unusual time profiles observed in some type 1 events suggested that the emission might be beamed.

Information made public since the declassification of these events (*11*) has made it clear that there is a less exotic interpretation of type 1 events. It now appears that both type 1 and 2 events result directly from interactions of energetic particles with the SMM satellite. Type 1 events are encounters with high-energy positrons [see, for example, (*12*)]. Each positron that is stopped in the satellite material annihilates to produce two 0.511-MeV photons. The excess shortward from the line (see Fig. 1B) could result from positron bremsstrahlung and from a degradation of 0.511-MeV photons in the lead plate. The high photon yield for positrons relative to the bremsstrahlung photon yield from electrons explains the photon signature of the type 1 events. The time histories of both type 1 and type 2 events are produced by changing particle densities as the SMM satellite traverses positron and electron clouds. However, type 3 events do appear to represent close encounters of SMM with a satellite carrying a nuclear reactor. During "fly-by," the GRS records, for a few minutes, the gamma-ray glow of this satellite.

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2. The "burst window" near 300 keV is read out every 64 ms and the "main channel window" between 4.1- and 6.4-MeV energy is read out every 2.048 s. Typical effective areas for normally incident photons for these three systems are 10 $cm^2$ at 50 keV, 219 $cm^2$ at 500 keV, and 300 $cm^2$ at 20 MeV, respectively. The instrument is also equipped with several active scintillator shields that serve to reject energetic charged particles. The signals from energetic charged particles in the main channel spectrometer are vetoed by the coincident shield signals. Energetic particles entering from the forward solar direction are detected in a 1-cm-thick front plastic shield which has a geometric area of 1170 $cm^2$ and a nominal energy threshold of 500 keV. This thin front shield only attenuates photons from the solar direction but is thick enough to produce a detectable energy loss for charged particles. Side and back CsI detectors and a back plastic shield serve a similar role for particles entering from the side and back directions to complete the $4\pi$ coverage. The time resolution for the shield elements is 8.192 s. The instrument is further shielded in the solar direction by 0.3 g $cm^{-2}$ of Al (the SMM cover) and a 38-cm diameter disk of Pb with a thickness of 0.83 g $cm^{-2}$ to prevent saturation effects in the main channel spectrometer from the intense low-energy solar flare x-rays. Both the Pb disk and the SMM cover are outside of the active shields. We also make use of two detectors in the Hard X-Ray Burst Spectrometer (HXRBS) which are sensitive to charged particles. One of these is a small detector (1 $cm^2$) meant to monitor the intense flux of trapped charged particles >1 MeV in the South Atlantic Anomaly (SAA detector) and the second is the total photon and charged particle rate in the HXRBS instrument >300 keV (HXRBS-CD) [L. E. Orwig, K. J. Frost, B. R. Dennis, *Solar Phys.* **65**, 25 (1980)].
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1 February 1989; accepted 27 March 1989


# Geomagnetic Origin for Transient Particle Events from Nuclear Reactor–Powered Satellites


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**Transient events observed since 1980 by the Gamma-Ray Spectrometer experiment on the Solar Maximum Mission satellite (SMM) have been identified with radiation emitted from 18 different Soviet nuclear reactor–powered satellites. Most of these satellites are similar to Cosmos 954 and 1402 which reentered the atmosphere. Gamma radiation from these satellites was detected when they passed within about 400 to 500 kilometers of SMM. Positron annihilation line radiation (511 kiloelectron volts) and charged-particle events were detected when SMM encountered clouds of positrons and electrons emitted by these satellites and stored up to tens of minutes in the geomagnetic field. The rate of these events varied from about 1 in 5 days to over 30 per day and was strongly dependent on the operating altitudes of the Cosmos satellites and density of the upper atmosphere.**


