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ABSTRACT

The spectrum of the total (diffuse and discrete sources) cosmic γ-ray background over the 0.3 - 27 MeV range has been measured with a 7.0 cm dia. x 7.0 cm long uncollimated NaI(Tℓ) scintillation counter located on a boom 7.6 m from the Apollo 15 Service Module. Data on cosmic γ-rays were taken during Transearth Coast at various boom extensions, detector gains, and with the plastic anticoincidence scintillator enabled and disabled. The energy loss spectrum at full extension with the anticoincidence enabled, corrected for monochromatic spacecraft γ-rays, is 0.18 counts $(cm^2\text{-sec-MeV})^{-1}$ at 1 MeV, in agreement with previous measurements on the Ranger III and the ERS-18. At 5 MeV, the Apollo measurement of 7×10^{-3} counts $(cm^2\text{-sec MeV})^{-1}$ is about a factor of 5 below that determined from the ERS-18. Corrections for line contributions and spacecraft continuum at higher energies give a steep equivalent

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photon spectrum with a broad feature in the 1-3 MeV region. This flattening can be reduced but not eliminated with an estimated correction for spallation effects in the detector, leaving a spectrum which we interpret as an upper limit to the true cosmic photon spectrum in the 0.3 - 27 MeV range. At 3 MeV, this limit is a factor of three and at 27 MeV a factor of ten above a power law which extrapolates from measurements below 1 MeV. We have also measured a flux of 0.03 ±0.015 photons $(cm^2\text{-}sec)^{-1}$ at 0.51 MeV which may be mostly of local origin.

CONTENTS

ILLUSTRATIONS

I. INTRODUCTION

We report a new measurement of the total cosmic gamma-ray spectrum in the range from 0.3 to 27 MeV obtained on Apollo 15. Previous measurements in this range have extended only to 6 MeV. These data were obtained with an isotropic scintillation counter similar to that used on the Ranger III (Metzger et al., 1964) and ERS-18 (Vette et al., 1970). The new high precision data permit extension and clarification of the spectrum above 1 MeV, where recent balloon (Damle et al, 1971; Vedrenne et al., 1971) and earth satellite observations (Golenetski, 1971) have caused doubts as to the validity of the ERS-18 data. Furthermore, Fishman (1972) has suggested that most of the counts near 2 MeV are not of cosmic origin but are associated with cosmic ray produced spallation products decaying in the scintillation counter crystals. The observational situation has been recently reviewed by Pal (1972). These results are of interest because of the considerable discussion regarding the astrophysical and cosmological importanct of γ-rays in this region.

II. INSTRUMENTATION

The Apollo 15/16 gamma-ray spectrometer (Adler and Trombka, 1970) consists of a 7.0 cm dia x 7.0 cm long NaI(Tℓ) central detector viewed by a 3" photomultiplier. Except at the photomultiplier end, the crystal is surrounded by a 1 cm thick plastic scintillator shield which detects charged particles. The plastic scintillator is viewed by a 1-1/2" photomultiplier and has a threshold of about 1.0 MeV for generating an anticoincidence event when interactions occur in the most optically unfavorable location. Central detector events with no shield anti-coincidence are pulse-height analyzed into 511 channels and are transmitted at a maximum event rate of 369 counts/sec. The shield rate, the coincidence rate, and the livetime are transmitted every 0.328 seconds. The spectrometer and associated electronics are enclosed in a thermal shield and mounted on a boom which could be extended from one side of the Service Module by an astronaut. The components carried on the boom present $\sim 5\,gm/cm^2$ averaged over all directions. The astronaut could fully deploy the detector to 7.6 m from the spacecraft edge or position it at intermediate distances using stopwatch timing. Furthermore, he could step the high voltage supply or disable the anti-coincidence.

III. RESULTS

(a) Energy Loss Spectra

The data reported here were obtained during portions of the Transearth Coast of Apollo 15 from about 2200 4 August to 1500 7 August 1971, and represent ~4 hours of operation in the extended position. During this period the earth and moon solid angles were always less than 10^{-2} sr and in the fully extended boom position, the spacecraft subtended ~0.28 sr. Spectra were obtained with the detector at various boom positions, with the anti-coincidence both on and off, and with the high voltage set to give several energy ranges up to 27 MeV. Although data were obtained over a 0.16 to 27 MeV range, the analysis reported here is based on energy losses >0.3 MeV. Calibration was obtained with a Hg^{203}

source and by means of known, easily identifiable spacecraft background γ-rays. Counting rate anisotropies, if they exist, were averaged out over long runs from which these results were derived, since the Command/Service Module rotated ~3 RPH in the ecliptic plane.

