THE COSMIC γ-RAY SPECTRUM NEAR 1 MeV OBSERVED BY THE ERS-18 SATELLITE

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In this paper, we wish to report new data obtained on the total, or omnidirectional, cosmic γ-ray flux in the 250 keV to 6 MeV range. Flux in this energy range up to 2 MeV was first detected on the Ranger 3 (Metzger *et al.*, 1964) and has been confirmed up to 0.5 MeV and extended to lower energies by a series of rocket (Gorenstein *et al.*, 1969; Seward *et al.*, 1967) and balloon measurements (Bleeker *et al.*, 1966; Rocchia *et al.*, 1967). Observation of the spectrum at higher energies has become of considerable importance since the recent successful detection of galactic 100 MeV γ-rays by the OSO-3 (Clark *et al.*, 1968).

The Environmental Research Satellite-18 was launched April 28, 1967, along with the Vela 4 satellites into a highly elliptical orbit of 117500 km apogee and 15000 km perigee. This 7.8 kg satellite, in addition to carrying a number of small radiation detectors designed to measure magnetospheric particles and cosmic rays, had a large detector to measure the cosmic γ-ray spectrum in the energy range 0.25–6 MeV. This detection system consisted of a 7.65 cm long × 6.35 cm diameter NaI (Tl) scintillation counter with a 1 cm thick plastic anti-coincidence shield for charged particle rejection. The shield counter covered all but one circular face of the NaI crystal. A drawing of the detector arrangement is given in Figure 1. Six channels of pulse height analysis permitted spectral measurement into the 5 energy bands given in Table I, as well as a lower energy integral channel, and an integral channel >6 MeV. The anti-coincidence was switched between on and off by the spacecraft commutator about every 500 sec in order to access the counting rates due to cosmic ray energy losses. The difference in counting rate for these two modes can serve as a calibration using the cosmic ray beam.

A more complete description of the satellite and its experiments has been given elsewhere (Peterson *et al.*, 1968). Although the information bandwidth of the ERS-18 was only 6 Hz, and only a small fraction of this was devoted to the γ-ray experiment, the measurement is soon limited by systematic effects rather than counting statistics. The satellite spends a large fraction of its 48-hour orbit in regions where magnetospheric particles are not detectable by the charged particle detectors with threshold energies of 40 keV for electrons and 380 keV for protons.

Data reported here were obtained primarily during May and June, 1967, when the local time of satellite apogee was generally directed toward the dusk meridian.

L. Gratton (ed.), Non-Solar X- and Gamma-Ray Astronomy, 335–341. All Rights Reserved

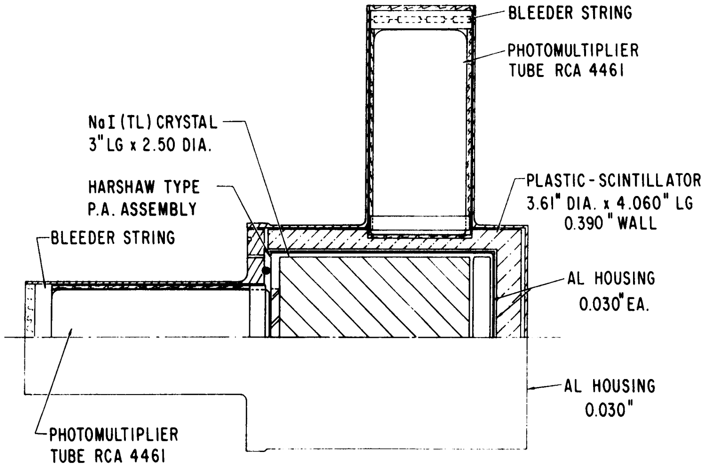

Fig. 1. The isotropic γ-ray detector which was included in the ERS-18 payload and which detects energy losses in the 0.25 to 6.0 MeV range.