About 6 months following the launch of NASA's Solar Maximum Mission satellite (SMM) an anomalous class of background events was discovered by Rieger in data from the Gamma-Ray Spectrometer (GRS) experiment [see the accompanying report (*1*) for a description of the instrument]. The spectra of these events were dominated by a strong line feature near 511 keV (the positron-electron annihilation energy); the events first appeared on 30 April 1980. Our subsequent analysis revealed two other classes of transient background events. The second class consisted of events observed in the charged particle shield of the experiment at different times than the 511-keV events, but with similar time profiles (*1*). The third class exhibited a high-energy continuum from 300 keV to about 7 MeV and had relatively symmetric rise and fall times, with typical durations of a few minutes. All of these events occurred during the operational phase of Cosmos 1176 (it is currently in a 900-km storage orbit), a reactor-powered satellite similar to Cosmos 954 which entered the atmosphere in 1978 (*2–4*). The origins of these events were known in 1981 (*5*), but were classified until August 1988.

Our early analysis indicated that the third class of events was associated with times when Cosmos 1176 approached to distances less than about 400 km of SMM. Our analysis further indicated that the radiation was primarily the result of gamma rays emitted from the reactor-powered spacecraft. An example of a spectrum from such a satellite is shown in the accompanying paper (*1*).

The origins of the 511-keV and particle events were initially a mystery because there was no association between the intensity of the events and the distance of separation of the two spacecraft. In fact, events were observed when the spacecraft were separated by distances in excess of 5000 km. An additional characteristic of these events is that they occurred when the SMM spacecraft was at low geomagnetic latitudes.

The origins for these events were suggested by one of us (K.W.M.); this model is outlined below. Reactors produce intense fluxes of gamma rays and neutrons from fission (the neutrons produce additional gamma radiation in the MeV range from neutron capture). The gamma rays produce MeV electrons by the Compton scattering process, and electrons and positrons by pair production. The electrons and positrons


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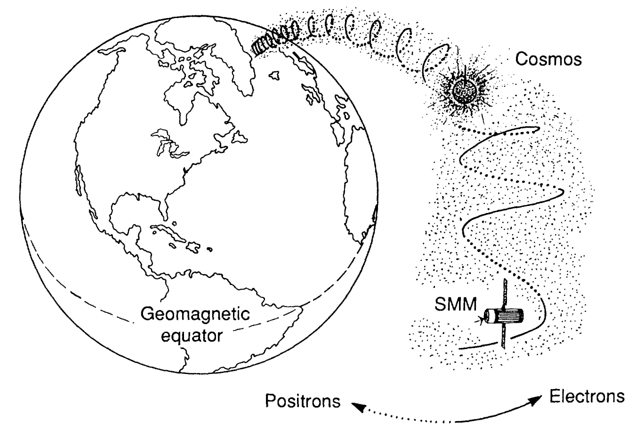


**Fig. 1.** Illustration of model explaining origin of positron and electron events detected by SMM from nuclear reactor–powered satellites. The electrons and positrons emitted from Cosmos are stored on geomagnetic field lines; electrons drifting eastward and positrons westward. The events occur when SMM traverses a cloud of particles.

have energies from hundreds of keV to several MeV and therefore can only escape from the satellite if they are produced in its outer layers. After emerging from the satellite, the particles travel in helical trajectories in the earth's magnetic field (*6–8*) (Fig. 1). Those electrons and positrons with small pitch angles with respect to the magnetic field enter the atmosphere and are lost almost immediately; those with large pitch angles can survive for longer times (a few hundred seconds for 1-MeV electrons or positrons emitted at about 250 km), bouncing back and forth between magnetic mirror points (bounce period of about 0.1 s). Estimates of survival times for particles emitted by Cosmos 1176 have been made by Hones and Higbie (*9*). As indicated in Fig. 1, the positrons drift westward and the electrons eastward as they spiral along the field lines. This drift occurs because of the gradient and curvature of the magnetic field. The longitudinal drift velocity is energy-dependent and is about 10° per minute at 1 MeV (*6*).

