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ON EMISSION LINES IN THE COSMIC GAMMA-RAY BACKGROUND

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ABSTRACT

We calculate the composite spectrum of γ-rays resulting from the decay of ^{56}Ni to ^{56}Co to ^{56}Fe throughout the history of the universe. The results for several cosmological models are presented and compared with the *Apollo 15* measurements at low resolution of the cosmic background. The radioactivity background is a significant fraction of the total, and several of its features may be detectable.

Subject headings: cosmic rays — cosmology — gamma rays — nuclear reactions

We present here some calculations of the anticipated contribution of radioactive ^{56}Ni and its daughter ^{56}Co to the cosmic γ-ray background. The basic theory was presented by Clayton and Silk (1969). Our purpose is only to present some generalized formulae reflecting broader considerations and to compare improved numerical calculations using latest values both for the Hubble parameter H_0 and for the Galactic age with the observed cosmic background as reported from *Apollo 15* observations (Peterson *et al.* 1973). Some of our results were included in a recent review paper (Clayton 1973).

If the universe is homogeneous and isotropic so that its metric is of the Robertson-Walker type, we find that the differential flux today due to each line emitted with energy E_i is

$$\frac{\partial^2 F_i}{\partial E \partial \Omega} = \frac{c}{4\pi} \frac{g_i n(^{56}\mathrm{Fe})}{E_i} \frac{R(t_0)}{\dot{R}(t_E)} f(t_E)\,, \tag{1}$$

where the notation is that of Clayton and Silk (1969) and where, in addition, $R(t_0)$ is the scale factor today and $\dot{R}(t_E)$ is its derivative at the epoch of emission t_E. The present energy E of the photon appears implicitly through t_E. This result assumes that the emission feature is strictly a line and is not, for example, degraded by Compton scattering. If the class of models is further restricted to Friedmann models, equation (1) reduces to

$$\frac{\partial^2 F_i}{\partial E \partial \Omega} = \frac{c}{4\pi} \frac{g_i n(^{56}\mathrm{Fe})}{E_i H_0} f(t_E) \left[1 - 2q_0 + 2q_0 \frac{E_i}{E}\right]^{-1/2} . \tag{2}$$

If one further restricts the models to those Friedmann models for which $R(t) = at^{1/\gamma}$, one obtains the specific result presented by Clayton and Silk (1969).

We wish to compare a composite spectrum containing all of the lines expected in the $A = 56$ spectrum with the measurements of Peterson *et al.* (1973) from *Apollo 15*. Figure 1 shows this comparison for the Einstein–de Sitter model, the Friedmann model having $q_0 = \frac{1}{2}$. The density required for this model with the latest value (Sandage 1972) of the Hubble parameter $H_0 = 55\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ is $\rho_c = 5.9 \times 10^{-30}\ \mathrm{g\ cm^{-3}}$. In estimating $n(^{56}\mathrm{Fe})$ in equation (2), however, we have assumed that only the *observed* (Oort 1958) density $\rho = 0.028\rho_c$ has an iron concentration equal to that of the Sun, and that the remaining "hidden mass" has never contained ^{56}Fe that was ejected in the usual explosive way as ^{56}Ni (Hainebach *et al.* 1974). If we live in such a universe, therefore, Figure 1 suggests that the unobserved mass does not contain such ^{56}Fe; otherwise the calculated background would significantly exceed that observed. This result seems to us noteworthy. The so-called hidden mass would have to be of a special type. Ostriker, Peebles, and Yahil (1974) argue that galactic masses are severely underestimated, moreover, in which case our calculated curves should have their normalization increased by the same factor. The calculated curves are based on two different assumptions concerning the rate $f(t)$ of galactic nucleosynthesis: (1) the solid line assumes an exponential decline in nucleosynthesis to a value today e^{-2} times the initial rate in galaxies, and (2) the dashed line assumes a constant rate of nucleosynthesis. For both cases the galaxies are taken to have a mean age of 9.8×10^9 years, so that nucleosynthesis in the average galaxy began 2×10^9 years after the big bang if $H_0 = 55\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$. This mean galactic age is consistent with the indications from nuclear cosmochronology (Fowler 1972). We did assume that the galactic beginnings were somewhat spread in a Gaussian manner about that mean age, however; and that spread, which we took to be 10^9 years at $1/e$ in the Gaussian distribution, removes any discernible line edges at the redshift $z = 2.5$ corresponding to the mean birthdate of galaxies. Such redshifted edges showed conspicuously in the figures of Clayton and Silk (1969), but we see here that they are undetectable unless all galaxies began nucleosynthesis at exactly the same epoch.

