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A NEW COMPONENT OF COSMIC GAMMA RAYS NEAR ONE MEV OBSERVED BY THE ERS-18 SATELLITE

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GODDARD SPACE FLIGHT CENTER
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I. INTRODUCTION

In this letter we wish to confirm and discuss in detail new data on the total omnidirectional cosmic γ-ray flux in the 0.25 MeV to 6 MeV range obtained by the Environmental Research Satellite-18 (ERS-18) which were presented in a preliminary form earlier (Vette, et al., 1969). Diffuse cosmic γ-rays between 0.07 MeV and 1 MeV were first detected on the Ranger III (Metzger, et al., 1964) and confirmed between 20 keV and 0.5 MeV by balloon and satellite measurements (Bleeker and Deerenberg, 1969; Schwartz, 1969). Extension of the spectrum to higher energies has become of considerable importance since the recent successful detection of galactic γ-rays > 100 MeV by the OSO-III (Clark, Garmire and Kraushaar, 1968). The ERS-18 measurements indicate an additional component of γ-rays in the 1 - 6 MeV range above that expected by simple extrapolation of the spectrum below 1 MeV to higher energies.

II. DESCRIPTION OF EXPERIMENT

The ERS-18 was launched April 28, 1967, along with the Vela 4 satellites into a highly elliptical orbit of 117,500 km apogee and 15,000 km perigee. The 7.8 Kg satellite (Peterson et al., 1968a) contains a number of radiation detectors designed to measure magnetospheric particles, cosmic-rays, solar X-rays and cosmic γ-rays. A large detector, designed to measure the cosmic γ-ray spectrum in the energy range 0.25 - 6 MeV, consisted of 7.65 cm long x 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. Six channels of pulse height analysis permitted spectral measurements in the five energy loss bands given in Table I. In addition, total counting rates were monitored in integral channels at 25 keV and 6 MeV. The anti-coincidence was switched on and off by the spacecraft commutator about every 500 seconds in order to assess the counting rates due to cosmic-ray energy losses. The difference in counting rate for these two modes served as a calibration using the cosmic-ray beam and verified operation of the anti-coincidence system.

The satellite spent a large fraction of its 48-hour orbit in regions where magnetospheric particles were not detectable by the charged particle detectors whose lowest threshold energies were 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. Near apogee at 18 earth radii the earth subtends a solid angle of about 10^{-2} steradian; earth albedo γ-rays therefore produced a completely negligible flux. Furthermore, because of the high perigee (2.4 earth radii) the satellite did not appreciably penetrate the high energy trapped proton zones which could induce radioactivity in the satellite and the NaI crystal. This effect has plagued previous experiments on the OSO-I (Peterson, 1965) and on the ERS-17 (Peterson, 1968b) but did 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. Although the information bandwidth of the ERS-18 telemetry was 6 Hz, and only a small fraction of this was devoted to the γ-ray experiment, the measurement was nevertheless limited by systematic effects rather than counting statistics.

III. DATA ANALYSIS

Rates obtained with the anti-coincidence on and off are shown in Table I and Fig. 1, after converting to energy loss spectra by dividing by the channel width and by the isotropic geometry factor, 54 cm^2. Since the difference between the two rates must be due to cosmic-ray effects, the data shows that energy losses due to cosmic-rays and photons are about equal in the highest channels. The rates are not a true measure of the incident spectrum since neither photons nor cosmic-rays necessarily lose all their energy upon interacting with the detector. Obtaining the actual input spectrum is a difficult process and generally requires some knowledge of the photon spectrum to energies well above the highest energy loss channel.

