MeV Electron Populations as Measured on DMSP

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Abstract

A dosimeter flown on the DMSP F7 spacecraft during solar minimum from January 1984 through October 1987 measured electron fluxes and dose behind four different dome thicknesses. The spacecraft was in an 840 km, circular, polar orbit with a 101 minute orbit period. Using sophisticated display and analysis software developed for the CRRES program, the DMSP data base was re-examined. Displays of the data set uncovered previously unseen phenomena to include > 2.5 MeV electron penetrations to low magnetic latitudes during magnetospheric storm periods. During three periods (1 August 1984, 8-9 February 1986 and 12 September 1986) the > 2.5 MeV electrons were measured penetrating all the way to the magnetic equator. This is the first known report of these particles at the magnetic equator at 840 km. The particle penetrations occurred during periods of high magnetic activity as indicated by K_p and other indices.

radiation belts, we discovered another dynamic phenomenon in the high energy electrons which also presently defies current textbook explanation. MeV electrons appear far equatorward of typical outer zone latitudes (in some cases all the way to the magnetic equator) during magnetically disturbed periods as measured by K_p . Although the particles have only been seen to persist for 2 DMSP orbits (approximately 3 hours), their high energy (> 2.5 MeV) could be hazardous to space systems and EVA activities. In any event, the phenomenon needs to be better measured, modelled and understood if we plan to expose man to long periods of EVA in space.

The paper below is divided into 3 sections, data presentation, magnetospheric conditions and a discussion. The periods to be studied are the 5 periods of lowest latitude (lower than 20° North Magnetic Latitude) penetration of > 2.5 MeV electrons measured on DMSP between January 1984 and October 1987. The periods are given in Table I together with the K_p value at the time of the events. The instrument used to make the measurements is well documented in the articles referenced above, and will not be discussed here.

I. INTRODUCTION

Data from the Combined Release and Radiation Effects Satellite (CRRES) have demonstrated conclusively that additional radiation belts can be formed in the inner magnetosphere under certain conditions. The largest event that was measured during the 14 month lifetime of CRRES occurred in March 1991. Following the passage of a large solar wind shock (initiating a strong Storm Sudden Commencement), in the midst of an intense, high energy solar particle event, a second proton belt with energies up to 50 MeV and a third electron belt with energies in excess of 30 MeV formed in the slot region, between 2 and 3 R_E . This major change in the inner magnetosphere has been documented in [1-3], and dose maps of the newly configured radiation belts can be found in [4-5].

The dynamical processes that control the formation of these additional belts are not understood at this time. In fact, only since the verification of the belts using CRRES data has the problem been taken seriously. Previous early indications of a second belt by McIlwain [6] and low altitude measurements of additional belts by a dosimeter on the DMSP/F7 satellite [7] were largely ignored. The CRRES data have rejuvenated interest in inner magnetosphere particle dynamics.

As part of the process to understand the phenomena related to major solar-initiated disturbances of the radiation belts, we re-examined the DMSP dosimeter data using the sophisticated data display software developed for CRRES. Instead of revealing an understanding of the formation of the additional

TABLE I

PERIODS > 2.5 MeV ELECTRONS REACHED 20° N.
 MAGNETIC LATITUDE

DATE	TIME FIRST OBS.	EQUATOR	NO. PASSES	KP
01 AUG 84	09:35 UT	YES	1	6
05 SEP 84	08:10 UT	NO	2	6+
08 FEB 86	22:11 UT	YES	2	9-
12 SEP 86	08:45 UT	YES	2	7+
13 OCT 86	20:57 UT	NO	1	7-

II. DATA PRESENTATION

The data in this paper were taken behind dome 2 for low linear energy transfer (LOLET) particles which deposit 50 keV to 1 MeV in a silicon detector behind a hemispherical detector 232.5 mils aluminum thick (1.55 gm/cm^2). The particles that can produce valid counts in the detector are > 2.5 MeV electrons and > 135 MeV protons. (All the particles of interest for this study are assumed to be electrons, since protons were not seen in other detector channels on the dosimeter at the time of the events.) Since the detector measures particles over 180° inside a hemispherical dome,

pitch angle information on the particles which might help in determining the source region is not available. The data were binned in 1° latitude and in 4 separate longitude regions of 0 to 90° , 90 to 180° , 180 to 270° , and 270 to 360° . Daily averages were calculated for each bin. Approximately 4 years of data were collected and processed from 1984 through 1987.