TABLE I

ERS-18 counting rates

Channel	Energy loss range range (MeV)	Rate, anti-coincidence on (counts/cm²-sec-MeV)	Rate, anti-coincidence off (counts/cm²-sec)
1	>0.025	–	31.7
2	0.25–0.6	0.940	0.970/MeV
3	0.6–1	0.286	0.328/MeV
4	1–2	0.144	0.173/MeV
5	2–3.7	0.0526	0.079/MeV
6	3.7–6	0.0355	0.0637/MeV
7	>6	–	2.62

Near apogee at 18 earth radii the earth subtends a solid angle of about 10^{-2} steradian, and earth albedo γ-rays produce a completely negligible flux. Furthermore, because of the high perigee (2.4 earth radii) the satellite does not appreciably penetrate the high energy proton zones which can induce radioactivity in the satellite and the NaI crystal. This effect has plagued previous experiments (Peterson, 1965; Peterson *et al.*, 1968) but does not contribute an observable background rate to this experiment. Furthermore, the data presented here were selected from intervals during which there was no evidence of detectable particle fluxes in interplanetary space above those attributable to galactic cosmic rays. Data obtained during the solar proton events of late May and early June have been excluded from the analysis.

The rates obtained with the anti-coincidence on and off are shown in Table I and Figure 2 after converting to energy loss spectra by dividing by the channel width and by the isotropic geometry factor, 54 cm^2. Clearly, with the anti-coincidence off cosmic ray energy losses dominate the spectrum at the higher energies. The difference between the two rates must be due to charged particles. The expected spectrum due to edge effects of minimum ionizing cosmic rays isotropic on the detector has been computed using a Monte Carlo method and interplanetary cosmic-ray intensity of 3.07/cm^2-sec, as measured on the Vela satellites at the time (J. R. Asbridge, private

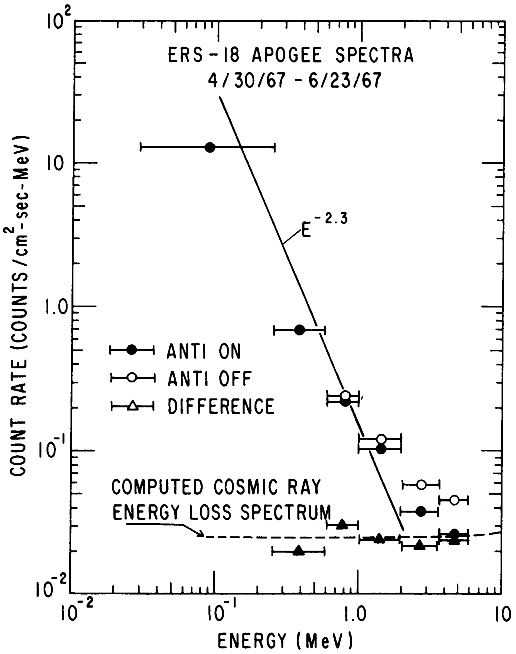

Fig. 2. The spectrum measured in interplanetary space with the anti-coincidence shield turned on and off. The difference is compared with that predicted due to cosmic-ray energy losses in the crystal edges. The anti-on rates are interpreted as due to cosmic γ-rays.

communication). This computed spectrum, shown as a dotted line in Figure 2, is flat at energy losses below that corresponding to ionization losses by particles traversing the length or diameter of the crystal. That the theoretical spectrum due to particle losses agrees so closely with the observed one is taken as substantial evidence that the anti-coincidence performed properly and that the calibration had not appreciably changed in orbit. Furthermore, the integral rate (>6 MeV) measured in the central detector agrees with the independently measured cosmic ray flux by Asbridge to within 17%, giving one considerable confidence in the entire system operation.

The energy loss spectrum with the anti-coincidence on must therefore be due to γ-rays incident on the detector. No known process has sufficient cross-section for cosmic rays to produce an appreciable γ-ray flux in passing through the 8 gm/cm^2 of average satellite material adjacent to the γ-ray counter. Approximately $\frac{2}{3}$ of the 4π steradian solid angle is shielded only by the guard counter and its container plus the solar cell panels. Only about 5% of the cosmic rays will interact in traversing the satellite material to begin the electromagnetic and nucleonic cascades which develop to their maximum in about 100 gm/cm^2. The γ-rays in our region of observation are produced by secondary interactions in the cascade process. A detailed Monte Carlo calculation of the cascade development in a small amount of matter has not been carried out. However, we can obtain some experimental evidence for the lack of coupling due to cosmic rays by searching for correlations in the γ-ray channels associated with the modulation of galactic cosmic rays by solar activity associated with the events of May–June 1967. During this period the sea level cosmic-ray indices varied some 10%, and the intensity at the satellite by 30%. The correlation coefficients between the integral (>6 MeV) channel and the 1–2, 2–3.7, and 3.7–6.0 MeV channels were typically 0.3 with the anti-coincidence on and 0.5 with the anti-coincidence off. We have also summed the total number of counts in each γ-ray channel over two specific time periods; one when the >6 MeV channel was counting less than 145 c/sec and one when it was counting this value or greater. These sums were compared with the integrated counts of the >6 MeV channel and the neutron monitor counts over the same time period. From these results we can infer that the contribution from γ-rays produced in the satellite is less than $10 \pm 10\%$ for any channel. The comparison of our cosmic ray rates with the Vela results and the fluctuations of the γ-rates of 5% over the time period reported here lead us to assign a systematic error to these results of not more than 20%.