The expected energy loss spectrum of minimum ionizing cosmic-rays isotropic on the detector, including edge effects, has been computed using a

Monte Carlo method and an interplanetary cosmic-ray intensity of $3.07/\mathrm{cm}^2$-sec which was measured on the Vela satellites simultaneously (J. R. Asbridge, private communication). The computed spectrum, shown as a dotted line in Fig. 1, is flat at energy losses below that corresponding to ionization losses by particles traversing the diameter of the crystal. That this calculated 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 energy loss calibration had not appreciably changed in orbit. Furthermore, the total integral rate (>6 MeV) measured in the central detector, after a 10 per cent edge effect correction, agrees with the independently measured cosmic-ray flux by Asbridge to about 5 per cent. This provides additional 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 from space or produced in the satellite itself. No known process has sufficient cross-section for cosmic-rays to produce an appreciable γ-ray flux in passing through the $8\ \mathrm{gm/cm}^2$ of average satellite material adjacent to the γ-ray counter. Although a detailed Monte Carlo calculation of the cascade development in a small amount of matter has never been carried out, one can estimate that only about 5 per cent of the cosmic rays will undergo nuclear interaction in traversing the satellite. The electromagnetic and nucleonic cascades which follow develop to their maximum intensity after about

100 gm/cm^2. Our direct experience on balloon flights indicated that 7 gm/cm^2 of Al surrounding detectors similar to the ERS-18 does not result in an additional flux detectable above cosmic-ray produced atmospheric γ-rays.

A further experimental measure of the coupling between cosmic-rays and measured γ-rays can be obtained by searching for correlations of the γ-ray counting rates 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 per cent and the intensity at the satellite by 30 per cent. 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 averaged the counting rate in each γ-ray channel over two specific time periods--one when the > 6 MeV channel was counting less than 142 c/sec and one when it was counting this value or greater. The differences between these averages were small compared with the differences between the averages for the > 6 MeV channel or the neutron monitor indices 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 percent $\pm$ 10 per cent for the highest energy channels. The comparison of our cosmic-ray rates with the Vela results, as well as estimates of background effects, lead us to assign an estimated total systematic error to these fluxes of not more than 20 per cent. The relative error between the channel-by-channel results are considerable smaller than this.

IV. INTERPRETATION OF RESULTS

The ERS-18 data are shown in Fig. 2 compared with previous results obtained on Ranger III in space (Metzger, et al., 1964) and on the OSO-I in low altitude earth orbit (Peterson, 1966). These measurements were all obtained with detection systems similar to the ERS-18, and none provided direct information on the directionality of the incident radiation except for the inference that the incident γ-rays cannot be highly anisotropic. A portion of the Ranger III counting rate above 1 MeV attributed to an instrument artifact is not shown. The OSO-I upper limit is obtained directly from the counting rate over the geomagnetic equator using the 2.8π solid angle factor subtended by space at 550 Km as the conversion factor. The interpretation of the OSO-I data was considerably more complicated than those of the ERS-18 and Ranger III because of background effects of (a) the 200 Kg spacecraft, (b) earth albedo γ-rays, (c) induced radioactivity and (d) gain calibration problems. These effects produce a measured total flux considerably above the ERS-18 result. However, from the distinct latitude dependence of the counting rates, it seems clear that an appreciable fraction of the OSO-I rate must be due to cosmic-ray production. An OSO-I lower limit based on the assumption that the background latitude effect due to earth albedo and spacecraft production is less than that due to primary cosmic-rays is also shown in Fig. 2.

Since the difference in the measured cosmic-ray flux between the ERS-18 and Vela 4 is essentially zero, a restriction on the integral γ-ray spectrum may be made assuming that the maximum cosmic γ-ray contribution must be less than that due to the estimated systematic errors in the ERS data. The twenty per cent maximum error corresponds to a > 6 MeV photon-produced rate of 0.60 c/cm^2-sec; the true integral rate is perhaps much less.

Indicated in Fig. 3 and Table I are theoretical fluxes based on the interpretation of the 0.01 - 1.0 MeV γ-rays as due to Compton scattering of intergalactic electrons on the 3° K radiation. These spectra are normalized in the 30 - 300 keV range where good agreement is obtained among the various experiments. The original idea of Felten and Morrison (1966) indicated a simple power law spectrum whose differential number index was about -2.3. The more recent spectrum of Brecher and Morrison (1969) takes into account the distribution of radio galaxy spectral indices and luminosities as well as cosmological factors. At energies above a few hundred keV, the energy loss spectrum as measured by the detector cannot be directly compared with either of the two theoretical photon spectra. The theoretical spectra which are fitted to the data below 1 MeV after correction to energy loss will produce counting rate spectra well below the measured data points in the 1 - 6 MeV range. We interpret this as indicating an additional cosmic γ-ray component above that accounted for by extrapolating the known diffuse background to higher energies. No reasonable extrapolation of lower energy data can completely account for the ERS-18 data.