On the basis of the above scenario, we proposed that the events exhibiting the 511-keV gamma-ray line occurred when SMM traversed a cloud of positrons stored in the earth's magnetic field. These positrons annihilate in passive material in the spectrometer's aperture, emitting two 511-keV photons, one of which is detected. The spectrometer is covered with 0.31 g $cm^{-2}$ of aluminum (spacecraft material) and 0.83 g $cm^{-2}$ of lead (*1*). The lead is in the form of a disk 38 cm in diameter and is affixed to the skin of the satellite in order to reduce dead-time effects from intense solar flare emission below a few hundred kiloelectron volts. This amount of passive material is sufficient to stop electrons with energies below about 1.5 MeV, depending on their angles of incidence. The particle events observed in the top and bottom plastic anticoincidence shields of the detector (*1*) occurred when SMM traversed clouds of electrons emitted by Cosmos 1176. Over 80% of the particles are observed in the top plastic detector, indicating that the events are primarily caused by particles entering its forward aperture.

This suggested origin of the 511-keV photon and electron events was supported by our analysis of the motions of particles along geomagnetic field lines. The trajectories of particles for each event were traced backward along the field line crossing SMM until they reached the 260-km altitude of Cosmos 1176. We found that, with the exception of two events [events 6 and 7 shown in figure 1 of Hones and Higbie (*9*); these positrons drifted a large distance before detection], the source locations were consistent with the positions of Cosmos 1176 obtained from its orbital elements. In addition, the estimated source locations for all the 511-keV events were found to be slightly to the west of the actual position of Cosmos 1176 at the time of the detection, while the locations for the electron events were to the east. This is consistent with the direction of drift for these particles across field lines. A more elegant description of how positrons and electrons emitted by Cosmos 1176 reached the SMM spectrometer makes use of the McIlwain $L$ parameter (distance in Earth radii where a given field line crosses the geomagnetic equator, $R_e$) and is described by Hones and Higbie (*9*). Our report provides detailed confirmation of the origin of the SMM events.

The geomagnetic model (Fig. 1) also provides a possible explanation for why the events observed by the GRS primarily occurred at low geomagnetic latitudes. Field lines reach their greatest distance from the earth at the geomagnetic equator, giving particles emitted at the 260-km operational altitude of Cosmos 1176 the opportunity to "ride" to the 560-km altitude of SMM.

We can estimate the intensities of the positrons and electrons in clouds encountered from Soviet reactor-powered satellites using some simplifying assumptions. We assume that the Pb and Al over the aperture stops all electrons with energy less than 1.5 MeV and that all electrons with energies above 2 MeV are able to reach the top plastic detector and be recorded. We also estimate that for every three positrons that stop in the passive material, one 511-keV photon will intersect the central NaI detector. With this simple approximation, the 511-keV events primarily come from positrons below about 1.5 MeV, while the charged-particle events come from electrons greater than about 2 MeV. A typical peak intensity for 511-keV events is about 10 $s^{-1}$ (see Fig. 2). This corresponds to a peak positron flux less than about 1.5 MeV of about 0.2 particle $cm^{-2}$ $s^{-1}$ (the effective area for detecting 511-keV photons is ~150 $cm^2$). A peak particle rate of about 2000 $s^{-1}$ is representative of what has been observed for the electron events (Fig. 3); assuming an effective area of about 1200 $cm^2$ for the plastic detectors, we estimate that a typical peak electron flux encountered above 2

