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Identification of an Unexpected Space Radiation Hazard

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Prepared by

J. B. BLAKE
Space and Environment Technology Center
Technology Operations
The Aerospace Corporation
El Segundo, CA 90003

M. S. GUSSENHOVEN AND E. G. MULLEN
Phillips Laboratory/GPSP
Hanscom AFB, MA 10731

R. W. Fillius
University of California, San Diego
La Jolla, CA 92093

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE MATERIEL COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

Engineering and Technology Group

THE AEROSPACE CORPORATION
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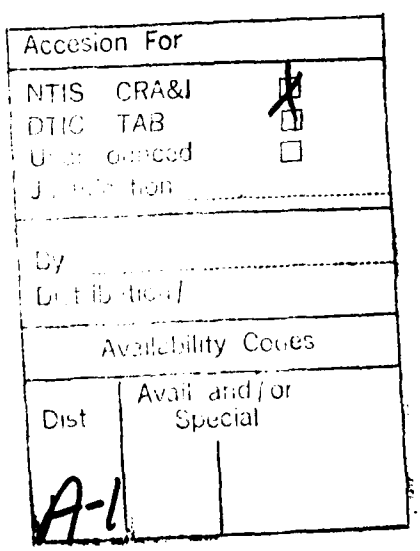
Capt. Leslie Belsma, Captain USAF
Project Officer

Wm. Kyle Sneddon, Captain USAF
Deputy, Industrial & International Division



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Identification of an Unexpected Space Radiation Hazard

J. B. Blake[1], M.S. Gussenhoven[2], E.G. Mullen[2], and R.W. Fillius[3]

Abstract

A new radiation belt was formed on 24 March 1991 by the interaction of a strong shock in the solar wind with the Earth's magnetosphere. This brief report describes observations of the moment of creation by sensors aboard the CRRES (Combined Release and Radiation Effects Satellite).

I. INTRODUCTION

On 22 March 1991 at 22:47 UT an X-ray event and a 3B optical flare were observed on the Sun. These occurrences were followed almost four hours later by another solar X-ray event. Energetic particles, both ions and electrons, began to arrive in the vicinity of the Earth about 0730 UT on 23 March. These particles were followed by the arrival of a strong shock in the solar wind at the Earth at 03:42 UT on 24 March, presumably from the solar–flare events mentioned above, although this assignment is not certain. Almost immediately following arrival of the shock, sensors aboard CRRES (Combined Release and Radiation Effects Satellite) observed the injection of protons and electrons with energies of 10s of MeV to form a new radiation belt between the well-known Inner Zone and Outer Zone.

The energies and intensities of the newly-injected particles were such that they greatly increased the radiation dose received by a spacecraft in the region of space occupied by the new radiation belt. The purpose of this paper is to describe how the content of this new radiation belt was determined.

II. SATELLITE AND INSTRUMENTATION

The CRRES satellite was launched on 25 July 1990 into an orbit with an apogee of 33,575 km, a perigee of 323 km, and an inclination of 18.2°. The observations discussed in this paper were made with four different sensors.

One of these sensors was nearly identical to that flown as part of the University of California, San Diego (UCSD) complement aboard Pioneer 10 and Pioneer 11 by Fillius and McIlwain [1], a Cerenkov counter employing a water-methanol radiator. A photomultiplier detected the optical radiation (Cerenkov light) emitted by a particle that exceeded the speed of light in the radiator. (Recall that the speed of light is a function of the index of refraction of the medium, about 1.28 in water-methanol). The three nominal energy thresholds were > 6 MeV, > 9 MeV, and > 13 MeV for electrons. The proton energy thresholds were hundreds of MeV. The Cerenkov counter had directional sensitivity. In the following for convenience, we will refer to the Cerenkov channels by their electron thresholds.

The second and third sensors consisted of single, shielded silicon detectors. The sensors were described by Blake and Imamoto [2]. The two shields required protons to have 20 MeV and 50 MeV, respectively, to penetrate, and the electronic thresholds were set high enough to ensure that there was no sensitivity to electrons of any energy. The nominal proton energy channels were 20 to 80 MeV and 50 to 110 MeV.