Figure 2 shows a similar calculation for a low-density universe ($q_0 = 0.014$ corresponding to $\rho = 0.028\rho_c$ with an iron concentration equal to the Sun's). The models $f(t)$ for galactic nucleosynthesis are again an exponential decline (*solid curve*) to a rate e^{-2} times the initial rate and a constant rate (*dashed line*). Since

1975ApJ...198..241C

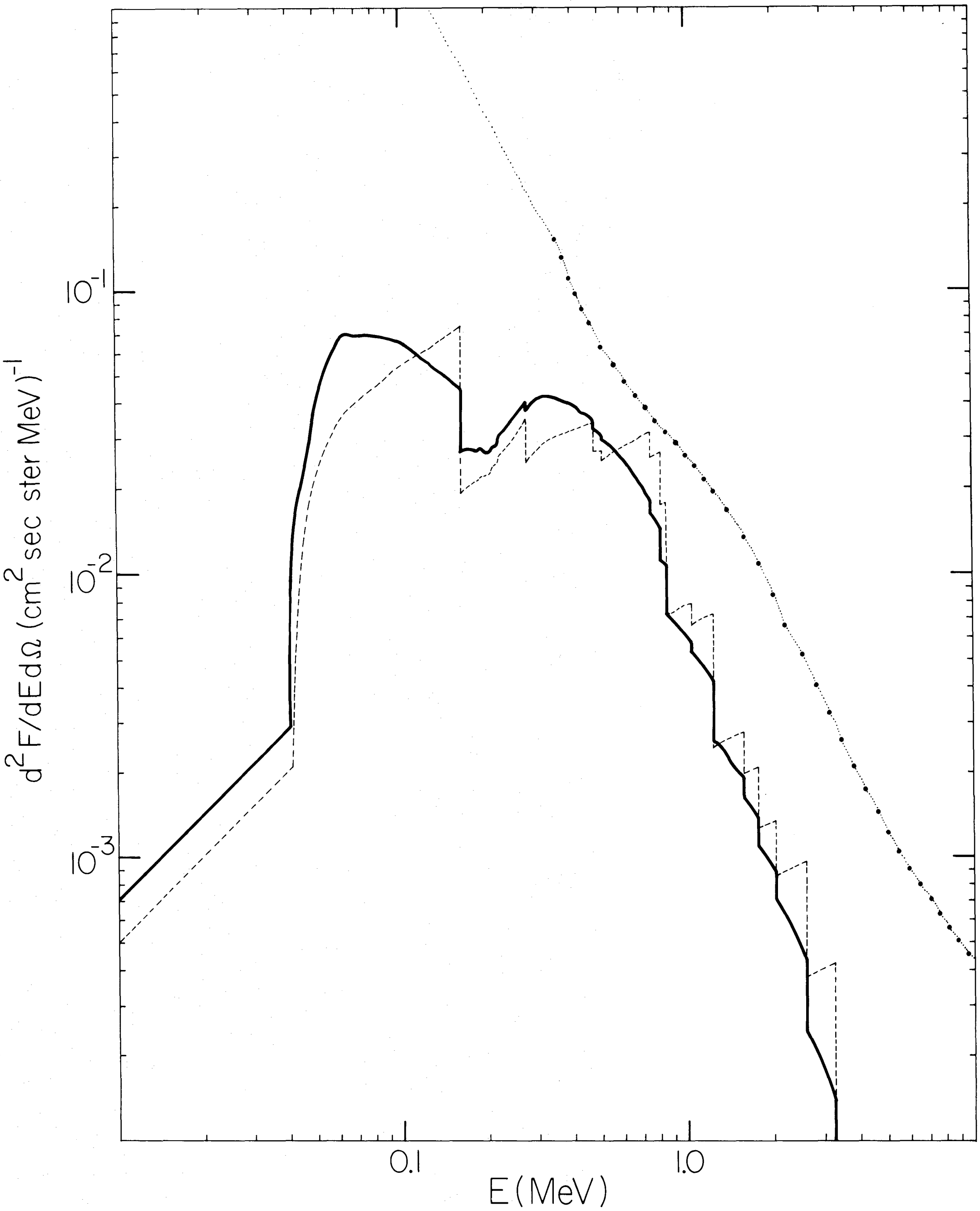

FIG. 1.—The composite $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ γ-ray spectrum in the Einstein–de Sitter ($q_0 = \frac{1}{2}$) universe. The solid line is calculated for exponential models of galactic nucleosynthesis beginning 9.8×10^9 years ago and decaying as $\exp(-2t/9.8 \times 10^9\ \mathrm{yr})$, whereas the dashed curve is calculated for a constant rate of nucleosynthesis beginning at the same time. The dotted curve shows for comparison the *Apollo 15* observations. The iron density is solar only in the observed 2.8% of the total density.

the universe is older in this model, the galactic ages are also taken to be older (about 13×10^9 years) so that the redshift in the mean epoch when nucleosynthesis began is again $z = 2.5$. This age is also consistent with nuclear cosmochronology (Fowler 1972).