Figure 1 shows energy-loss spectra, corrected for livetime, channel width, and the isotropic detector geometry factor of 57.5 cm^2, for several important data modes. Here counts have been summed over channels consistent with the detector energy resolution which was 8.6% at 662 keV. With the exception of the strong line at 0.51 MeV, most of the γ-ray lines measured inboard largely disappear with boom extension, leaving a continuum extending to 27 MeV, on which is superposed a number of weak lines. Since the intensity changed only about a factor of five, while the spacecraft solid angle changed a factor of 20, most of the rate in the extended position is not of spacecraft origin. From a detailed analysis of the rates vs solid angle, we estimate $\sim 6.6 \times 10^{-3}$ c(cm^2-sec-MeV)$^{-1}$ at 2.4 MeV and $\sim 1.9 \times 10^{-3}$ c(cm^2-sec-MeV)$^{-1}$ at 5 Mev are due to the spacecraft. These are 0.1 and 0.2, respectively, of the spectrum with the boom extended.

The flat energy loss spectrum of 0.052 c(cm^2-sec-MeV)$^{-1}$ above 5 MeV with the anti-coincidence disabled in the extended position agrees with that expected from the shield rate of 450 c/sec, from which a cosmic-ray flux of 3.50 (cm^2-sec)$^{-1}$ may be derived. The large ratio of cosmic-ray to photon energy losses near 27 MeV requires effective charged particle rejection, which could not be measured before launch to the required accuracy. However, preliminary results from an identical experiment on the Apollo 16 in April 1972 confirm the Apollo 15 differential energy loss spectrum below 10 MeV to within ~12 percent. We interpret this as indicating that there were not systematic differences in the behavior of the instruments.

The energy loss spectrum with the anti-coincidence enabled in the extended position is shown with other measurements obtained in cislunar space in Figure 2. The NaI(Tℓ) Apollo 15/16 detector is identical in size to the CsI(Tℓ) detector in Ranger III, both of which differ only slightly from the NaI(Tℓ) crystal on the ERS-18. The 8 kg mass on the end of the Apollo 15 boom is nearly the same as that of the total ERS-18, while the Ranger III detector carried only ~3 kg. Clearly, the present data are in good agreement with previous measurements below ~2 MeV, but are well below the 3.7 - 6.0 MeV point measured by the ERS-18, which is apparently erroneous.

(b) Equivalent Photon Spectra

The equivalent photon spectra have been obtained from the precision energy loss spectra in Figure 1 and 2 by using a measured response "library" and a matrix inversion technique as described by Adler and Trombka (1970). The γ-ray lines are separated from the continuum by using an iterative procedure developed by Trombka (Trombka, et al., 1970; Reedy, Arnold, and Trombka, 1972). Here the pulse-height spectrum is transformed to photon space where lines appear as discontinuities, which may be subtracted by requiring the remaining continuum to be slowly varying with energy. This procedure results in the removal of 2.5 c/sec over the 0.6 to 3.5 MeV range due to lines or about 17% of the energy loss spectrum, and leaves a smooth equivalent photon continuum shown in Figure 3.

(c) Spallation Correction

Fishman (1972) has suggested that radioactive spallation nuclei produced by cosmic-ray interactions in the scintillation crystals may account for a large fraction of the counting rate measured in the 1-3 MeV region. Although a direct measurement of this effect in the cosmic-ray beam is difficult and has not been accomplished, calculations and laboratory measurements by Fishman (1972) and Dyer and Morfill (1971 and private communication), have indicated the spectra shape and approximate magnitude of the energy loss spectrum. We have attempted to correct the spectra of Figure 3 for this effect by subtracting from the equivalent energy loss spectrum a spallation model spectrum whose normalization was a free parameter. Since spallation contributes mostly to the energy losses in the 0.6 to 3 MeV range, the normalization was determined, rather arbitrarily, by the criterium that the resultant photon spectrum be relatively smooth. This was found to occur when a spallation spectrum, based on the work of Fishman (1972) and Dyer and Morfill (private communication) but of approximately half their intensity was subtracted out. As shown in Table 1, this results in removal of about 16% of the energy loss spectrum in the 0.6 to 3.5 MeV range and a negligible amount at higher energies. Subtracting a much larger spallation component, such as the full Dyer and Morfill value, would give no energy losses in the 1-2 MeV range, while still requiring an external photon component above 3 MeV, which is not physically possible. Although there seems no doubt that a spallation energy loss contribution exists, its spectral shape and intensity is only approximately known.