In order to find the spectrum of the excess component, Monte Carlo computer programs have been developed to compute the energy loss spectrum in the detector for any incident photon spectrum. The calculations for the two theoretical diffuse background spectra shown in Fig. 3 may be compared with the measured spectrum and differences taken to find the excess rates. The results appear in Table I. Data in the 0.25 - 0.6 MeV range have not been included in the following analysis because of (a) the uncertain correction for satellite absorption, (b) the rather wide energy window, and (c) the near agreement of the two theoretical spectra at lower energies. The total excess counting rate above that accountable by the extrapolated diffuse component varies from 0.31 to 0.36 c/cm^2-sec over the 0.6 - 6.0 MeV range and is 2.5 to 5.5 times larger than the extrapolated diffuse background, depending on the model spectrum used to extrapolate from lower energies into this range.

V. DISCUSSION

These results must be discussed in terms of other measurements of the total cosmic γ-ray spectrum. Based on an analysis of balloon data, Bleeker and Deerenberg (1969) have found the spectrum over the 20 - 220 keV range to be even steeper than we have used with an index 2.45 ± 0.10. The cosmic flux in the 7.9 - 110 keV range is known to be isotropic to within a few per cent (Schwartz, 1969) except for the contributions due to galactic point sources. No directional measurements are available in the 0.2 - 10 MeV range. The OSO-III > 100 MeV results indicate both a diffuse background component and a galactic "line" source.

We assume that the ERS-18 γ-ray flux contains a component due to an extrapolation of the isotropic diffuse background spectrum and an excess counting rate of about 0.35 c/cm^2-sec in the 0.6 - 6 MeV range. Since nothing is known about the directionality of the excess component, several possible origins must be considered.

a) <u>Galactic Point Sources</u>. A collection of point X-ray-type sources radiating strongly in the MeV range could produce the excess. Although no X-rays greater than 500 keV from known sources have yet been detected, firm upper limits on the Crab Nebula of 1.7×10^{-3} c/cm^2-sec-MeV at 1 MeV and 1.0×10^{-3} c/cm^2-sec-MeV at 5 MeV have been obtained (Peterson, et al., 1966; Schwartz, private communication). These limits are factors of 1.3 and 2.5 above an extrapolation of the hard X-ray spectrum of the Crab Nebula to higher energies. To account for the excess flux observed by ERS-18 would require some 50 sources radiating at the present Crab upper limit and even more using its extrapolated X-ray spectrum. At least some of such a large number of discrete sources radiating this strongly would most likely have been discovered by now.

b) <u>A Galactic "line" Component.</u> A galactic disc component of cosmic γ-ray radiation with an average intensity 2.0×10^{-4}/cm^2-sec-rad has been detected at 100 MeV (Clark, Garmire and Kraushaar, 1968). Explanation of our excess of 0.31 c/cm^2-sec as a line component would require an average flux of .020 c/cm^2-sec-rad in the 1 - 2 MeV range.

Extending the high energy spectrum steeply to lower energies is ruled out by the work of Clark, Garmire and Kraushaar (1968) who state that the line source spectrum is rather flat in the 100 MeV range. In order to be consistent with the upper limits obtained on the OSO-III over the 7.7 - 210 keV range (Schwartz, 1969), explanation of the ERS-18 excess in terms of a galactic "line" source requires a new component which is flat below 1 MeV and falls off steeply above 6 MeV.

c) An Extragalactic Component. If the ERS-18 excess is to be interpreted as an additional isotropic component above that due to the spectrum extrapolated from lower energies, it seems clear this component must fall steeply in the 6 - 100 MeV range to connect with OSO-III 100 MeV results. The OSO-III experiment indicates, in fact, that the diffuse cosmic source spectrum at 100 MeV is steeper than that of the galactic line source.