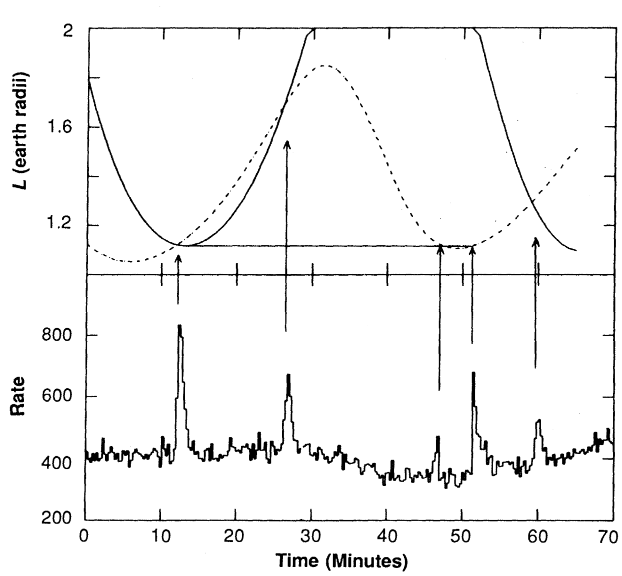


**Fig. 2.** (**Top**) Comparison of the variation of the McIlwain $L$ parameters for SMM (dashed curve) and Cosmos 1818 (solid curve) during the time when five transient 511-keV annihilation line events (**bottom**) were detected by the SMM gamma-ray spectrometer. Time is relative to 3 March 1987 1240 UT. Rate is in counts per 16.4 s.

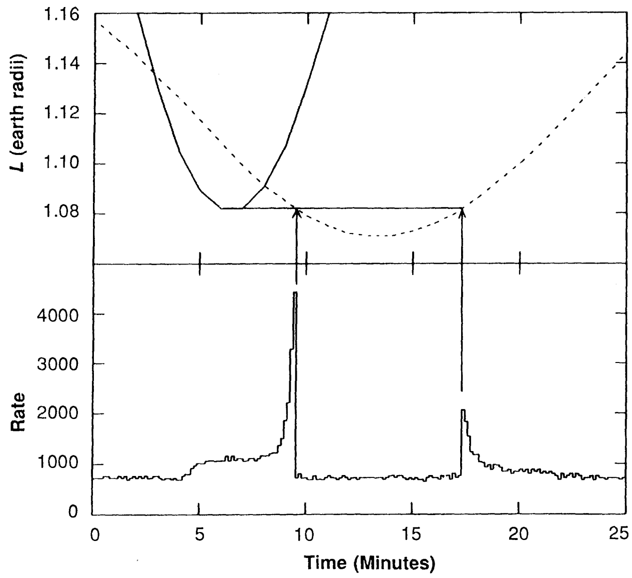


**Fig. 3.** (**Top**) Comparison of the variation of the McIlwain $L$ parameters for SMM (dashed curve) and Cosmos 1818 (solid curve) during the time when two transient electron events (**bottom**) were detected in the plastic scintillation counters of the SMM/GRS. Time is relative to 10 February 1987, 1340 UT. Rate is in counts per 0.5 $s^{-1}$.

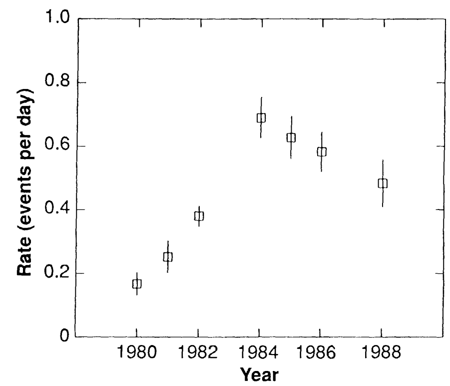


**Fig. 4.** Rate of detection of bursts of annihilation radiation (511-keV line) found in a computer search of the SMM data. Rates plotted (errors statistical) are the average number of events detected in a given year divided by the number of days Cosmos reactor-powered satellites were operational. Events from Cosmos 1818 and 1867 are not included.

MeV is about 2 $cm^{-2}$ $s^{-1}$. The integral fluxes of positrons and electrons depend on the energy spectra, but it is clear that the electron fluxes are about an order of magnitude higher than the positrons. This large difference is explained by the fact that the cross section for producing positron-electron pairs in spacecraft materials, such as aluminum, only becomes comparable to the Compton scattering (which produces only electrons) cross section at energies above 15 MeV.

In spite of this large difference in intensities, the GRS detector has observed roughly equivalent numbers of electron and positron events. Because the positron events are concentrated in a narrow line at 511 keV, the GRS is a more sensitive detector of MeV positrons than MeV electrons, significantly increasing the signal-to-noise ratio.