(d) Cosmic Photon Spectrum

The photon spectrum incident on the central detector, shown in Figure 3 as a dashed line, has also been corrected for continuum production in the spacecraft using data obtained in various boom positions and an estimate of the effective solid angle. The contribution of the various components over the 0.6 - 3.5 MeV and the 3.5 - 9.0 MeV ranges are summarized in Table 1. Despite the many corrections, about 50-75% of the energy losses cannot be accounted for by presently understood local processes and therefore must originate externally. Obtaining the photon spectrum incident isotropically on the spectrometer requires a correction for local matter. Taking this to be equivalent to a uniform shell 5.0 gm/cm^2 thick of Al surrounding the NaI crystal, and correcting for absorption, but not scattering results in the final photon spectrum shown in Figure 3. We have assumed the photon continuum extends as $E^{-2.0}$ above 27 MeV; however, the result is rather independent of this shape.

Systematic errors, which are difficult to estimate, completely dominate the statistical uncertainties in this analysis. Correcting for the spacecraft lines can be done to high precision. The effective solid angle for continuum production in the spacecraft may be less certain. No correction has been made for production in local material, which is believed to be small (Vette et al., 1970). We estimate the equivalent photon spectrum, before correction for spallation, to be accurate to about ±20%. The spallation correction cannot be much larger than that indicated in Figure 3. Correcting for absorption, but not scattering, results in an upper limit to the external flux.

These results may be compared to those of others who have presented spectra at various stages of correction. The Apollo 15 photon equivalent continuum is considerably below that determined from ERS-18, which had no corrections for γ-ray lines, effects of local material, or spallation, and which apparently had an instrumental malfunction at higher energies. The final photon Apollo 15 spectrum is compared direction with balloon and low altitude satellite work (Vedrenne et al., 1971; Golenetskii et al., 1971) in Figure 4. The result of Damle et al. (1971) is considerably above the other work and is therefore not shown. Although the low latitude observations should not require a significant correction for spallation, they do require an altitude and latitude dependent model to correct for cosmic-ray produced γ-rays, and in some cases, an additional large correction for counter efficiency.

The new results, in addition to being in reasonable agreement with the more recent work above 1 MeV, also agree with data near 100 keV (Pal, 1972) when extrapolated as an E^{-2} power law. Furthermore, the Apollo spectrum is consistent with new data on the diffuse component near 30 MeV by Pinkau (Mayer-Hasselwander et al., 1972), and by Share, Kinzer and Seeman (1972) at NRL.

Figure 4 shows some of these results, as well as that of Kraushaar et al. (1972) at 100 MeV obtained from the OSO-3.

Also shown in Figure 4 is a single power law which has been suggested (Pal, 1972) as capable of representing the total cosmic γ-ray spectrum between $\sim$0.02 and 1.0 MeV. It is clear that the derived Apollo 15 spectrum is well above this extrapolation and even though we interpret our result as an upper limit, we do not believe that the remaining small corrections and uncertainties can reduce the final cosmic spectrum to the extrapolated value.

IV. DISCUSSION

Assuming that the γ-ray fluxes are of extragalactic origin (Stecker, Vette, and Trombka, 1971) a number of workers have attempted to account for the spectra shown in Figure 4. Compton scattering of electrons leaking from radio galaxies (Brecher and Morrison, 1969), redshifted γ-rays from π° decays produced by cosmic-ray collisions at an early epoch of the expanding Universe (Stecker, 1971), nuclear γ-rays from supernovae in distant galaxies (Clayton and Silk, 1969), intergalactic electron bremsstrahlung (Arons, McClay and Silk, 1971; Stecker and Morgan, 1972) and matter-antimatter annihilation (Stecker, Morgan and Bredekamp, 1971) have all been suggested. Vette et al. (1970), in attempting to account for the ERS-18 data, fitted a model in which a π° decay component produced at an epoch with a redshift $\approx$70 was superposed on a Compton scattering X-ray background. Based on the present data, large fluxes at very early epochs are no longer required, and a π° decay component, if it exists at all, must have originated in a lower density universe at more recent times. Although the final spectrum of Apollo 15 does require an additional component above a simple power law, it appears that several combinations of the various models can provide a fit to the data.