The fifth sensor was a telescope consisting of a stack of 6 silicon detectors. There were 16 energy channels from 6 to 100 MeV. The instrument is discussed in detail by Violet et al. [3].

III. OBSERVATIONS AND DISCUSSION

Figure 1 shows the countrate in the e > 6 MeV and p 20 to 80 channels as a function of time as CRRES moved inbound at a distance from the surface of the Earth of approximately 1.65 R_E (L ≈ 1.65). The plot begins just prior to arrival of the shock at the Earth. The countrate is low in both channels as would be expected in the region between the Inner Zone and Outer Zone. This region is often referred to as the Slot Region for obvious reasons. Abruptly, both channels show orders-of-magnitude increases in countrate as well a strange,

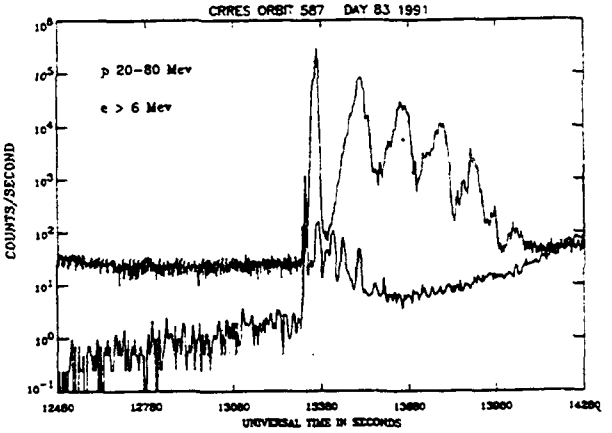

Figure 1. A plot of the countrate in the 20 to 80 MeV and e > 6 MeV channels as CRRES moved inbound during the time period of the arrival of the strong shock in the solar wind. The enormous increases in countrate occurred within approximately one minute of the arrival of the shock at the boundary of the magnetosphere. The electron channel saturated the counter in the data system. The actual countrate exceeded 10^6 per second.

"picket fence" structure. In fact, the first peak in the electron channel would be an order of magnitude larger except that its scaler has rolled over. Subsequently, CRRES moves below an altitude of 1.0 R_E (L = 2) and out of the region of newly injected particles.

The interpretation of the structure is outlined in Figure 2, which is a cartoon of the event. If particles are injected in an

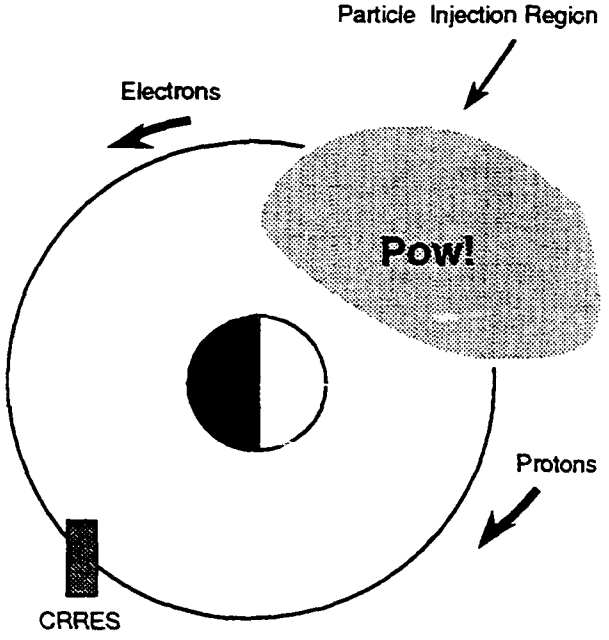

Figure 2. A cartoon of the injection event. The positive and negative particles move around the Earth in opposite directions and, as they move, they spread out because of differing energy and particle identity.