Figure 1 shows the daily average LOLET flux counts (in raw counts) for 1986 in the 0 to 90° longitude region as a function of geomagnetic latitude in degrees. The enhanced bands near 60° latitude are the horns of the outer zone electrons as projected down to 840 km. The asymmetry of the flux levels, North versus South, is due to the offset dipole of the Earth. The enhanced band between -35 and $+20^\circ$ latitude is the South Atlantic Anomaly (SAA) which contains both electron and proton data. (The SAA is not the subject of this paper.) The filling of the region between the outer and inner belts south of the SAA happened during the formation of additional electron and proton belts in February 1986 [7]. The additional electron belt created during the February event is seen to slowly degrade over an approximately six month period at this altitude. The lack of any particle penetration between approximately 20 and 35° North Latitude should be noted.

Figure 1: Daily averages of >2.5 MeV electron (and >135 MeV proton) flux counts measured between longitudes of 0 and 90° for 1986.

Figure 2 is similar to Figure 1 except that it is for the 180 to 270° longitude region, directly opposite the SAA where inner belt particles mirror above the 840 km altitude of the satellite. The outer zone horns are again seen as intensifications near 60° magnetic latitude, but here they are more symmetric since the magnetic field is closer to equal intensity North and South. Three periods, 8-9 February 1986, 12 September 1986 and 13 October 1986, show >2.5 MeV electrons penetrating out of the outer zone region down toward (and in the first two cases through) the magnetic equator. How these particles can penetrate to such low magnetic latitudes is at this time a mystery, not explainable by existing theory and/or diffusion processes. Since these levels of high energy electron penetrations have never been reported before,

the problem has not been addressed. If these particles are found to extend to lower altitudes where the Space Station can and will operate, to perform EVA will be more hazardous, and prediction capabilities for onset, intensity level and lifetime of these events will be necessary.

Figure 2: Daily averages of >2.5 MeV electron (and >135 MeV proton) flux counts measured between longitudes of 180 and 270° for 1986.

Figure 3 shows a blowup of the period from 1 January through 1 April 1986 from Figure 2 with a gray scale adjustment to accent the high levels of variability in the outer zone MeV electrons. These electron increases have been reported previously [8] and have been attributed to energization by an induced substorm electric field within the magnetosphere [9]. Fujimoto and Nishida [10], on the other hand, propose a recirculation process for energization of electrons in the radiation belt. Whatever the mechanism, getting high energy electrons into the higher latitudes is not the question of interest in this paper. The question is, "how do the particles supposedly cross the magnetic field lines so easily to get all the way to the equator?". The figure shows the relatively high level of fluxes near the magnetic equator on 8 February 1986. The intensity variation from South to North (the direction the satellite was travelling when the electrons were measured) is believed to be a temporal variation and not a positional variation. There is no reason to believe that the mechanism that transported the electrons across field lines is exclusive to this altitude. In fact there is some evidence of this phenomenon near 20000 km as measured by a Los Alamos Scientific Laboratory (LASL) dosimeter on one of the Global Positioning Satellites (GPS) during this event [11]. If the hypothesis holds that this process is altitude independent, then at any altitude when large increases of MeV electrons occur in the outer zones, there is the possibility that MeV electrons will extend to low latitudes, and perhaps, all the way to the equator. Since these are transient events, they will only be seen if the observation platform is in the right place at the right time, and their relative infrequency makes them extremely difficult to detect or monitor. Other indicators which will be addressed below may be used to provide alerts

of these events.

Figure 3: Daily averages of >2.5 MeV electron (and >135 MeV proton) flux counts between longitudes of 180 and 270° for the period from 1 January to 1 April 1986.

Figure 4 shows a time profile of 1 minute relative flux values as a function of Universal Time (UT) for protons >35 MeV (top), electrons >1 MeV plus protons >130 MeV (middle), and electrons >2.5 MeV and protons >135 MeV (bottom) for a selected period on 8 and 9 February 1986. During the 8 hour period shown, the satellite starts in the Southern outer zone region moving southward. The satellite then goes through the Southern polar cap and starts north going through the Southern outer zone again; then through the low latitude region opposite the SAA; through the northern outer zone, polar cap and outer zone again; and then through the low latitudes and SAA before starting over again in the Southern outer zone. The satellite makes 5 passes through the region of interest during this time interval. The high latitude (polar cap and normal outer electron zone) region, the low latitude region where deep electron penetration occurs, and the SAA region are gray-scaled from lightest to darkest, respectively. Here, the electron penetrations in the bottom 2 panels are seen all the way from one outer zone horn to the other. They are not accompanied by protons as can be seen by the lack of any enhancement in the top panel. They are also as intense for the >2.5 MeV electrons at the low magnetic latitudes as they are in the outer zone horns. For this event the deep electron penetration lasted for 2 orbits (the longest event seen), at least 2 hours. It is believed that since the time it takes for 2.5 MeV electrons to make one full revolution about the Earth at this altitude is about 40 minutes, and since the particles are not seen at all longitudes, they must be only quasi-trapped. If they are only quasi-trapped, this would mean that the source would have to last over one hour. This is much longer than the injection events seen on CRRES, and therefore must be associated with additional dynamic processes. This event occurred on the dayside of the Earth, but other events, such as the September 1986 event, occurred on the nightside; so, although longitude is a factor at 840 km, local time is not.