The analysis process used here subtracts out all discrete γ-ray lines and produces a smooth continuum, as presented in Figure 3. Discrete γ-rays of cosmic origin, if they exist, would therefore be removed along with known spacecraft and spallation contributions. Only considerable further analysis can separate these components, and place valid limits on possible cosmic components.

The γ-ray line near 0.51 MeV has an intensity after correction for spacecraft production and local absorption estimated to be $3.0 \pm 1.5 \times 10^{-2}$ photons $(cm^2\text{-}sec)^{-1}$. The uncertainty is an estimate of the effect of systematic errors in the correction for weak γ-ray features near this energy and for detector efficiency and absorption. The 0.51 MeV γ-ray measured on Apollo 15 cannot originate in the spacecraft since this component decreases less rapidly with spacecraft solid angle than the continuum. The intensity of the line seems inconsistent with upper limits on the cosmic flux at 0.51 MeV of $<10^{-2}$ photons $(cm^2\text{-}sec)^{-1}$ obtained from balloon measurements (Chupp et al., 1970) and on the Ranger III (Metzger et al., 1964). Since the Ranger III, which also measured in interplanetary space, had considerably less matter locally to the detector, it may be possible to attribute the flux to annihilation of positrons produced by cosmic-rays or spallation β^+ decays in the local mass. It is also possible that low energy positrons of either solar or cosmic origin with a flux of $\sim 10^{-2}$ $(cm^2\text{-sec})^{-1}$ could stop and annihilate in the inert matter surrounding the detector. Such a mechanism has been suggested by Stephens (private communication) and is in fact consistent with the interplanetary medium flux of 2×10^{-2} positrons $(cm^2\text{-sec})^{-1}$ at ~ 2 MeV reported by Cline and Hones (1969). Haymes (Johnson, Harnden and Haymes, 1972) has reported a γ-ray line at ~ 470 keV whose intensity is 2×10^{-3} photons $(cm^2\text{-sec})^{-1}$ originating from the galactic center. The γ-ray line measured on Apollo 15 is definitely at 0.511 ± 0.012 MeV, and the 2σ upper limit to a γ-ray at 0.47 MeV is $\sim 2 \times 10^{-3}$ photons $(cm^2\text{-sec})^{-1}$, based on the analysis of four hours of data.

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REFERENCES

Adler, I., and Trombka, J. I., 1970, Physics and Chemistry in Space, Vol. 3, ed. J. G. Roederer and J. Zahringer (New York: Springer-Verlag).

Arons, J., McCray, R., and Silk, J., 1971, Ap. J., 170, 431.

Brecher, K., and Morrison, P., 1969, Phys. Rev. Letters, 23, 802.

Chupp, E. L., Forrest, D. J., Sarkady, A. A., and Lavakare, P. J., 1970, Planetary and Space Science, 18, 939.

Clayton, D. D., and Silk, J., 1969, Ap. J. (Letters), 158, L43.

Cline, T. L., and Hones, E. W., 1970, ACTA Phys., 29, Supp 1, 159.

Damle, S. V., Daniel, R. R., Joseph, G., and Lavakare, P. J., 1971, Astrophys. and Sp. Sci., 14, 473.

Dyer, C. S., and Morfill, G. E., 1971, Astrophys. and Sp. Sci., 14, 243.

Fishman, G. J., 1972, Ap. J., 171, 163.

Golenetskii, S. V., Mazets, E. P., Il'inskii, V. N., Aptekar, R. L., Bredov, M. M., Gur'yan, Yu. A., and Panov, V. N., 1971, Astro. Letters, 9, 69.

Johnson, W. N., III, Harnden, F. R., Jr., and Haymes, R. C., 1972, Ap. J. (Letters), 172, L1.

Kraushaar, W. L., Clark, G. W., Garmire, G. P., Borken, R., Higbee, P., Leong, C., and Thorsos, T., 1972, preprint (submitted to Ap. J.).

Mayer-Hasselwander, H. A., Pfeffermann, E., Pinkau, K., Rothermel, H., and Sommer, M., 1972, Ap. J. (Letters), 175, L23.

Metzger, A. E., Anderson, E. C., Van Dilla, M. A., and Arnold, J. R., 1964, Nature, 204, 766.

Pal, Y., 1972, Proceedings of IAU Symposium #55, Madrid, Spain, (in press).

Reedy, R. C., Arnold, J. R., and Trombka, J. I., 1972, (submitted to J.G.R.).

