Man-Made Transients Observed by the Gamma-Ray Spectrometer on the Solar Maximum Mission Satellite

ERICH RIEGER, W. THOMAS VESTRAND, DAVID J. FORREST, EDWARD L. CHUPP, GOTTFRIED KANBACH, CLAUS REPPIN

Since launch in early 1980 the Gamma-Ray Spectrometer (GRS) onboard the Solar Maximum Mission (SMM) satellite has monitored the sun at gamma-ray energies. In addition to observations of solar flares, cosmic gamma-ray bursts, and precipitating radiation belt electrons, the instrument has detected a new class of high-energy transient events that cannot be attributed to any of these phenomena. The duration of these transients can range from 1 second to more than 10 minutes. The average event rate between 1980 and 1986 was about five per month. However, in February 1987 this rate increased by more than a factor of 25 and continued at this high level until June 1988. These transients can be subdivided into three classes: (i) 0.511-megaelectron volt annihilation line events, (ii) particle events, and (iii) broad-band photon continuum–like events. Evidence is presented that these transients are not of natural origin. It is found that the most likely sources of these events are reactors in earth orbiting satellites. Apart from the threat these reactors pose upon accidental reentry, the reactor-generated transients may have a deleterious effect on cosmic observations obtained with gamma-ray detectors in low earth orbit.

THE SOLAR MAXIMUM MISSION (SMM) satellite was launched on 14 February 1980 into a near circular orbit with an inclination of 28.5°. Its initial altitude was 570 km, which has since decayed to 460 km. The primary objective of the seven experiments on SMM is to measure the photon flux from solar flares over a broad energy range. The Gamma-Ray Spectrometer (GRS) is one of these experiments and consists of three sensor systems, each covering nonoverlapping energy bands (*1*). These include an X-Ray System (10 keV to 200 keV) with 1.024-s time resolution, the Main Channel Gamma-Ray Spectrometer (0.280 keV to 9 MeV) with 16.384-s time resolution, and a High Energy Monitor (10 to 140 MeV) with a temporal resolution of 2.048 s (*2*).

During its nearly 9-year operation the GRS has provided a wealth of new information from more than 160 solar flares and more than 140 cosmic gamma-ray bursts. It has also recorded particle events from precipitating radiation belt electrons. Transient events are identified in the GRS data by a visual screening of the count rate in two energy bands near 300 keV and 500 keV (energy bins with widths of 80 and 100 keV, respectively). Excesses in either band are flagged as an event. These events are subsequently examined over the whole energy range of the instrument and for charged particle counting characteristics.

Solar flares are identified by their steep spectra, which produce higher rates in the low-energy x-ray bands relative to higher energy bands. This identification can usually be confirmed by coincident observations made at other wavelengths (*3*). Typical cosmic gamma-ray bursts have a much flatter spectra and therefore appear significantly weaker in low-energy x-rays than at higher energies. Again, data from other SMM instruments as well as reports from the National Oceanic and Atmospheric Administration are used to confirm a nonsolar origin. A significant fraction of the GRS cosmic burst events identified with this procedure have been confirmed by burst detectors on other spacecraft.

In addition to these photon events, which show little response in the shield elements, particle events have also been detected. They appear most often when the satellite is close to the trapped particles in the South Atlantic Anomaly. Typically these transients have a duration of several minutes. They show up most prominently in the count rate of the front and back plastic shield detectors. From the steep decrease of the count rate with energy and the low response in the HXRBS-CD and SAA monitors (*2*) we conclude that the particle spectrum is very soft. Most probably they arise from the precipitation of radiation belt electrons (*4*).

In addition to solar flares, cosmic gamma-ray bursts, and soft particle events, GRS has recorded transient events that cannot be attributed to any of these natural phenome-

E. Rieger, G. Kanbach, C. Reppin, Max-Planck-Institut für Physik und Astrophysik, Institut für extraterrestrische Physik, 8046 Garching, Federal Republic of Germany.
W. T. Vestrand, D. J. Forrest, E. L. Chupp, Department of Physics and the Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH 03824.