In both of these figures it is apparent that the radioactivity background is expected to be a substantial fraction of the measured cosmic background, which is there shown as a dotted curve. The calculated curves have structure that one can hope to see with a high-energy-resolution detector, as Clayton and Silk (1969) first pointed out. The magnitude of the step at each

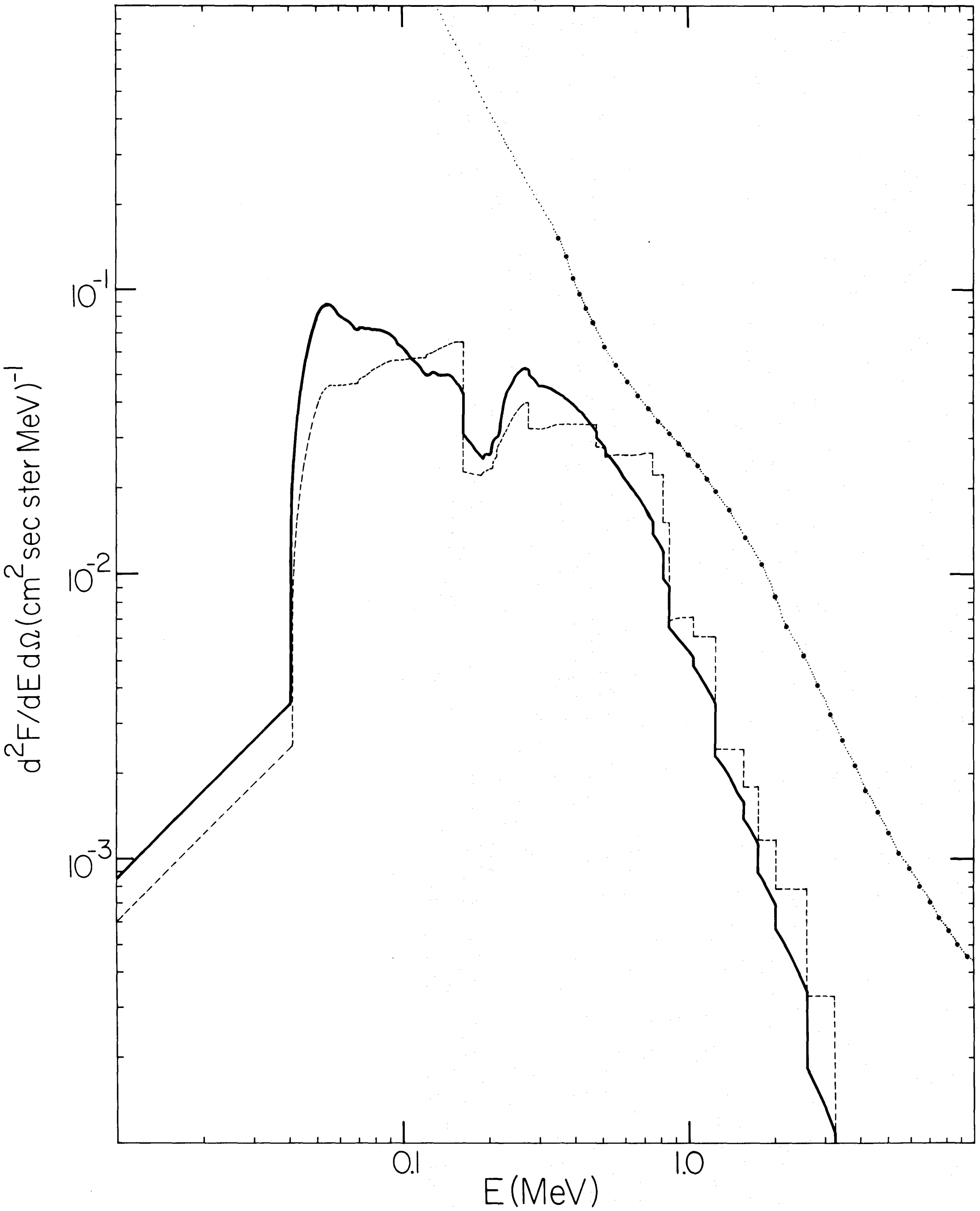

FIG. 2.—The same format as in Fig. 1, except that the model universe has $q_0 = 0.014$ (the low-density universe) and the nucleosynthesis began 13×10^9 years ago. The solid-curve nucleosynthesis decays as $\exp(-2t/13 \times 10^9\ \mathrm{yr})$ whereas the dashed rate is constant.