Share, G. H., Kinzer, R. L., and Seeman, N., 1972, Proceedings of IAU Symposium #55, Madrid, Spain, (in press).

Stecker, F. W., 1971, Nature, 229, 105.

Stecker, F. W., and Morgan, D. L., Jr., 1972, Ap. J., 171, 201.

Stecker, F. W., Morgan, D. L., Jr., and Bredekamp, J., 1971, Phys. Rev. Letters, 27, 1469.

Stecker, F. W., Vette, J. I., and Trombka, J. I., 1971, Nature, 231, 122.

Trombka, J. I., Senftle, F., and Schmadebeck, R., 1970, Nuc. Inst. and Methods, 87, 37.

Vedrenne, G., Albernhe, F., Martin, I., and Talon, R., 1971, Astron. & Astrophys., 15, 50.

Vette, J. I., Gruber, D., Matteson, J. L., and Peterson, L. E., 1970, Ap. J. (Letters), 160, L161.

Table 1

Composition of Apollo 15 Energy Loss Spectrum

Transearth Coast, Deployed Position

Composition	Energy Range	
	0.6 - 3.5 MeV	3.5 - 9.0 MeV
γ-Ray Lines	15.9%	3.7%
Spallation in NaI crystal	15.8%	0.5%
Spacecraft Continuum	10.2%	21.7%
Cosmic Upper Limit	58.1%	74.1%
Total	100.0%	100.0%

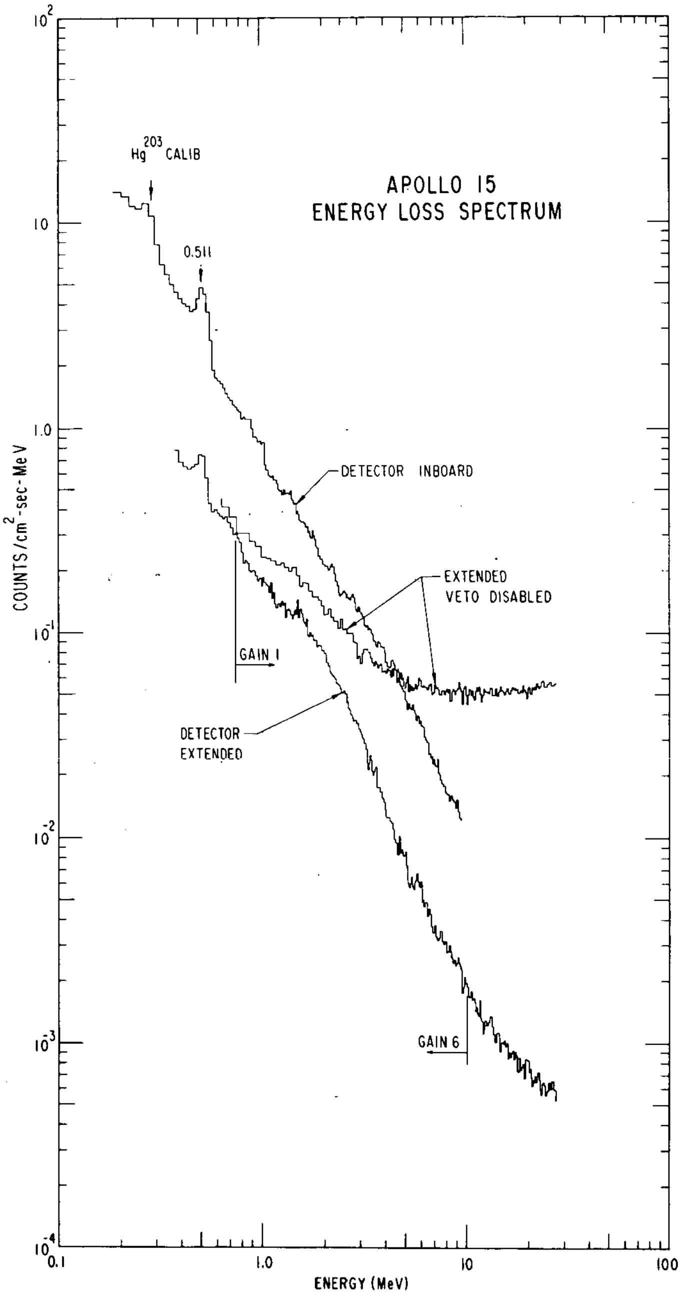

Figure 1. Energy loss spectra in the 7.0 cm dia x 7.0 cm long NaI(Tℓ) scintillation counter measured on Apollo 15 during Transearth Coast. Since the rates decreased only a factor of about 5 when the detector was extended to 7.6 m, while the solid angle subtended by the spacecraft decreased a factor of 20, we interpret most of the rate in the extended position to be associated with cosmic γ-rays. The spectrum with the anticoincidence disabled agrees with that expected from cosmic-rays passing through the crystal edges.