A number of explanations have already been advanced to explain the ERS-18 results. The spectrum of Brecher and Morrison (1969), which fits the data in the 3 keV to 1 MeV range rather well, also apparently fits the measured ERS-18 energy-loss spectrum. However, as already shown in Table I, when proper account is taken of the detector response this source fails considerably to account for the new results.[1]

Clayton and his co-workers (Clayton, Colgate and Fishman, 1969; Clayton and Silk, 1969) have suggested that γ-ray fluxes in the 1 - 3 MeV range may be produced by the process $Ni^{56} \xrightarrow{6.1d} Co^{56} \xrightarrow{77d} Fe^{56}$ if Ni^{56} is

[1] It also conflicts with the OSO-III datum, which was plotted a factor of ten too high in their paper.

synthesized in supernovae explosions. Each decay chain produces an average of nearly 5 γ-rays, with energies extending to 3.47 MeV. Clayton and Silk have integrated the fluxes expected due to a reasonable rate of supernovae explosions per galaxy over cosmological distances and predict a detectable flux at the earth. This explanation requires a rapid fall off in the flux above 3.26 MeV; this was not observed on the ERS-18. Furthermore, they also predict 77d decay times to be occasionally observed at the higher energies due to supernovae in nearby galaxies. Although the total variation observed during the May-June period was only $\pm$ 5 per cent, the nearly continuous data extending over a 13-month lifetime of the ERS-18 is only now being reduced to look for 77-day effects. Although this particular nuclear process does not explain the new data, the possibility of nuclear γ-rays cannot be excluded.

Stecker (1969a, 1969b,) has proposed that π^o meson decay photons occurring as a result of cosmic-ray interactions at a high density epoch of the expanding universe would be red shifted and result in a spectrum peaked in the 1 - 10 MeV range for a Z_{max}, the earliest time of cosmic-ray acceleration, of about 100. Since Stecker's theory makes definite spectral predictions, we have attempted to fit his models to the new data in the 0.6 - 6.0 MeV range making maximum use of the ERS-18 energy loss spectrum. By using the normalization as a minimization parameter, the energy loss spectrum computed from the Stecker photon spectrum of a given

Z_{max} is least-square fitted (the relative errors are minimized) to the two excess energy loss spectra given in Table I and shown again for convenience in Table II. The results of this fitting are indicated in Table II and Fig. 3 using a Z_{max} of 50, 70, 100 and 150. The total photon spectrum lies a factor of 1.5 to 3, depending on the energy, above the energy-loss spectrum and clearly indicates the essential importance of correcting for the detector response. The standard deviation of the relative errors between the fit and measured values, σ_{rel}, are also given in Table II. The errors assigned to the calculated values are based on least square fitting differences rather than the smaller relative errors in the measured data.

A comparison of calculated and observed excess indicates that $Z_{max} = 100$ provides the best fit for a power law background, and $Z_{max} = 70$ results in the best fit for the Brecher-Morrison spectra. The photon fluxes for these cases are shown plotted in Fig. 3. Although the spectra based on the Stecker model can be adjusted to fit the ERS-18 excess in the 0.6 - 6.0 range rather well, the predicted flux at 100 MeV lies at least a factor of three above the measurement of 1.2×10^{-6} photons/cm^2-sec-Mev-ster (letting $\Delta E = E$) reported from the OSO-III measurement at 100 MeV. Of course, if one uses the data point at 100 MeV in conjunction with the ERS-18 data, a higher Z_{max} value will be obtained which produces a poorer fit for the 0.6 - 6.0 MeV interval. Since the reported 100 MeV results may be high by a factor of two or three (Garmire, private communication), it is premature to present such a fit. Furthermore, the prediction of the Stecker model at 100 MeV depends mainly on the assumed cosmic ray spectral index at Z_{max}, rather than on Z_{max} itself. A determination of Z_{max} is best made near the peak of the gamma ray spectrum.

We believe the ERS-18 data have indicated clearly an additional component of the cosmic γ-ray spectrum. The Stecker model provides a photon spectrum which quantitatively agrees with the measured results by using a Z_{max} somewhere between 70 - 100. Several other possible source mechanisms cannot be definitely ruled out by the present experiment. New experiments with greater spectral resolution, higher energy coverage, and directional sensitivity are needed to test theoretical models more definitively. The important cosmological implications of these models should give considerable impetus to carrying out such experiments.