The 511-keV events are an excellent monitor of reactors in orbit in spite of the presence of strong instrumental, atmospheric, and galactic annihilation lines (*10*). These "reactor" events can also be distinguished from annihilation line events observed during solar flares, which are associated with intense continuum and nuclear line radiation (*11*). Over the 8-year operational period of SMM, these distinctive 511-keV events were detected only when a nuclear-powered spacecraft was in operation. These events have been identified at NRL by means of both a computer search, during routine production data analysis, and by visual screening of archival microfilm.

As shown in figure 4 of Rieger *et al.* (*1*), the rate of the background events varied over the 9-year lifetime of the SMM satellite. Various publications [for example, (*2*–*4*)] list probable identifications of reactor-powered satellites. Furthermore, the orbital characteristics of most of these satellites are similar to those of Cosmos 954 and 1402, which reentered the atmosphere; they typically are launched into orbits with about 65° inclination and operational altitudes of about 260 km. We have used the GRS experiment to confirm the presence of nuclear reactors on satellites with these parameters. This has been done by determining the times when SMM passed within about 400 km of one of the candidate satellites and looking for an increased response in the gamma-ray continuum above 300 keV. Such an increase is shown in figure 3 in the accompanying report (*1*). Listed in Table 1 are satellites determined from GRS observations to contain nuclear reactors as power sources. Annihilation line and electron events were also detected from all these satellites. Cosmos 1299 has also been identified (*2*–*4*) as a reactor-powered satellite; however, we found no evidence in the SMM data for nuclear emission from this satellite during its 12-day operational period.

We have obtained background-corrected measurements of the average 0.8- to 8.0-MeV rates observed from the Cosmos satellites, operating at ~260 km, when these satellites came within about 400 km of SMM and were within the broad aperture of the GRS. These rates have been normalized to detection at a distance of 300 km. The average rate measured from all these satellites is about 0.2 gamma $cm^{-2}$ $s^{-1}$ or emissivity of about $2 \times 10^{15}$ gamma $s^{-1}$ (~0.4 kW in gamma-ray power) in the 0.8- to 8.0-MeV band. [A gamma-ray emissivity in a lower energy band, 0.3 to 7 MeV, over an order of magnitude higher than our average, was estimated by Rieger *et al.* (*1*) for Cosmos 1867; however, the estimated distance of closest approach to SMM used in their calculation was about a factor of 2 higher than the true distance.] The mean rates that we observed from individual satellites operating at 260 km were all within 25% of the above average, suggesting that the power sources and shielding configurations on these satellites were similar.

On the other hand, the rates of 511-keV events detected from 1980 to 1988 from these Cosmos satellites varied significantly over this time period. Shown in Fig. 4 are the 511-keV event rates per operating reactor-powered satellite as derived from our computer search. Shown only are data taken for the Cosmos satellites that operated at ~260 km (see discussion below concerning effects observed from Cosmos 1818 and 1867). The rate of 0.511-MeV events in 1980 from Cosmos 1176 was about one every 5 days. From that time on the rates exhibited an increase, with a peak rate occurring around 1984. The rate since 1984 appears to be decreasing; the last point comes from data accumulated from June through September 1988 when Cosmos 1900 was operating.

A plausible cause for the temporal variation of these events is the varying density of the upper atmosphere because of changes in solar activity. SMM was launched near the peak of the last solar cycle; minimum solar activity appears to have occurred in 1986 (*12*) and has increased as the next peak in the solar cycle approaches. The average density at 200 km decreases by about a factor of 5 from solar maximum to solar minimum (*13*). Because the lifetime of the positrons is inversely proportional to the atmospheric density at their mirror points, the positrons will remain trapped in the geomagnetic field for much longer times. There is, therefore, a greater likelihood that SMM will encounter a cloud of positrons during solar minimum than at solar maximum.