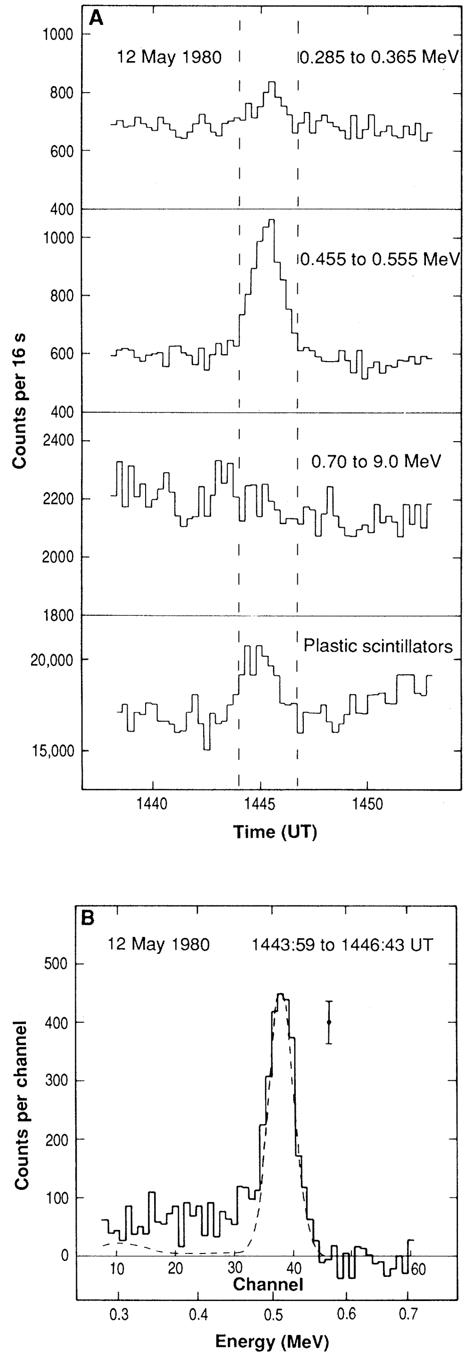


Fig. 1. (**A**) Time history of a single peaked slow rise and fall 0.5-MeV event (type 1). (**B**) Energy loss spectrum of the event shown in (A), formed by summing counts between the dashed lines. The error bar indicates 1-sigma limits from signal/background statistics (*13*). The dashed curve is the instrument's normalized response to the 0.511-MeV line. Note the excess shortward from the line.

na. This new class of transients was first discovered shortly after the launch of SMM. At first, the time profile of individual events did not allow us to differentiate them from natural phenomena. However, subsequent study of their spectral properties and periodic occurrence has allowed us to distinguish them from other events and to classify them into three different types.

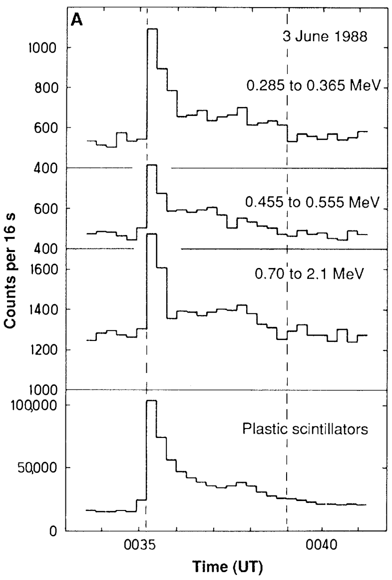
The events that were first detected and that remain the most common and prominent transients are called type 1. The observational signature for these events is a higher count rate at 0.5 MeV than at 0.3 MeV. The duration of these events ranges from a few seconds to more than 10 min. However, their intensity versus time profiles show great variation. Figure 1A shows an example of a long duration single-peaked event, as observed in different energy bands and in the plastic shields. The time history shows a broad symmetrical pulse. Figure 1B shows the time-integrated energy loss spectrum for the event displayed in Fig. 1A. Notice that a strong line feature is apparent at 0.5 MeV. Analysis of this spectrum shows that the line feature is an unbroadened and unshifted positron annihilation line at 0.511 MeV. The agreement of the data with the instrument response for a line at this energy is shown in Fig. 1B.

Type 2 events, in contrast to the type 1, have a higher rate at 0.3 MeV than at 0.5 MeV. They also have a much higher response in the plastic shields relative to the main channel spectrometer than type 1. This is evident in Fig. 2A which shows the time history of a type 2 event. The large variety of temporal rate profiles characteristic of the type 1 events is also seen in type 2 events. The spectra of type 2 events do not show the line emission at 0.511 MeV that is typical for the type 1 events, but they do contain a high-energy tail as displayed in Fig. 2B.