apparently localized region in the Earth's magnetosphere, they will move in packets around the Earth, repeatedly passing the observer. Because the drift speed is energy-dependent, the particles spread out in longitude with time. In the scientific literature, these packets are referred to as "drift echoes." Figure 3 shows the countrate in a relatively narrow, differential energy channel in the proton telescope. The separation of the peaks is in excellent agreement with that calculated for a proton energy of 29 MeV. This agreement gives confidence in the interpretation of the countrate structure as drift echoes. Figure 4 shows the countrate for an integral electron channel, e > 6 MeV. The countrate vs time in this counter is very different than that from the proton counter plotted in Figure 3. This difference is due to the fact that the electron detector has an integral response with a uniform efficiency above 6 MeV. The "sawtooth" in the countrate vs time is a measure of the energy spectrum; the lower energy but more abundant electrons arrive later. As indicated in Figure 4, a peak in the flux occurs at 15 MeV; at lower energies the flux decreases. The Earth's magnetic field acted as a giant magnetic spectrometer, permitting a

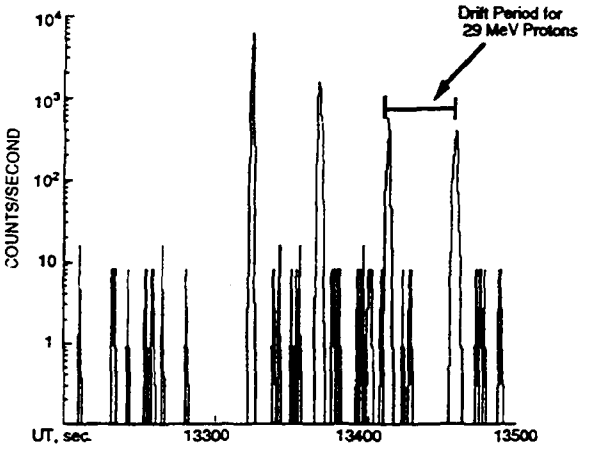

Figure 3. A plot of the countrate vs time in a relatively narrow proton channel 26 – 36 MeV. The characteristic "picket fence" of a drift echo is clearly seen. The separation in time is an unambiguous measure of the proton energy.

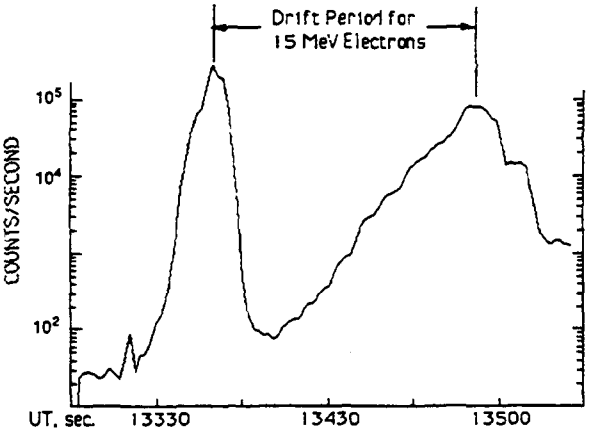

Figure 4. A plot of the countrate vs time in an integral electron channel, e > 6 MeV. Because the detector is measuring particles with a broad spectrum of energies, the profile is a ramp rather than narrow peaks.

detailed measurement of the particle energy spectra. These measurements allowed us to accurately determine the electron energy spectrum in the new radiation. Without these fortuitous observations, such a determination would have been impossible. Since the presence of electrons in the Earth's radiation belts with energies from 15 MeV to greater than 50 MeV was completely unexpected, no sensor was on board capable of spectral measurements in this energy range.

It is most informative to examine the radial profiles of the sensor counting rates as a function of radial distance. (In this

plot, the radial profile is labeled by L. The L value is the radial distance of the equatorial crossing of a magnetic field line from the Earth's center. Figure 5 displays the radial profiles two days before the injection event, two days after the event, and six months after the injection event for the 20 to 80 MeV proton channel and the third Cerenkov channel, nominally > 13 MeV electrons.

In the top panel, which gives the "before" profile, the 20 to 80 MeV Inner-Zone proton countrate shows a broad peak near L = 1.5. Outside of L = 2, the proton intensity is much less and decreases to a background rate due to Galactic cosmic rays near L = 3. The Cerenkov counter channel shows a small peak inside L = 2, which is due to protons with energies of several hundred MeV. Outside of L = 2, this channel is at the background rate due to Galactic cosmic rays.