ACKNOWLEDGMENT

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TABLE I

ERS-18 MEASURED AND CALCULATED RATES*

Channel	Energy Range (MeV)	Measured Rate Anti-off	Measured Rate Anti-on	$0.146\ E^{-2.3}$ Background Photon flux	$0.146\ E^{-2.3}$ Background Calc rate	$0.146\ E^{-2.3}$ Background Excess rate	Brecher-Morrison Background ($\mu = 0.3$) Photon flux	Brecher-Morrison Background ($\mu = 0.3$) Calc rate	Brecher-Morrison Background ($\mu = 0.3$) Excess rate
1	> 0.025	7.15^{+}	--	--	--	--	--	--	--
2	0.25 - 0.6	0.970	0.940	1.32	0.829	0.111	1.60	1.10	-0.155
3	0.6 - 1.0	0.328	0.286	0.265	0.095	0.191	0.364	0.144	0.141
4	1.0 - 2.0	0.173	0.144	0.0665	0.019	0.125	0.108	0.0405	0.103
5	2.0 - 3.7	0.079	0.0526	0.0147	0.0030	0.0496	0.051	0.0084	0.044
6	3.7 - 6.0	0.064	0.0355	0.00414	0.0013	0.0342	0.025	0.0037	0.031
7	> 6.0	2.62^{+}	--	--	--	--	--	--	--
sum	0.6 - 6.0	--	0.429^{+}	0.207^{++}	0.0651^{+}	0.364^{+}	0.398^{++}	0.121^{+}	0.308^{+}

* All rates are counts/cm^2-sec-MeV, and all fluxes are photons/cm^2-sec-MeV unless otherwise indicated.

$^{+}$ c/cm^2-sec

$^{++}$ photons/cm^2-sec

TABLE II

CALCULATED AND OBSERVED ERS-18 RATES USING STECKER MODEL

	Power Law Background Subtracted Rate (counts/cm^2-sec-MeV)				
Energy Loss Range (MeV)	Z = 50 σ_{rel} = .26	Z = 70 σ_{rel} = .13	Z = 100 σ_{rel} = .096	Z = 150 σ_{rel} = .21	Obs. Excess
0.6 - 1.0	0.125 $\pm$ .032	0.166 $\pm$ .022	0.202 $\pm$ .019	0.244 $\pm$ .051	0.191
1.0 - 2.0	0.092 $\pm$ .024	0.108 $\pm$ .014	0.114 $\pm$ .011	0.108 $\pm$ .023	0.125
2.0 - 3.7	0.058 $\pm$ .015	0.058 $\pm$ .008	0.057 $\pm$ .005	0.052 $\pm$ .011	0.050
3.7 - 6.0	0.041 $\pm$ .011	0.037 $\pm$ .005	0.032 $\pm$ .003	0.023 $\pm$ .005	0.034
	Rate (counts/cm^2-sec)				
0.6 - 6.0	0.334 $\pm$ .097	0.358 $\pm$ .060	0.365 $\pm$ .049	0.347 $\pm$ .088	0.364

	Brecher-Morrison Background Subtracted Rate (counts/cm^2-sec-MeV)				
Energy Loss Range (MeV)	Z = 50 σ_{rel} = .21	Z = 70 σ_{rel} = .067	Z = 100 σ_{rel} = .15	Z = 150 σ_{rel} = .36	Obs. Excess
0.6 - 1.0	0.110 $\pm$ .021	0.140 $\pm$ .011	0.165 $\pm$ .022	0.191 $\pm$ .059	0.141
1.0 - 2.0	0.081 $\pm$ .015	0.091 $\pm$ .007	0.093 $\pm$ .012	0.084 $\pm$ .026	0.103
2.0 - 3.7	0.051 $\pm$ .010	0.049 $\pm$ .004	0.046 $\pm$ .006	0.040 $\pm$ .012	0.044
3.7 - 6.0	0.036 $\pm$ .007	0.031 $\pm$ .002	0.026 $\pm$ .003	0.018 $\pm$ .006	0.031
	Rate (counts/cm^2-sec)				
0.6 - 6.0	0.295 $\pm$ .056	0.302 $\pm$ .023	0.297 $\pm$ .040	0.269 $\pm$ .083	0.308