A third type of transient has also been identified, but is observed much less frequently than the first two types. These type 3 events are difficult to distinguish from type 2 in our screening procedures because they have about equal rates at both 0.3 MeV and 0.5 MeV. However, their distinguishing characteristic is that they have a very small response in the plastic shields relative to the main channel response, suggesting that they are photon events. Figure 3A shows the time history of a type 3 event in several main channel energy bands and the plastic shields. The temporal characteristics of type 3 are always a simple Gaussian-like profile with a duration of a few minutes. Type 3 events are definitely nonsolar in origin, because several have been observed when the sun was occulted by the earth. Their energy loss spectrum is mainly a continuum and can extend to energies of about 7 MeV. These events are generally weak so we have summed over several of the more intense events to display a generic type 3 event energy-loss spectrum (Fig. 3B). There is clear evidence here for the 0.511 MeV annihilation line with a low-energy tail.

Our initial analysis of type 1 events after their discovery in 1980 indicated that these high-energy transients differed in many respects from what was known about solar flares and cosmic gamma-ray bursts. We originally thought that a new class of cosmic events had been discovered. However, as the number of identified events increased, a clear periodic recurrence rate relative to the orbital period of the SMM satellite was discovered. This provided strong evidence that these events could not be of natural origin. After a briefing to NASA headquarters at the end of 1980 we were informed that they were generated by nuclear power sources on satellites in near earth orbit. However, a detailed explanation of the cause of these events was classified until recently.

During the period 1980 to 1986 the average event rate was about five per month. In February 1987, however, it dramatically increased by more than a factor of 25 and stayed at this high level until 17 June 1988



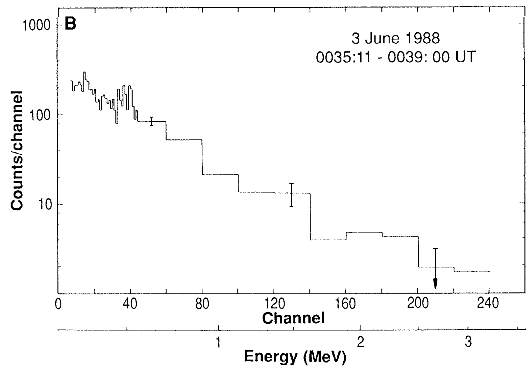
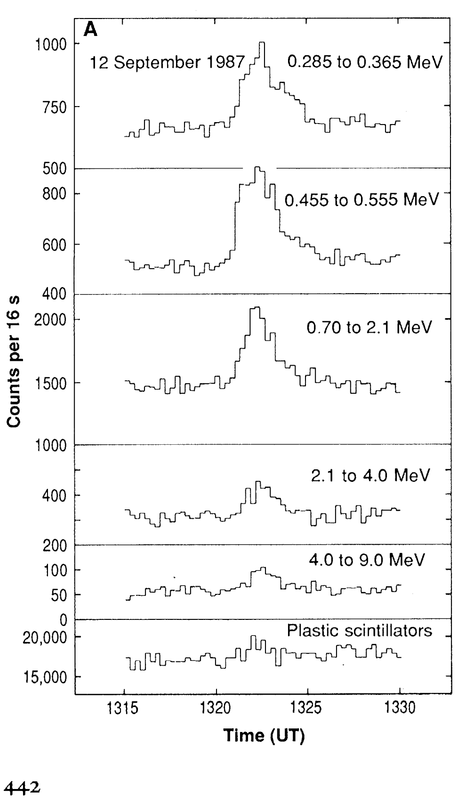


Fig. 2. (**A**) Time history of a type 2 event. (**B**) Energy loss spectrum of the event shown in (A), formed by summing counts between the dashed lines. The error bars are 1-sigma limits from signal/background statistics (*13*).



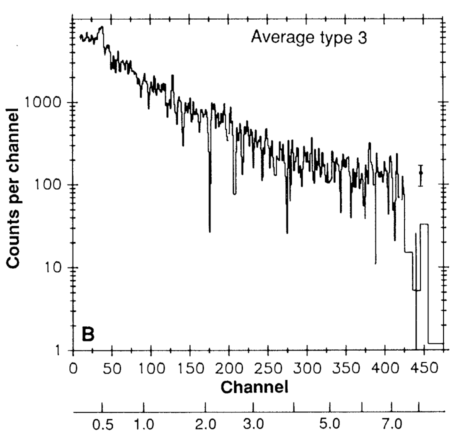


Fig. 3. (**A**) Time history of a type 3 event. Notice that the event is visible in the highest energy band shown. (**B**) Superimposed energy loss spectra of several type 3 events. Notice the 0.511-MeV feature and the cutoff above about 7.5 MeV (channel 425). The error bar indicates 1-sigma limits from signal/background statistics (*13*).