The middle panel shows the dramatic change in the particle population that resulted from the injection event. A second proton peak has appeared at a higher altitude with a relative minimum between the original one and the newly injected particles. The Cerenkov channel shows a larger change; between L of 2 to 4, its countrate is orders of magnitude above the rate shown in the top panel in the same region of the magnetosphere. In this region the countrate is due to electrons with energies > 13 MeV, not relativistic protons as is the case inside of L = 2. The "thick" countrate curve around the peak intensity results from the fact that the electron flux depended upon the angle between the electron velocity vector and the ambient magnetic field. The Cerenkov counter was scanned by the spinning CRRES spacecraft, and all pitch angles are shown in the plot.

The third panel shows that the intensities of the new particles had decreased over the six-month period following the injection event, and the spatial location of the peaks had moved to a lower altitude. The intensity dependence of the electrons upon pitch angle had decreased.

IV. CONCLUSIONS

The electrons and protons injected into the Earth's magnetosphere in this event are highly penetrating and represent a threat to spacecraft orbiting in that region of near-Earth space. The dramatic increase in radiation dose is described by Gussenhoven et al. [4]. The injection event was completely unexpected and may have been a unique occurrence in magnitude during 35 years of space research. However, the response of the early particle sensors to such an event is not obvious, therefore a definitive conclusion is difficult to make. The formation, evolution, and decay of the high-energy-electron belt is now being addressed. The decay of the new radiation belt is complex. It is clear that further understanding of radiation belt processes is needed for the design of space systems.

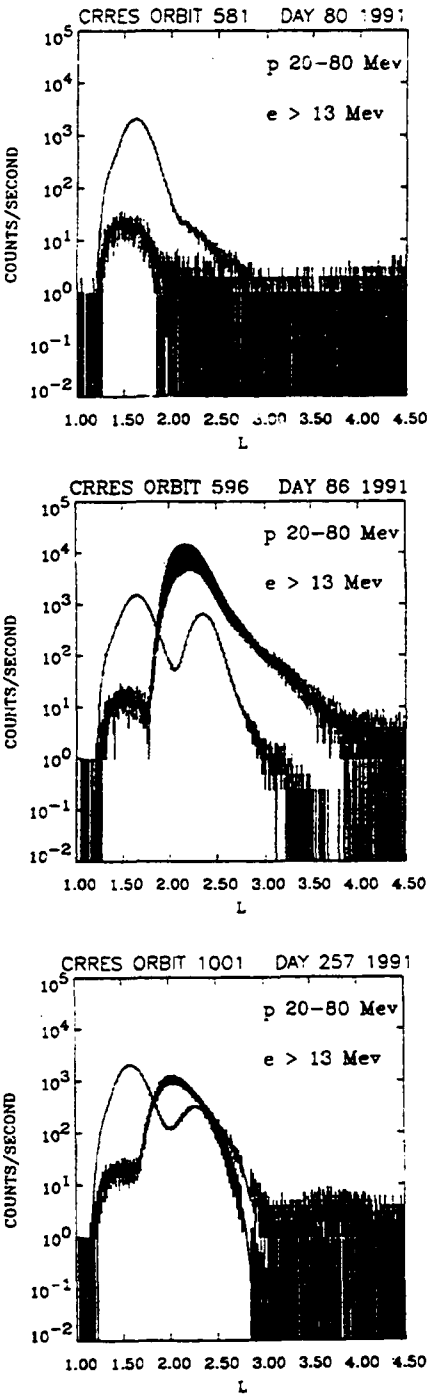

Figure 5. The three panels show the radial profiles for the 20 to 80 MeV proton channel and the e > 13 MeV electron channel for an orbit just before the injection event, just afterwards, and six months afterwards. The major change in the energetic particle population caused by the injection event and the evolution of the particle population with time can be seen.

V. ACKNOWLEDGEMENTS

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