Figure 4: 1 minute relative flux values as a function of UT for HILET Dome 2 (top), LOLET Dome 1 (middle) and LOLET Dome 2 (bottom) for selected periods on 8 and 9 February 1986. The high latitude (polar cap and outer zone electron horn) region, low latitude electron penetration region, and SAA region are gray-scaled from lightest to darkest, respectively.

III. MAGNETOSPHERIC CONDITIONS

The state of the magnetosphere at any specific instant is a complex function of the external conditions impinging on it such as solar wind speed and plasma density, solar particle energies and flux levels, interplanetary magnetic field intensity and direction, and internal conditions such as previous field and particle conditions, orientation of the geographic and geomagnetic axes, thermal conditions, and current systems. In spite of the ultra complexity of the dynamic processes, near-Earth indices such as the worldwide geomagnetic index (K_p), the auroral electrojet index (AE), the ring current index (Dst) ([12] and references therein for the magnetic indices) and the auroral boundary index [13] can be used to gain a general idea of the magnetosphere stability level at any time. The simplest parameter to obtain and the one most commonly used, K_p , is included in Table I for the 5 periods under study. In all cases the events occurred during periods when K_p was 5 or greater, indicating large magnetic storms. Below we will examine the Dst and auroral boundary indices to better understand the exact magnetospheric conditions during the low latitude electron events.

Figure 5 is the hourly Dst index as determined from ground station magnetometers for the 5 months of the events under study (August 1984, September 1984, February 1986, September 1986 and October 1986 from top to bottom) plotted versus day of month. The Dst for all of the events exceeded -100 nT with the February event exceeding -300 nT. Since the Dst is an indicator of the strength of large scale current systems (primarily the ring current), large changes in Dst indicate that large amounts of energy have been injected into the current system. This implies that the magnetic substorm(s)

which provided the energy must have been very large and major magnetic variations must have occurred throughout the magnetosphere. All the events seen on DMSP occurred during large changes in Dst, although events were not seen during all large changes in Dst. This is not surprising since satellite position is crucial to observing the electrons.

Figure 5: Hourly Dst index plotted as index in nT versus day of month for the 5 months of the events under study (August 1984, September 1984, February 1986, September 1986 and October 1986 from top to bottom).

Figure 6 is the equivalent midnight boundary of the auroral oval plotted as a function of magnetic latitude versus day of month in the same general format as Figure 5 above. This boundary represents the maximum southward movement of 100 eV electrons (although other electron energies up to 30 keV are used in deriving the index). Here we see that the low energy particles move southward, in most cases rapidly southward, during the event periods listed in Table I. This southward motion is not unlike the southward movement of the >2.5 MeV electrons seen in Figures 2 and 3, even though the higher energy particles seem to come in faster, further, later and last longer except at the lowest latitudes where they do not become stably trapped. All the indices taken together indicate a period of major activity in the magnetosphere during the high energy electron events.

IV. DISCUSSION

We have seen that >2.5 MeV electrons can penetrate all the way to the magnetic equator at 840 km at longitudes opposite the SAA during periods of major magnetospheric disturbances as indicated by magnetic and auroral oval indices. The phenomenon, although it may be associated with additional radiation belt formations, is not the same as that

Figure 6: Equivalent midnight boundaries of the auroral oval plotted as a function of magnetic latitude versus day of month for the 5 months of the events under study (August 1984, September 1984, February 1986, September 1986 and October 1986 from top to bottom).

which created new high energy electron and proton belts in February 1986 and March 1991. Each of the electron events observed lasted only briefly, less than 2 to 3 hours, and occurred during highly active magnetic conditions. In the February 1986 event the electrons were observed on the dayside while in September 1986 they were observed on the nightside indicating no local time effect.

Looking back at Figure 2, we see that >2.5 MeV electrons routinely get into the outer belt regions at 840 km and are very dynamic in nature. They are, in fact, an important part of the outer zone electron population. We also know that the process by which they are accelerated up to MeV energies and gain entry into the outer belt regions are still not fully understood, although induction electric fields are felt to play a major role. (Magnetic fields can vary, but they can't increase the energy of a particle.) Given that the particles are available at high latitudes at 840 km, given that there are major gradients and decreases in the magnetic field strength during the electron events listed in Table I, and given that the particles are not seen to rapidly move in and out in L-shell like the injection events that produced the new radiation belts in March 91 as detected on the CRRES satellite, it is not unreasonable to believe that some sort of a cross-field diffusion process could move the particles in toward the magnetic equator. Nishida [14] suggested that at low altitudes a cross-field diffusion process could be used to transport particles into the magnetosphere (in his case that of Jupiter) "If the solar wind particles penetrate directly to low altitudes in the polar region, as in the Earth's cleft (or here the Earth's outer electron zone), they can be transported toward lower

latitudes across the field by the diffusion process, violating both second and third invariants; the diffusion flux is directed inward in this case as the source of particles is located on outer magnetic shells." This may or may not prove to be the mechanism, but some sort of cross-field movement is necessary to explain the events measured on DMSP.