The ERS-18 data are shown in Figure 3, compared with other positive measurements of the diffuse component, over the entire X- and γ-ray range. In addition to the balloon, satellite and OSO-3 γ-ray data referenced previously, the 250 eV flux recently reported by Bowyer *et al.* (1968) and by Henry *et al.* (1968) is indicated. Also shown are measurements obtained on the OSO-3 over the 7.7–200 keV range (Hudson *et al.*, 1969). The fluxes near 1 MeV are not corrected for efficiency or photo fraction, since this correction is dependent on the spectral shape to the highest energies. At energies below about 100 keV, the diffuse component is known to be isotropic to within 10%; at 100 MeV the galactic disk is the strongest emitter, and only an upper limit to the diffuse (non-galactic) component at this energy has been presented (Clark *et al.*, 1968).

The data in the 30 keV to 1 MeV range obey a power law spectrum with a number index of -2.2 (Gould, 1967). This component has been interpreted as due to intergalactic electrons scattered on the 3K radiation (Felten and Morrison, 1966). If this is indeed the case, the power law should continue at least as steep to the highest energies. Two other possible production mechanisms, bremsstrahlung (Silk and McCray 1969; Stecker and Silk, 1969), and proton-antiproton annihilation (Stecker, 1969a) would predict an even steeper power law above 1 MeV. This is clearly inconsistent with the ERS-18 data above about 1 MeV. We therefore conclude that a second component of cosmic γ-rays contributes an appreciable flux above about 1 MeV.

The ERS-18 data contribute little to the detailed spectra of this component and nothing about its directionality. A possible origin is nuclear γ-rays, of either galactic or extragalactic origin. Although quantitatively, with the present understanding of

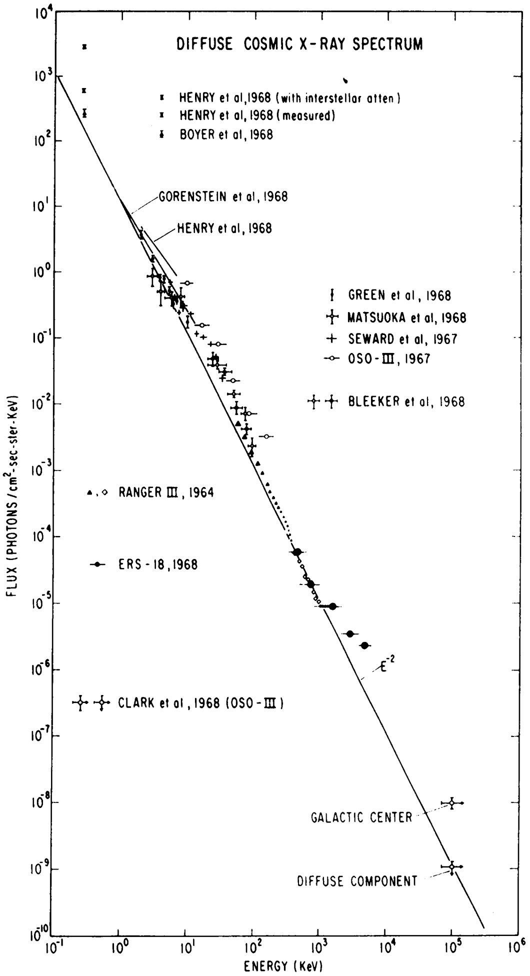

Fig. 3. Measurements of the total cosmic background spectra over the 250 eV to 100 MeV range. The fluxes are known to be generally isotropic at the lower energies and originate in the galactic plane at 100 MeV. The ERS-18 data on the total, on 4π flux, lie considerably above an extension of the lower energy power law spectrum.

galactic cosmic ray processes, this source seems unlikely (Ginzburg and Syrovatskii, 1964). Such a spectrum would drop steeply above about 10 MeV. Another possibility would be due to extension of the 100 MeV galactic component to lower energies with a harder spectrum than observed below 1 MeV. The 1–10 MeV range then becomes the crossover range where the spectrum hardens, and anisotropy becomes evident.