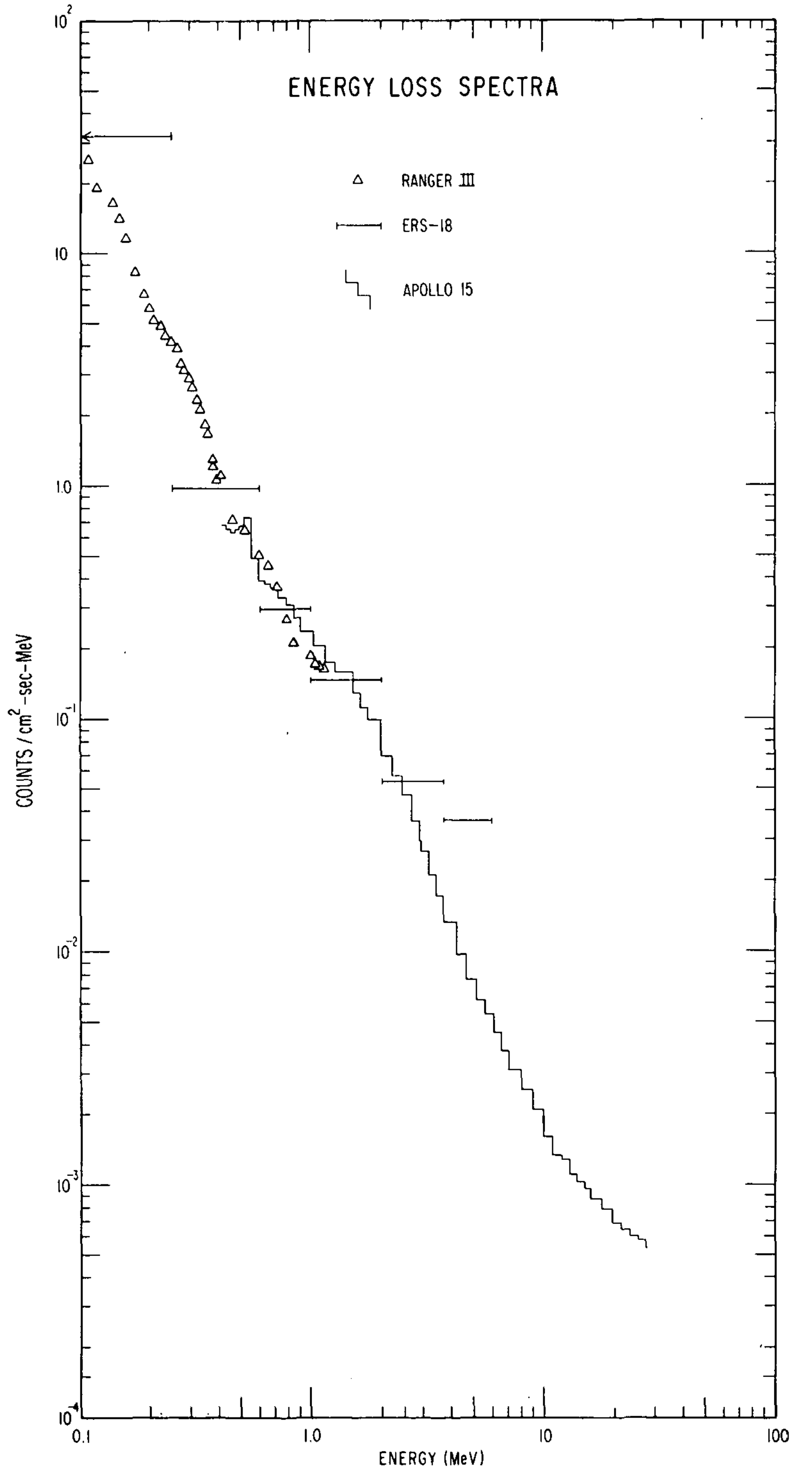

Figure 2. Energy loss spectra are compared directly with other measurements obtained outside the magnetosphere. These data were obtained with counters that differ only slightly in geometry and materials.