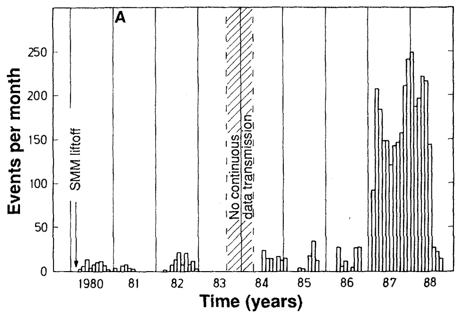


Fig. 4. Monthly event rate of high-energy transients of all three types.

(see Fig. 4). Up to December 1988, the GRS screening procedure has detected more than 3000 high-energy transients. The distribution of event types is 81.5%, 16.0%, and 2.5% for types 1, 2, and 3, respectively. Figure 5 is a blow-up of a 50-day interval within the active period between February 1987 and June 1988. The pattern shown repeats with modifications every 48 days. This 48 days is the precessional period of the orbit of the SMM satellite. It is apparent that the events are not distributed randomly over time, but recur from day to day with a time lapse of 23 hours and 30 min, which gives the impression of trains of events. This is the time span that the SMM satellite needs to get back to the same geographic position. We see also that the different types of events (identified in the legend to Fig. 5) follow in succession on certain trains with type 2 and type 3 events generally preceding the type 1 events. It is therefore logical to assume a common source for all three event types. More detailed explanations of some of our observations, which are based on recently declassified information, are given by Share *et al.* (*5*) and Hones and Higbie (*6*).

As already mentioned, the type 1 and type 2 events exhibit similar temporal and occurrence characteristics, suggesting that they are related. From the relatively high response in the plastic shields of type 2 events we conclude that they are produced by energetic electrons interacting with the SMM satellite and the GRS detector. However, unlike the soft particle events from precipitating radiation belt electrons that show low response in the HXRBS-CD and SAA detectors, type 2 events show a relatively high response in these detectors. This indicates that the type 2 electron spectra are hard (that is, high-energy electrons predominate). The precipitating particle events were especially numerous during 1981 and 1982, years of high solar activity. The type 2 events, however, do not show this temporal behavior. Their frequency was low from 1980 to 1986 and increased rather abruptly in February 1987 (Figs. 4 and 5). The high-energy continuum measured in the main channel spectrometer and shown in Fig. 2B could result from the leakage of a small fraction of these energetic electrons through the plastic shields, but most of the recorded counts must come from photons that arise from bremsstrahlung produced by these high-energy electrons as they interact with the satellite material and the high-Z Pb attenuator disk (*2*).

The type 3 events are different from the other types. The time profile is a simple slow rise and fall curve (Fig. 3A) and they show little evidence for particles in the plastic shields. Their main channel energy loss spectrum shows a very hard and quasi-continuous distribution extending to at least 7 MeV (Fig. 3B). Based on our knowledge of the instrument operation and response, we conclude that the type 3 events are produced by hard x-rays and gamma rays from near encounters with another earth orbiting satellite. From this model we can estimate the radiated gamma-ray intensity of this second satellite by assuming the gamma-ray emission is constant and isotropic. Adopting a relative velocity between SMM and the other satellite (near equatorial/near polar orbits) of 11 km/s and using the measured emission time interval from half maximum to maximum of about 60 ± 15 s (Fig. 3A), we obtain a distance of closest approach in the range of 660 ± 170 km. The photon flux in the energy range 0.3 to 7 MeV recorded by the GRS during the maximum of the 12 September 1987 event (shown in Fig. 3A) is 0.62 ± 0.1 cm^{-2} s^{-1}, assuming that the radiation is incident along the detector axis. Hence, the activity of this satellite is $(3.4 \pm 2.2) \times 10^{16}$ photons per second. If we assume a mean photon energy of 1 MeV we obtain (5.4 ± 3.6) kW of radiated power in the gamma-ray regime. This estimate is consistent with the power of the reactors believed to be carried by the Soviet Radar Ocean Reconnaisance Satellites (RORSATs) (*7, 8*) and the not yet flown American SP-100 space reactor (*9, 10*).

