole magnetic field with $M = 8.06 \times 10^{25}$ gauss-cm³. 34 particles were launched from each of 3321 points on a 81×41 grid over an $8 R_E \times 4 R_E$ region in the meridional plane, i.e., with a resolution of $0.1 R_E$. The results are shown in Figure 2. The color bar gives the number of escaped particles out of 34 at each point, with black indicating zero escaped particles. The boundary of the black region is the cutoff surface. The results are in good agreement with the analytic solution shown by the red line plot. Note that the raw computational results have been plotted with no interpolation. That is, each 0.1×0.1 surface plot facet represents the number of escaped particles from the point located at its center.

4. Results

[10] Figure 4 shows the modeled geomagnetic cutoff for 25 MeV protons at four snapshots in time from the MHD simulation. Each plot was produced by launching ~ 2 million particles: 106 particles were launched from each of 18000 points. The inner circle at $2.4 R_E$ is the inner boundary of our magnetospheric model. In each case, the plot shows a cross section of the cutoff surface (boundary of black region) in the x - z plane, corresponding to the noon-midnight sector in SM coordinates [Kivelson and Russell, 1995].

[11] The times shown in Figure 4 are: (a) 23:12 UT 23 Nov corresponding to a quiet pre-storm time, (b) 5:59 UT 24 Nov at the arrival of the initial shock in the inner magnetosphere, (c) 7:05 UT 24 Nov during a period of maximum solar wind density and dynamic pressure, and (d) 13:29 UT 24 Nov after a prolonged period of southward IMF when the Dst index is significantly enhanced. The latter three times are indicated in Figure 3 by the vertical dashed lines. The pre-storm location of the simulated cutoff shown in Figure 4a roughly corresponds to a surface of constant L shell at $L \sim 5.5$. The maximum earthward displacement to $L \sim 3.5$ shown in Figure 4c occurs at $\sim 7:05$ UT 24 Nov. Additional times during the storm were examined. It was

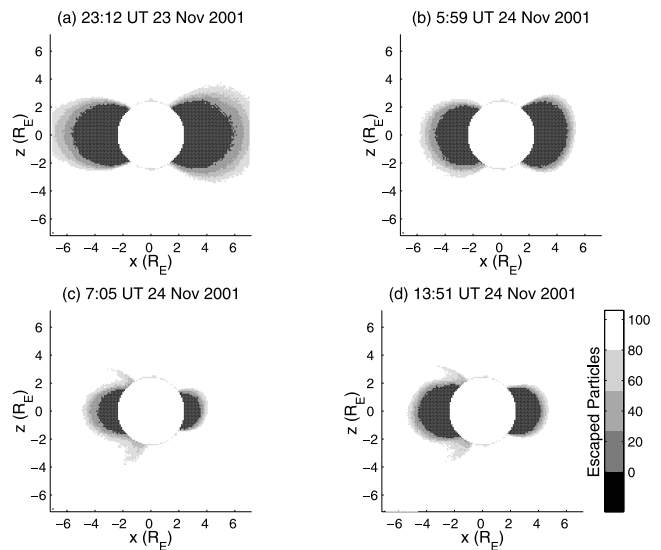


Figure 4. Modeled 25 MeV proton cutoff in SM coordinates at four snapshots in time from the MHD simulation. The boundary of the black shaded region is the cutoff surface. The cutoff is determined by following reverse particle trajectories. An escaped particle is one which exits a sphere at $r = 15 R_E$ before its total trajectory path length exceeds $1000 R_E$.

determined that the greatest earthward displacement of the 25 MeV proton cutoff surface occurred during the period of enhanced solar wind density, corresponding to a maximum compression of the geomagnetic field.

5. Discussion and Conclusions

[12] The storm simulation produces an earthward displacement of the 25 MeV proton cutoff surface, which reaches a maximum during a period of maximum solar wind density. The degree to which the cutoff surface is compressed is striking, indicating that direct access of SEPs plays a significant role in the observed ion injection. This earthward displacement coincides with the sudden proton injection observed in the HEO satellite data shown in Figure 1, although the time resolution of the data limits our ability to pinpoint the time of the injection. Examination of low altitude SAMPEX MAST data with a 90 minute orbital period shows evidence for SEP access to $L \sim 2.6$ at the time of the high density solar wind impulse arrival in the inner magnetosphere ($\sim 07:05$ UT), although the SAMPEX orbit is not favorable for making this determination until several hours later due to orbital plane position relative to the South Atlantic Anomaly (*J. B. Blake*, private communication).

[13] An ideal MHD description of the magnetosphere does not include a number of physical processes that are relevant to modeling geomagnetic cutoff. Perhaps the most important is the ring current. Current efforts to couple the LFM code with the Rice Convection Model (RCM), which models the inner magnetosphere using an adiabatic-drift formalism, will improve future cutoff calculations by including the effects of the ring current. It has been suggested that variation in the geomagnetic cutoff is caused

by suppression of the equatorial magnetic field due to ring current buildup [Leske *et al.*, 2001]. However, it is interesting to note that during the 24 Nov 2001 storm, significantly elevated flux levels first appear in the inner magnetosphere >10 hours prior to the minimum Dst, occurring at 18:00 UT. The Dst index indicates that the ring current buildup was not as significant at 5:59 UT nor 7:05 UT, relative to 13:51 UT where we would expect a significant ring current perturbation not included in the model. Thus, we would not expect Figures 4b and 4c to be greatly affected by the lack of a ring current in the model.