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ERS - 18 APOGEE SPECTRA
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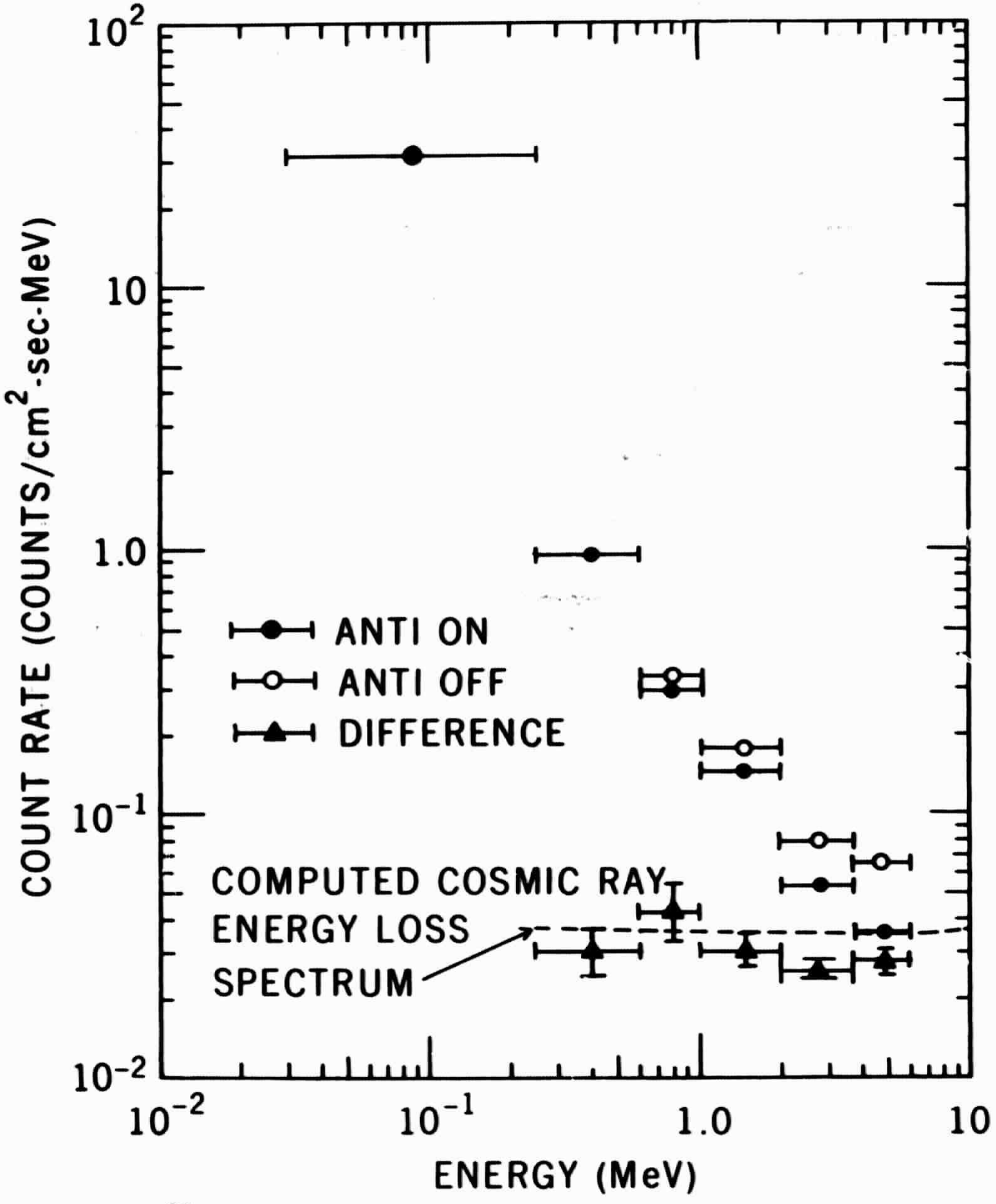