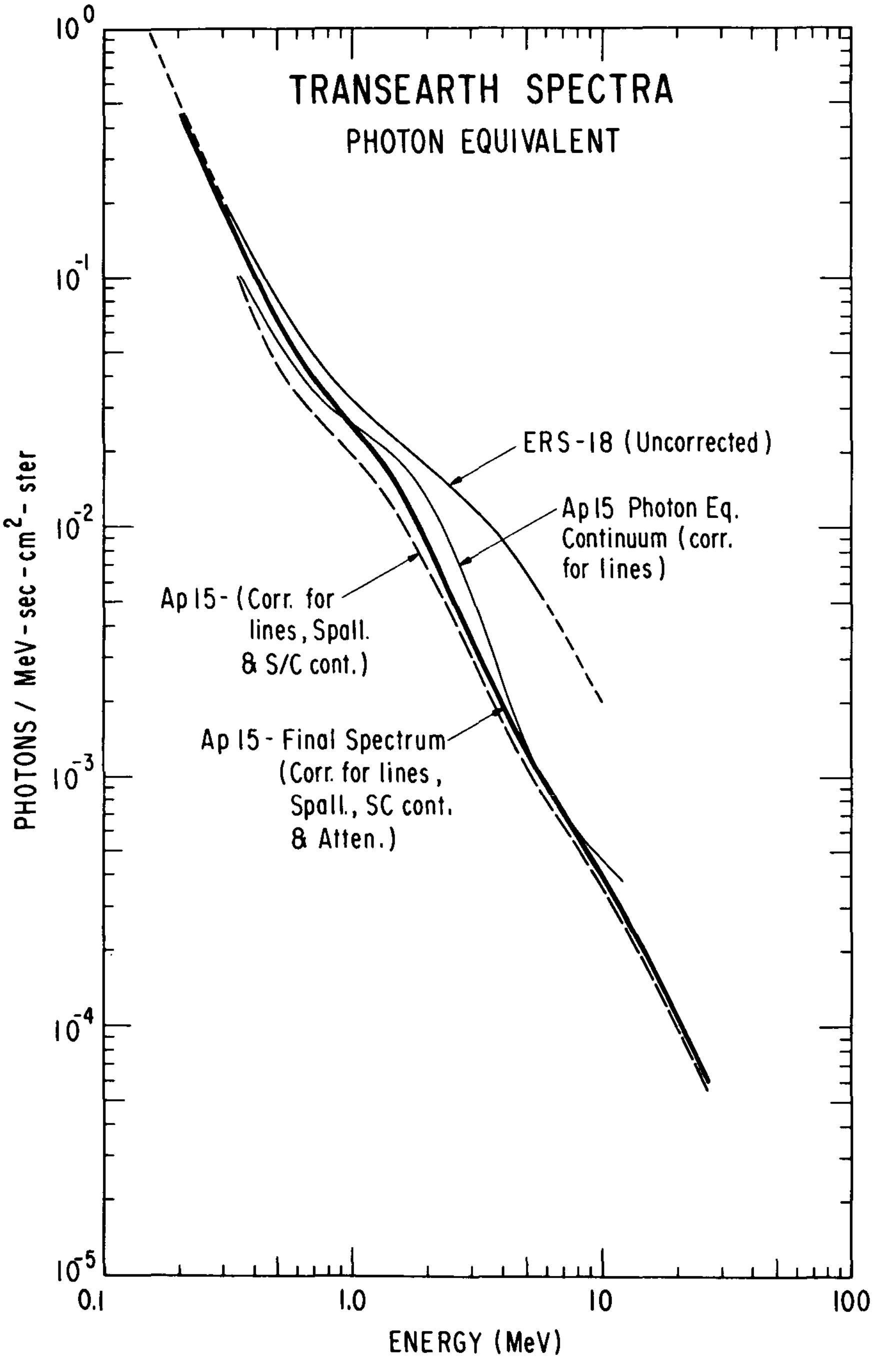

Figure 3. Equivalent photon spectra derived from the Apollo 15 are shown at various stages of data correction. First all components due to discrete γ-ray lines are removed, then the spacecraft continuum contribution, and an estimate of energy losses due to spallation nuclei are subtracted. The final result contains a correction for absorption of local material, assuming all energy losses at this stage are due to an external isotropic γ-ray flux.