rest frequency is

$$\Delta_i = \frac{c}{4\pi}\frac{g_i n(^{56}\mathrm{Fe})}{E_i H_0} f(t_0) \tag{3}$$

which measures the rate of nucleosynthesis today $f(t_0)$. We here note that the slope of the spectrum at energies just below each step depends upon the cosmological model in an interesting way. We have derived the result that the slope due to a single line E_i is

$$\left[\frac{d}{dE}\frac{\partial^2 F}{\partial E \partial \Omega}\right]_{E=E_{i(-)}} = \frac{\Delta_i}{E_i}\left(q_0 - \frac{\lambda}{H_0}\right) \tag{4}$$

for exponential models of nucleosynthesis wherein $f(t) = A\exp(-\lambda t)$. Since Δ_i, E_i, H_0, and this slope are measurable numbers, we have a new possibility for the measurement of q_0. Strictly speaking, it measures the ratio q_0/λ; but λ is largely determined by the measurement of Δ_i itself, since $f(t_0) = A \exp(-\lambda t_0)$. For nonexponential but continuous models of nucleosynthesis, equation (4) is still correct near the rest edges with the definition $\lambda \equiv -[\dot{f}/f]_{t_0}$. In actual practice it will prove difficult to determine q_0 from equation (4) unless λ is small enough that the term q_0 is not dominated by λ/H_0, for if λ is not small the uncertainty in its value will obscure q_0. The requirement that λ be not too large is, however, consistent with the requirement that the rest edges Δ_i be detectable in the cosmic background. If those edges are detectable, then λ is small enough to allow q_0 to be determined. Of course, λ must be independently determined from the size of the rest edges Δ_i and from the theory of nuclear cosmochronology (Fowler 1972). The slope due to the line is only obtainable after subtraction of the smoothly falling continuum upon which the radioactive spectrum is superposed.

The possibility of a steady-state universe is quite different; indeed, detection of rest edges of the required shape would be one of the most convincing demonstrations of the steady state. In that case the spectrum due to each emission line is

$$\frac{\partial^2 F_i}{\partial E \partial \Omega} = \frac{3c}{4\pi} \frac{g_i \langle n(^{56}\mathrm{Fe})\rangle E^2}{E_i^3}, \qquad (5)$$

where $\langle n(^{56}\mathrm{Fe})\rangle$ is the average density of ^{56}Fe in the universe. The spectrum shape is independent of the rate of nucleosynthesis in galaxies, but the normalization $\langle n(^{56}\mathrm{Fe})\rangle$ does depend on it through the comparison of the ^{56}Fe concentration within our Galaxy to the corresponding concentration within the average galaxy, which in the steady state has only one-half the age (approximately) of our Galaxy. We do not include a figure showing our calculation of the steady-state background. Superficially it resembles the dashed curve of Figure 1, except that the rest edges are somewhat bigger and the shortward slope somewhat steeper (eq. [5]).

It seems to us worth noting a few other features. (1) Inspection of Figures 1 and 2 reveals a sizable minimum between 200 and 300 keV. Although the calculated background at these energies is only about 10 percent of the observed background, this shallow feature may nonetheless be detectable. It would manifest itself as a several percent dip in the continuous background between 200 and 300 keV. (2) The relative flatness of the calculated background below 1 MeV suggests that a small change in slope near 1 MeV might be expected in the cosmic background. (3) The curious but obviously undetectable slope of the calculated curves below 0.1 MeV comes from the three-photon continuum in the annihilation of the positrons emitted by ^{56}Co (Leventhal 1973). (4) This entire discussion obviously fails if the γ-rays do not emerge without degradation from the source. This uncertainty is obviously more severe for ^{56}Ni ($\tau = 8^{\mathrm{d}}.8$) than it is for ^{56}Co ($\tau = 111^{\mathrm{d}}$). The unambiguous answer to this question will come not from supernova models but rather from γ-ray spectroscopy of an individual supernova of the type responsible for the nucleosynthesis of ^{56}Fe (Clayton, Colgate, and Fishman 1969). Until then we present these calculations as a target for γ-ray astronomy.

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