Figure 1

ENERGY LOSS SPECTRA
COSMIC γ-RAYS

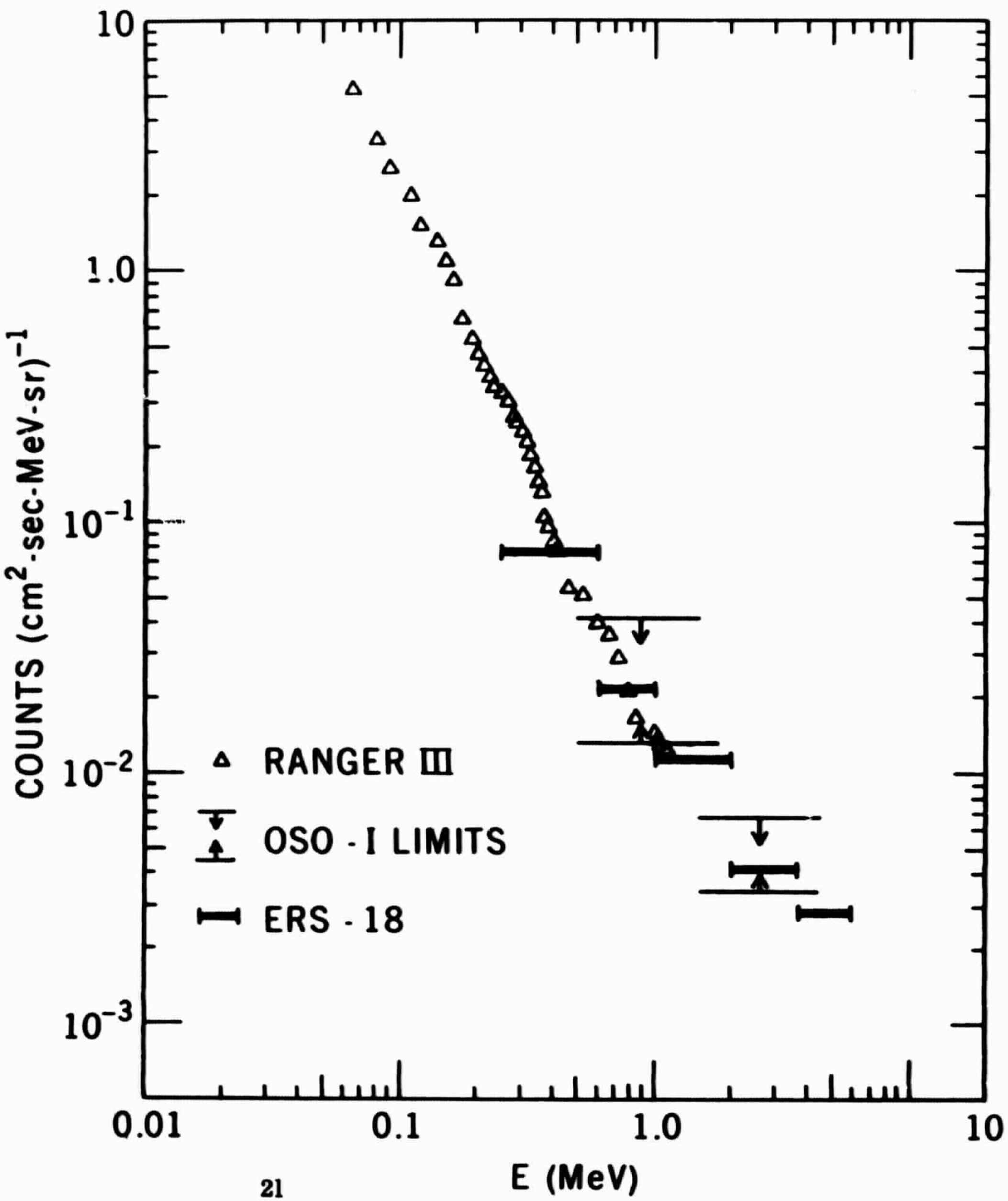

Figure 2

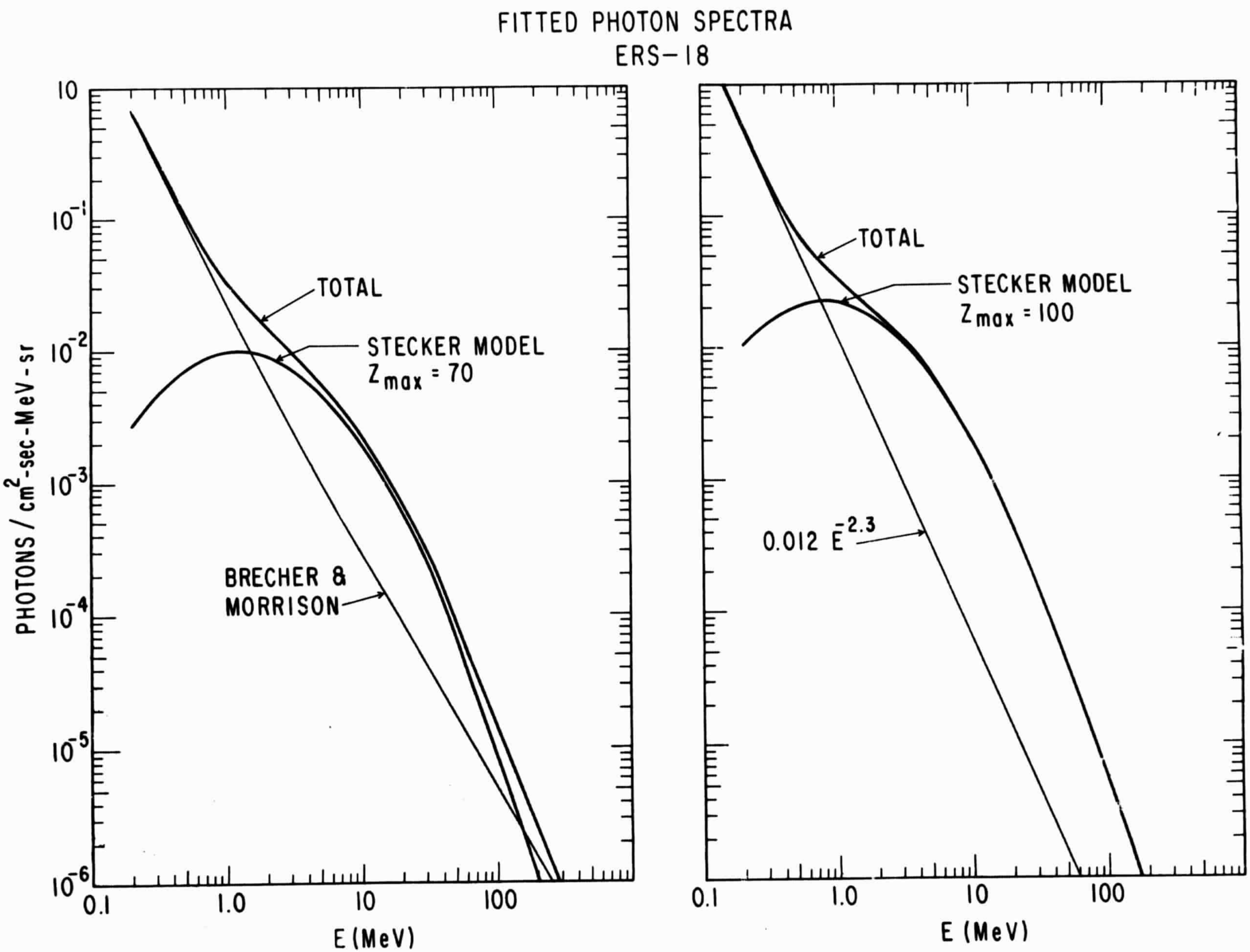
FITTED PHOTON SPECTRA
ERS-18
PHOTONS / cm²-sec-MeV-sr
10
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.1
1.0
10
100
E (MeV)
TOTAL
STECKER MODEL
Z max = 70
BRECHER &
MORRISON
TOTAL
STECKER MODEL
Z max = 100
0.012 E⁻²·³

Figure 3