Gussenhoven et al [15] showed that electron dose behind a dome thickness shielding of 0.55 gm/cm^2 (82.5 mils aluminum) for the highest average flux contours in the longitude region between 180 and 270° was between 3 and 10 rads(Si) per day (3.5×10^{-5} and 1.16×10^{-4} rads (Si) per second). If we assume that the dose in the event periods described here could reach as high as the highest average dose in the outer zone region at these longitudes, and if we assume that this dose can last up to 3 hours, then a single event could give as much as 1.25 rads (Si) behind 0.55 gm/cm^2 of shielding at 840 km if someone or something was exposed to it for the whole 3 hours (not a realistic assumption for most orbits). How these numbers would translate down to lower altitudes is not known. For the space station studies it was stated that "Exposures to the trapped-electron belts are expected to be small" [16], presumably due to the low inclination of the orbit. However, with these new data available, further studies might be warranted especially as related to EVA activities.

V. REFERENCES

- [1] E.G. Mullen, M.S. Gussenhoven, K. Ray and M. Violet, "A double-peaked inner radiation belt: Cause and effect as seen on CRRES", *IEEE Trans. Nucl. Sci.*, **38**, 1713, 1991.
- [2] J.B. Blake, M.S. Gussenhoven, E.G. Mullen, and R.W. Filius, "Identification of an unexpected electron space radiation hazard", *IEEE Trans. Nucl. Sci.*, **39**, 1761, 1992.
- [3] J.B. Blake, W.A. Kolasinski, R.W. Filius, and E.G. Mullen, "Injection of electrons and protons with energies of tens of MeV into $L < 3$ on 24 March 1991", *Geophys. Res. Lett.*, **19**, 821, 1992.
- [4] M.S. Gussenhoven, E.G. Mullen, D.H. Brautigam, E. Holeman, C. Jordan, F. Hanser and B. Dichter, "Preliminary comparison of dose measurements on CRRES to NASA model predictions", *IEEE Trans. Nucl. Sci.*, **38**, 1655, 1991.
- [5] M.S. Gussenhoven, E.G. Mullen, M. Sperry, K.J. Kerns and J.B. Blake, "The effect of the March 1991 storm on accumulated dose for selected satellite orbits: CRRES dose models", *IEEE Trans. Nucl. Sci.*, **39**, 1765, Dec. 1992.
- [6] C.E. Mellwain, "The radiation belts, natural and artificial", *Science*, **142**, 355, 1963.
- [7] M.S. Gussenhoven, E.G. Mullen, and E. Holeman, "Radiation belt dynamics during solar minimum", *IEEE Trans. Nucl. Sci.*, **36**, 2008, 1989.
- [8] S.M. Krimigis and E.T. Sarris, "Energetic particle bursts in the Earth's magnetotail", *Dynamics of the Magnetosphere*, D. Reisel Publishing Company, p. 599-630, 1979.
- [9] R.J. Pellinen and W.J. Heikkila, "Energization of charged particles to high energies by an induced substorm electric field within the magnetotail", *Jour. of Geophys. Res.*, **83**, 1544, 1978.
- [10] M. Fujimoto and A. Nishida, "Energization and anisotropization of energetic electrons in the Earth's radiation belt by the recirculation process", *Jour. of Geophys. Res.*, **95**, 4265, 1990.
- [11] T. Cayton, private communication, July 1993.
- [12] G. Rostoker, Geomagnetic Indices, *Reviews of Geophys. and Space Phys.*, **10**, 995, 1972.
- [13] D. Madden and M.S. Gussenhoven, Auroral Boundary Index from 1983 to 1990, GL-TR-90-0358, 37 p, Dec. 1990.
- [14] A. Nishida, "Outward diffusion of energetic particles from the Jovian radiation belt", *Jour. of Geophys. Res.*, **81**, 1976.
- [15] M.S. Gussenhoven, E.G. Mullen, R.C. Filz, D.H. Brautigam and F.A. Hanser, "New low-altitude dose measurements", *IEEE Trans. Nucl. Sci.*, **34**, 676, 1987.
- [16] F.A. Cucinotta, W. Atwell, M. Weyland, A.C. Hardy, J.W. Wilson, L.W. Townsend, J.L. Shinn and R. Katz, "Radiation risk predictions for Space Station Freedom Orbits", NASA Technical Paper 3098, 20 p, June 1991.