FIGURE CAPTIONS

1. Energy loss spectra in the 7.0 cm dia x 7.0 cm long NaI(Tℓ) scintillation counter measured on Apollo 15 during Transearth Coast. Since the rates decreased only a factor of about 5 when the detector was extended to 7.6 m, while the solid angle subtended by the spacecraft decreased a factor of 20, we interpret most of the rate in the extended position to be associated with cosmic γ-rays. The spectrum with the anticoincidence disabled agrees with that expected from cosmic-rays passing through the crystal edges.
2. Energy loss spectra are compared directly with other measurements obtained outside the magnetosphere. These data were obtained with counters that differ only slightly in geometry and materials.
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4. The cosmic photon spectrum derived from the Apollo 15 data agrees with previous results below 1 MeV, but is well below that determined from the ERS-18 at higher energies. Limits derived from balloon and low altitude satellite work, despite large corrections for efficiency and cosmic-ray produced γ-rays, are in agreement with the Apollo results.

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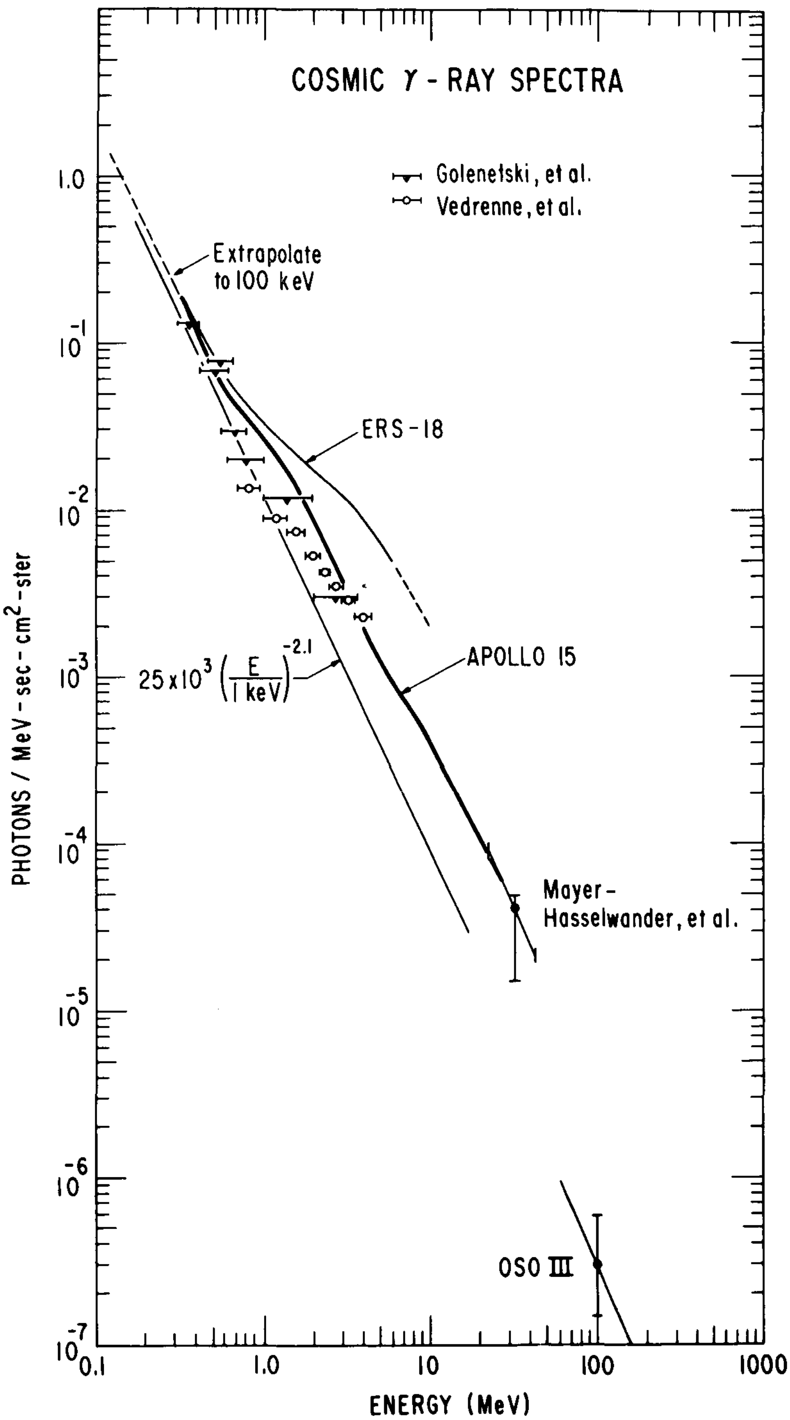

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