As noted in (*1*), however, the rates of 511-keV and electron events increased dramatically in February 1987. These rates were about a factor of 20 higher than what is shown for Cosmos 1900 in Fig. 4. The first of these events was observed within a day of the launch of Cosmos 1818, and within a few days of the launches of Cosmos 1816 and Cosmos 1817. GRS measurements of increases in the gamma-ray continuum when Cosmos 1818 passed within about 400 km, beginning within a day after its launch, unambiguously identified that satellite as the source of the electron and particle events. As shown in Table 1, Cosmos 1818 was launched into a considerably higher operational altitude (~790 km) orbit than earlier nuclear-powered satellites (~260 km); however, its orbital inclination was similar.

This higher altitude provides one explanation for the dramatic increase in the number of 511-keV and electron events. Our line of reasoning is similar to that used to explain the variation over the solar cycle. Particles from Cosmos 1818 that have mirror points at altitudes less than that of SMM (~470 km) can be detected. The atmospheric densities are typically a factor of 100 lower at 470 km than at 200 km (*13*). At these lower densities the electrons and positrons can remain trapped for about an hour, compared with minutes for the lower altitude systems. This significantly increases the probability that SMM will encounter such a cloud of particles. GRS measurements of both electron and positron events, as well as the gamma-ray continuum during nearby encounters of Cosmos 1818, continued until about mid-June 1987, when apparently the reactor was deactivated.

Cosmos 1867, having similar orbital parameters as Cosmos 1818, was launched on 10 July 1987. Once again the rate of positron and electron events rose precipitously and an unambiguous identification of the nuclear power source of this satellite was made from gamma-ray continuum observations within ~400 km. The GRS measurements indicate that the reactor on Cosmos 1867 operated for about 11 months (*1*).

The transient 511-keV gamma-ray and electron events exhibit a large variety of durations and shapes (*1, 9*). Durations vary from less than a second to tens of minutes and the individual events can occur several times an orbit. Two examples of events observed from Cosmos 1818 are shown in Figs. 2 and 3. Our analysis of these events follows that developed by Hones and Higbie (*9*), based on observations of Cosmos 1176 by SMM in 1980.

**Table 1.** Nuclear reactor–powered satellites observed by SMM.

| Cosmos identification number | Launch date | Altitude (km) | Inclination (deg) |
|---|---|---|---|
| 1176 | 29 April 1980 | ~260 | 64.8 |
| 1249 | 5 March 1981 | ~260 | 65.0 |
| 1266 | 21 April 1981 | ~260 | 64.8 |
| 1365 | 14 May 1982 | ~260 | 65.1 |
| 1372 | 1 June 1982 | ~260 | 64.9 |
| 1402 | 30 August 1982 | ~260 | 65.0 |
| 1412 | 2 October 1982 | ~260 | 64.8 |
| 1579 | 29 June 1984 | ~260 | 65.0 |
| 1607 | 31 October 1984 | ~260 | 65.0 |
| 1670 | 1 August 1985 | ~260 | 65.0 |
| 1677 | 23 August 1985 | ~260 | 64.7 |
| 1736 | 21 March 1986 | ~260 | 65.0 |
| 1771 | 20 August 1986 | ~260 | 65.0 |
| 1818 | 1 February 1987 | ~790 | 65.0 |
| 1860 | 18 June 1987 | ~260 | 65.0 |
| 1867 | 10 July 1987 | ~790 | 65.0 |
| 1900 | 12 December 1987 | ~260 | 65.0 |
| 1932 | 14 March 1988 | ~260 | 65.0 |