One hypothesis which fits the data has been advanced by Stecker (Stecker, 1969b; Stecker and Silk, 1969). He has suggested an additional isotropic component due to photons produced by π^0 decays when cosmic rays were first accelerated during the expansion following the ‘big-bang’. Such photons would now be red-shifted and depending on the epoch, would appear in the 1–10 MeV range. The cosmological interpretation of our data following this hypothesis is presented in the accompanying paper by Stecker.

The actual conversion of the ERS-18 data to a photon spectrum depends upon the shape of this spectrum at higher energies. We have considered the total flux to be composed of two components (a) a power law spectrum, which fits the data at low energy and (b) a peaked spectrum, similar to that proposed by Stecker to fit the data above 1 MeV. These spectra, which both extend to high energies, were then used as input for a Monte Carlo program which accounted for the relevant path-length distribution, cross-sections, efficiencies, etc. in a 7.5 × 6.35 cm diameter NaI(Tl) detector, and produced an energy loss spectrum. Parameters were adjusted to fit the measured energy loss spectrum. The power law flux requires an index of -2.0 to reproduce the measured energy loss spectrum up to a few hundred keV. A total flux of 1.3 photons/cm^2-sec at 1 MeV in the $Z = 100$ Stecker spectrum added to the power law contribution produces the required flatness near 1 MeV. The final results of this process are shown in Figure 4.

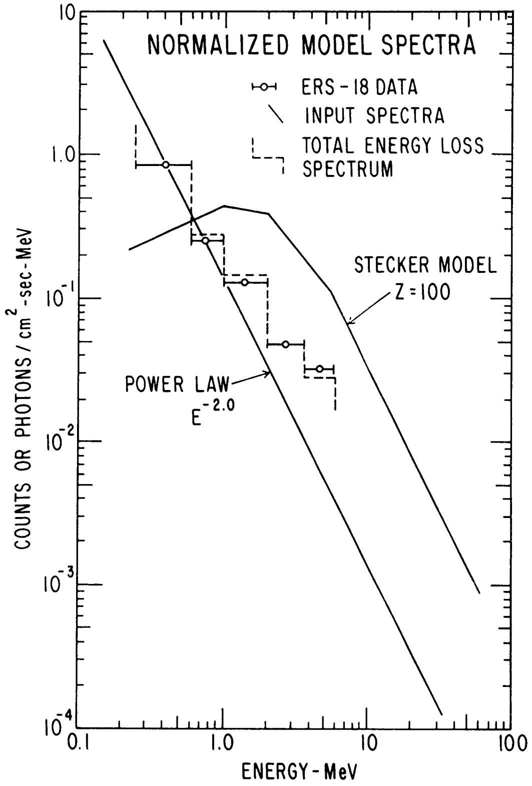

Fig. 4. The results of a computation in which a theoretical power law spectrum, and a red-shifted π^0 spectrum corresponding to a Stecker model of $Z = 100$ were inputed to a Monte Carlo program which takes into account the detector response at all energies. The resultant energy loss spectrum is compared with the ERS-18 data.

We believe the ERS-18 experiment has clearly measured cosmic γ-rays above 1 MeV. The spectrum is flatter than that observed at lower energies and suggests that a new component is present. These results are consistent with a component having the cosmological π°-decay origin suggested by Stecker. Although our results cannot definitely establish this process as the source mechanism, it is an exciting possibility which, if true, means we are viewing photons which have been red shifted by a factor of about 100. This is considerably greater than the red shift observed in quasars.

It is clear that additional measurements in this energy range are needed to obtain directional information as well as more detailed spectral data. This coupled with additional theoretical developments should lead to a more detailed understanding of the source mechanisms which clearly have cosmological implications.

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