[14] A direct quantitative comparison between the numerical results and the HEO data is not possible since an IGRF field model, which does not take into account the compression of the magnetosphere by the solar wind, is used to map the measured fluxes to the equatorial plane. However, one would expect the IGRF model to be a close approximation to the geomagnetic field in the inner zone where the new belt forms. Thus, the model results corresponding to 7:05 UT shown in Figure 4c indicate that an additional source of radial transport is necessary to explain SEP access to $L < 3$.

[15] In summary, our primary conclusion is that: In the 24 Nov 2001 storm, the observed proton injection and subsequent formation of a new radiation belt was triggered by a large solar wind density enhancement, which caused a dramatic compression of the SEP proton cutoff allowing direct MeV SEP access to $L \sim 3.5$. Additionally, in an ideal MHD magnetospheric model, the increased solar wind dynamic pressure due to a large density enhancement has a greater effect on compressing the equatorial position of the SEP cutoff than either the arrival of the leading shock front or significant Dst buildup after an extended interval of southward IMF B_z . In our model, ~ 25 MeV protons do not have direct access to $L < 3$ where the new belt appears. This suggests that resonant interaction with a shock induced pulse, as in Hudson *et al.* [1997], or other magnetospheric disturbance are an important source of radial transport in the inner zone. Further work is needed to fully understand the mechanisms for transport and trapping. Future work will include modeling of other high speed CME events, which produce a significant SEP source population and high density solar wind impulse. We will include inductive and diffusive processes by following the ion trajectories in time dependent fields, generated by the fully coupled LFM and RCM codes.

[16] **Acknowledgments.** This material is based upon work supported in part by the STC Program of the National Science Foundation under

Agreement Number ATM-0120950. Additional funding is from NASA LWS grant NAG5-12202. Many thanks to J.B. Blake at The Aerospace Corporation for providing HEO and SAMPEX data and helpful discussions. We thank J.G. Lyon and M.J. Wiltberger for providing 23–24 Nov 2001 LFM storm simulation results. We acknowledge data providers R. Lepping and K. Oglivie at NASA/GSFC and CDAWeb for the Wind data.

References

- Blake, J. B., W. A. Kolasinski, R. W. Fillius, and E. G. Mullen (1992), Injection of electrons and protons with energies of tens of MeV into $L > 4$ on 24 March 1991, *Geophys. Res. Lett.*, *19*(8), 821.
- Blake, J. B., D. N. Baker, N. Turner, K. W. Oglivie, and R. R. Lepping (1997), Correlation of changes in the outer-zone relativistic-electron population with upstream solar wind and magnetic field measurements, *Geophys. Res. Lett.*, *24*(8), 927.
- Freeman, J. W., and S. Orloff (2001), Specifying geomagnetic cutoffs for solar energetic particles, *AGU Monograph*, *125*, 191.
- Hudson, M. K., A. D. Kotelnikov, X. Li, I. Roth, M. Temerin, J. Wygant, J. B. Blake, and M. S. Gussenhoven (1995), Simulations of proton radiation belt formation during the March 24, 1991 SSC, *Geophys. Res. Lett.*, *22*(3), 291.
- Hudson, M. K., S. R. Elkington, J. G. Lyon, V. A. Marchenko, I. Roth, M. Temerin, J. B. Blake, M. S. Gussenhoven, and J. R. Wygant (1997), Simulations of proton radiation belt formation during storm sudden commencements, *J. Geophys. Res.*, *102*(A7), 14,087–14,102.
- Kivelson, M. G., and C. T. Russell (1995), *Introduction to Space Physics*, Cambridge Univ. Press, pg. 538.
- Leske, R. A., R. A. Mewaldt, and E. C. Stone (2001), Observations of geomagnetic cutoff variations during solar energetic particle events and implications for the radiation environment at the Space Station, *J. Geophys. Res.*, *106*(A12), 30,011–30,022.
- Li, X., I. Roth, M. Temerin, J. R. Wygant, M. K. Hudson, and J. B. Blake (1993), Simulations of the prompt energization and transport of radiation belt particles during the March 24, 1991 SSC, *Geophys. Res. Lett.*, *20*(22), 2423.
- Lorentzen, K. R., J. E. Mazur, M. E. Loper, J. F. Fennell, and J. B. Blake (2002), Multisatellite observations of MeV ion injections during storms, *J. Geophys. Res.*, *107*(A9), 1231, doi:10.1029/2001JA000276.
- Perry, K. L., M. K. Hudson, and S. R. Elkington (2000), Drift-resonant acceleration of protons via global ULF waves, *Eos Trans. AGU*, *81*(48), Fall Meet. Suppl., F1004.
- Slocum, P. L., K. R. Lorentzen, J. B. Blake, J. F. Fennell, M. K. Hudson, M. D. Looper, G. M. Masson, and J. E. Mazur (2002), Observations of ion injections during large solar particle events, AGU Fall Meeting, SH61A-0501.
- Smart, D. F., and M. A. Shea (2001), A comparison of the Tsyganenko model predicted and measured geomagnetic cutoff latitudes, *Adv. Space Res.*, *28*, 1733–1738.
- Smart, D. F., M. A. Shea, and E. O. Fluckiger (2000), Magnetospheric models and trajectory computations, *Space Science Reviews*, *93*, 305–333.
- Störmer, C. (1955), *The Polar Aurora*, Oxford Univ. Press, pg. 236.
- Tsyganenko, N. A. (1989), Determination of magnetospheric current system parameters and development of experimental geomagnetic field models based on data from IMP and HEOS satellites, *Planet Space Sci.*, *37*, 5–20.

M. K. Hudson, B. T. Kress, and K. L. Perry, Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755, USA. (bkress@dartmouth.edu)

P. L. Slocum, Space Science Applications Laboratory, The Aerospace Corporation, Los Angeles, CA, USA.