Plotted in the lower part of Fig. 2 is the time profile of charged particles observed in the plastic scintillation detectors of the GRS near 1350 UT on 10 February 1987. The upper part of the figure displays the McIlwain $L$ parameters for both SMM and Cosmos 1818. The charged particle rate increased just before the 5-min mark and then was relatively constant as SMM began crossing $L$ shells (with eastward-drifting clouds of electrons) that had been deposited a minute or so earlier by Cosmos 1818. During this period SMM and Cosmos were separated by about 6000 km, with SMM about 50° to the east of Cosmos. A sharp spike occurred at 9 min when SMM reached $L = 1.08\ R_e$; this was the minimum $L$ attained by Cosmos and it deposited radiation onto field lines near this value for a couple of minutes. This concentration of particles explains the peak observed by the GRS. The abrupt decrease in rate occurred at the same time that SMM moved to lower $L$ than the minimum reached by Cosmos. No electrons were therefore deposited on these fields. A sharp rise in rate, at reduced amplitude, was observed near 17 min as SMM traversed the cloud of electrons deposited over 10 min earlier by Cosmos. These electrons were observed about 90° to the east of the position where they were deposited; this rate of drift is consistent with that expected for MeV electrons.

The complicated time history of 511-keV photons displayed in Fig. 3 can be explained in a similar manner. The time profile begins at about 1240 UT on 13 March 1987. Prior to the 12-min mark, SMM was crossing $L$ shells lower than those reached by Cosmos. The spike near 12 min coincides with the time when SMM crossed field lines on which positrons had been deposited about a minute earlier. At this time SMM and Cosmos were separated by about 3200 km and SMM was about 15° in longitude to the west. This is again consistent with the expected westward drift of the positrons. The spike at about 27 min occurred when SMM crossed a cloud of positrons that had been emitted less than a minute earlier by Cosmos when it was a few degrees to the east in longitude, but over 8000 km away. The peak at 60 min occurred when SMM encountered positrons deposited about a minute earlier while Cosmos was about 2000 km away and about 15° to the east of SMM.

In contrast, the peaks shown in Fig. 3 at 46 and 52 min are due to positrons deposited by Cosmos 1818 about 35 min earlier when it reached its minimum $L$ value of $\sim 1.1\ R_e$. The sharp fall near 47 min and rise near 52 min mirror what is in Fig. 2 and have the same explanation; between these times SMM reached $L$ values below that reached by Cosmos and therefore no positrons were present. At the time that SMM detected these two spikes, it was located about 250° to the west of the longitude at which Cosmos deposited the positrons. This is again consistent with the expected westward drift of MeV positrons.

The transient events described here and in (*1*) and (*9*) represent a troublesome background for high-energy experiments on satellites. Weak and extended (in excess of about 20 min) encounters with positrons from Cosmos 1818 and 1867 have already compromised our galactic 511-keV observations (*10*). The times at which all these events occur are predictable, however (*9*); the operation of future satellites, such as NASA's Gamma Ray Observatory, may not be seriously impaired, unless the number of reactors in orbit or their operational power (or both) increase significantly.

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# Distribution and Detection of Positrons from an Orbiting Nuclear Reactor

E. W. HONES AND P. R. HIGBIE

**The Solar Maximum Mission (SMM) Gamma-Ray Spectrometer has on many occasions detected nuclear radiation produced by nuclear reactors carried on Soviet satellites. A unique feature of the observations is the measurement of bursts of 511–kiloelectron volt gamma rays that are thought to signal SMM encounters with positrons emanating from the Soviet satellites. A model of positron generation by an orbiting reactor has been developed that describes the resulting time-dependent distribution of positrons temporarily trapped in the geomagnetic field and estimates the response of the SMM spectrometer to passage through such distributions. The model successfully predicts onset times, durations, and intensities of the 511–kiloelectron volt gamma bursts, as we illustrate in a detailed analysis of one event, and thus confirms that these are due to positrons from the Soviet satellites. Reactor-generated positrons are potentially useful in magnetospheric research.**

DURING THE PAST TWO DECADES the Soviet Union has placed many nuclear reactor–bearing satellites in low earth orbits, often of ~260-km altitude and 65° inclination (*1–3*). After operating several months they are boosted to ~900-km orbits to delay, for many years, their reentry to the earth's atmosphere. In one case (Cosmos 954) a malfunction caused the reactor to reenter the atmosphere over Canada. Recovery of some of its parts allowed Western scientists to estimate that its operating thermal power level was in the range of tens to hundreds of kilowatts (*1*).