Type 1 events proved to be the most difficult to understand based on GRS data alone. They differ from those of type 2 in two important respects. First, their spectra contain a strong 0.511-MeV line; second, their particle count rate is comparatively low relative to that in the main channel spectrometer. The ratio was comparable to what we find in solar flares and cosmic gamma-ray bursts. Based on this we initially concluded that type 1 events were also photons measured during close encounters with another satellite. In analogy with the calculations given above for the type 3 events and using the data from the type 1 events shown in Fig. 1A, we derive a comparable positron production rate. This huge positron flux produced by the other satellite as well as the

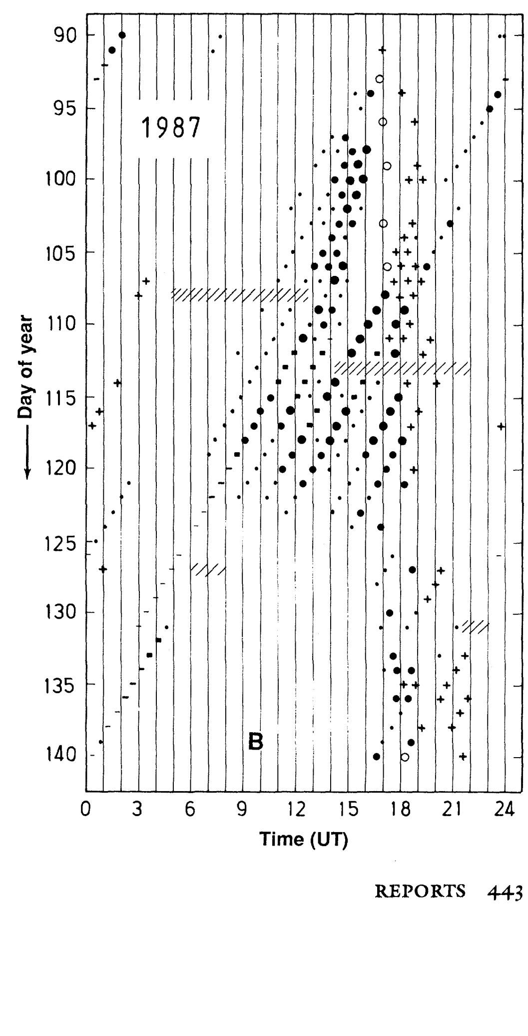


Fig. 5. Events on a day-by-day basis for a 50-day interval in 1987. Type 1 events: dots denote single peaked and bars double peaked events. The intensity of the type 1 events is indicated by the thickness of the dots and bars. Small: <500 counts per 16 s; medium: 500 to 1500 counts per 16 s; large: >1500 counts per 16 s; energy interval 0.455 to 0.555 MeV. Type 2 events are denoted by crosses and type 3 events by open circles. Dashed areas indicate data gaps.

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.

REFERENCES AND NOTES

1. D. J. Forrest *et al.*, *Solar Phys.* **65**, 15 (1980).
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 4π 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)].
3. *Preliminary Report and Forecast of Solar Geophysical Data, Flare List* (National Oceanic and Atmospheric Administration, Washington, DC).
4. W. L. Imhof, E. E. Gaines, J. B. Reagan, *J. Geophys. Res.* **78**, 4568 (1973).
5. G. H. Share, D. J. Kurfess, K. W. Marlow, D. C. Messina, *Science* **244**, 444 (1989).
6. E. W. Hones and P. Higbie, *ibid.*, p. 448.
7. W. E. Burrows, *Deep Black* (Random House, New York, 1986), p. 270.
8. N. L. Johnson, *Space Policy* **2**, 223 (August 1986).
9. J. R. Primack, *Nucl. Phys.*, in press.
10. St. Aftergood, *Space Policy* **5**, 25 (February 1989).
11. M. M. Waldrop, *Science* **242**, 1119 (1988).
12. E. W. Hones, Jr., *J. Geophys. Res.* **69**, 182 (1964).
13. The background is determined by interpolation of the count rate before and after the event.

14. We thank G. H. Share for comments and suggestions and K. Levensen for assistance in data processing. E.L.C. is Principal Investigator and D.J.F. is Instrument Scientist for the SMM GRS. This work was partly supported by Bundesministerium für Forschung und Technologie under grant 010 K 017-ZA/WS/WRK 0275:4 and by NASA under grant NAG-5720.

1 February 1989; accepted 27 March 1989

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

G. H. Share, J. D. Kurfess, K. W. Marlow,* D. C. Messina

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

G. H. Share and J. D. Kurfess, E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375.
K. W. Marlow, Condensed Matter and Radiation Sciences Division Naval Research Laboratory, Washington, DC 20375.
D. C. Messina, Sachs/Freeman Associates Inc., Landover, MD 20785.

*Present address: Sandia National Laboratories, Albuquerque, NM 87185.