These reactors have constituted unique sources of particles and gamma rays in space. Compton electrons and electron-positron pairs produced near the surface of the satellite by the intense reactor gamma-ray flux can escape. The Solar Maximum Mission (SMM) satellite, launched in early 1980, carried instruments that detected these particles and photons and led investigators to associate them with the Soviet reactor-bearing satellites (*4, 5*). Here we are concerned with the positrons, which are identified by their 511-keV annihilation radiation recorded by a gamma-ray detector on SMM.

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The unique properties of positrons as potential tracers for magnetospheric studies were pointed out by Hones (*6*) and hypothetical experiments were described in which reactor-irradiated copper was used as a source of positrons. It is now clear that a nuclear reactor is another potential source of positrons, a fact that, to our knowledge, received no attention prior to the SMM observations described in the accompanying papers.

Positrons emitted nearly perpendicular (90° ± 10°) to the magnetic field by a satellite spiral around the field lines and bounce between their northern and southern mirror points while drifting westward at an angular speed proportional to their kinetic energy. Those outside this range of pitch angles are scattered into the atmosphere and lost at their first or second mirror point because of the low (~260 km) satellite altitude. The geomagnetic field is fairly well described as that of a dipole magnet that is tilted about 11° relative to the earth's rotational axis and displaced about 400 km from the earth's center toward the western Pacific Ocean. This results in there being a region of low field strength over the south Atlantic Ocean, called the South Atlantic anomaly, where drifting particles undergo mirror reflections at lower altitudes than anywhere else and are thus most susceptible to atmospheric loss (*7*).

The expected westward drift of positrons and the expected influences on their lifetimes of the tilt and displacement of the dipole are evident in the distribution, over the earth, of the SMM-Cosmos relative positions during the events. This is illustrated by the following features of Fig. 1 which give qualitative support for the view that the SMM 511-keV gamma events were caused by interception of positrons from Cosmos 1176, temporarily stored in the magnetic field: (i) In all events SMM appears to be closely conjugate to Cosmos or to lie clearly to the magnetic west of it. (Detailed calculations of the satellites' geomagnetic locations show that SMM was at least a degree or so magnetically west of Cosmos in all events.) (ii) Events in the longitude range +150° to −150° (negative means west longitude) all have Cosmos in the northern (magnetic) hemisphere. This is a longitude region

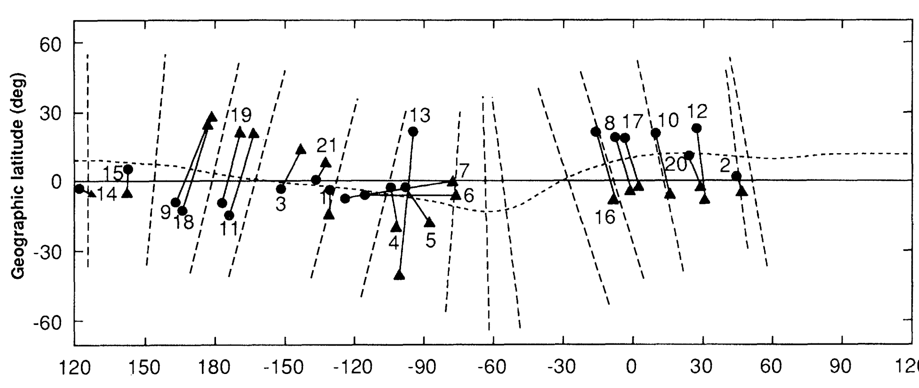


**Fig. 1.** Locations of SMM (observer) and Cosmos 1176 (source) at the times of 21 of the most intense 511-keV gamma events recorded by SMM during the 29 April to 6 September 1980 operating lifetime of Cosmos 1176. The events are numbered in the chronological order of their occurrence. The coordinates are geographic latitude and longitude. Solid lines join the satellite locations in each event. A dotted line traces the geomagnetic equator. Dashed lines connect magnetically conjugate points on the earth, thus depicting, approximately, magnetic meridians.