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MEASURING THE RATE OF NUCLEOSYNTHESIS WITH A GAMMA-RAY DETECTOR

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ABSTRACT

The gamma-ray lines emitted when ^{56}Ni decays to ^{56}Fe are shown to provide a photon flux which is a significant fraction of the diffuse background near 1 MeV. Successful measurement of the line profiles can reveal both the present and past rates of nucleosynthesis in the Universe.

Recent studies (Bodansky, Clayton, and Fowler 1968*a, b;* Clayton and Woosley 1969; Arnett and Truran 1969) of the theory of silicon-burning nucleosynthesis and of supernova light curves (Colgate and McKee 1969) have provided strong evidence in favor of the supposition that the nucleus ^{56}Fe was synthesized as ^{56}Ni. Clayton, Colgate, and Fishman (1969; see also Clayton and Fowler 1969) have used those arguments in assessing the detectability of young supernova remnants by means of the nuclear gamma-ray lines emitted following the decay of ^{56}Ni. In this Letter we show that these same gamma-ray lines may be expected to be a major component of the diffuse gamma-ray background and that the measurement of line profiles can, in principle, reveal the rate at which ^{56}Fe has been synthesized in the Universe.

If the Universe is homogeneous and if the gamma rays emitted following the decays of ^{56}Ni and ^{56}Co have not been absorbed, the average number density of gamma rays from these decays is simply the product of the average number density of ^{56}Fe nuclei and the number g_γ of gamma rays produced per ^{56}Fe nucleus. The flux of these gamma rays per unit solid angle is then

$$\frac{\partial F}{\partial \Omega} = \frac{c}{4\pi} g_\gamma n(^{56}\mathrm{Fe}) \, . \tag{1}$$

The average iron density is $n(^{56}\mathrm{Fe}) = 3.9 \times 10^{-12}$ cm^{-3} if we take an average density $\rho_0 = 3 \times 10^{-31}$ g cm^{-3} (Oort 1958) to be 70 percent hydrogen by mass and if we take $n(^{56}\mathrm{Fe})/n(^1\mathrm{H}) = 3.1 \times 10^{-5}$ (Cameron 1968; Grevesse and Swings 1969; Garz *et al.* 1969). The decay $^{56}\mathrm{Ni}(e^-, \nu)^{56}\mathrm{Co}$ with half-life $\tau_{1/2} = 6.1$ days is accompanied, on the average, by 2.1 gamma rays with energies between 0.163 and 1.56 MeV, and the subsequent decay $^{56}\mathrm{Co}(e^-,\nu)^{56}\mathrm{Fe}$ with half-life $\tau_{1/2} = 77$ days is accompanied by 2.8 gamma rays with energies between 0.511 and 3.47 MeV (Lederer, Hollander, and Perlman 1967). These gamma lines are listed in Table 1, along with the average number of each emitted per decay. We see that g_γ may be as great as 4.9 if each of these gamma rays emerges from the source without being absorbed. If the synthesizing objects are similar to supernovae, however, they require somewhat more than a week of expansion before becoming transparent to gamma rays; in this case about two-thirds of the ^{56}Ni gamma

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rays are absorbed in the expanding shell, thereby providing the late heating required for the peak in the supernova light curve (Colgate and McKee 1969). For the purposes of numerical discussion we will assume $g_\gamma = 2.1/3 + 2.8 = 3.5$, in which case equation (1) yields

$$\frac{\partial F}{\partial \Omega} = 3.3 \times 10^{-2}\ \mathrm{cm}^{-2}\ \mathrm{sterad}^{-1}\ \mathrm{sec}^{-1}\,. \tag{2}$$

The point to notice at once is that this flux is quite substantial. The cosmic X- and gamma-ray background between 50 keV and 1 MeV (Metzger *et al.* 1964) is well approximated by

$$\frac{\partial^2 F}{\partial E \partial \Omega} = \frac{10}{[E(\mathrm{keV})]^2}\ \mathrm{cm}^{-2}\ \mathrm{sterad}^{-1}\ \mathrm{sec}^{-1}\ \mathrm{keV}^{-1}\,. \tag{3}$$

TABLE 1

GAMMA-RAY LINES AND TOTAL FLUXES*

E_i (MeV)	Number per Decay	$n_g K_i c/4\pi$ (10^{-2} cm^{-2} sec^{-1} sterad^{-1})	E_i (MeV)	Number per Decay	$n_g K_i c/4\pi$ (10^{-2} cm^{-2} sec^{-1} sterad^{-1})
0.163	0.99	0.92	0.511	0.40	0.37
0.276	0.31	0.29	0.847	1.00	0.93
0.472	0.35	0.33	1.04	0.15	0.14
0.748	0.48	0.45	1.24	0.66	0.62
0.812	0.85	0.79	1.76	0.16	0.15
0.98	0.012	0.011	2.02	0.11	0.10
1.56	0.14	0.13	2.60	0.17	0.16
			3.26	0.14	0.13
Total ^{56}Ni	2.13	1.98	3.47	0.014	0.013
			Total ^{56}Co	2.80	2.60

* Data taken from Lederer, Hollander, and Perlman (1967). The group of seven lines at the left follows the decay of ^{56}Ni, and the group of nine lines at the right follows the decay of ^{56}Co. The fluxes correspond to average iron density $n(^{56}\mathrm{Fe}) = 3.9 \times 10^{-12}$ cm^{-3}.

If this spectrum is assumed to hold for all energies, the integral flux above 300 keV is

$$\frac{\partial F(E > 0.3\ \mathrm{MeV})}{\partial \Omega} = \int_{300}^{\infty} \frac{\partial^2 F}{\partial E \partial \Omega} dE = 3.3 \times 10^{-2}\ \mathrm{cm}^{-2}\ \mathrm{sterad}^{-1}\ \mathrm{sec}^{-1}\ \mathrm{keV}^{-1}\,. \tag{4}$$

Comparison with equation (2) shows that the gamma-ray flux from ^{56}Ni decay is roughly equal to the entire integral spectrum above 0.3 MeV. It is clear that if ^{56}Fe is formed in this way, the associated spectrum of line gamma rays should be a significant constituent of the observed spectrum. Their contribution may be even larger if the Universe contains hidden mass that has synthesized ^{56}Ni at earlier epochs.

Although simple density arguments yield the total flux expected from the nuclear lines, they do not fix the distribution of the lines in frequency, because gamma rays created at early epochs of the Universe will be detected today at redshifted wavelengths. It is, in fact, just this feature that makes possible a wholly new astronomical datum; that is, the redshift of the gamma-ray spectrum measures the time at which the ^{56}Fe was synthesized. Accordingly, the distribution in redshift of the gamma-ray spectrum provides a chronological account of the rate of nucleosynthesis.

Inasmuch as ^{56}Fe is probably synthesized within galaxies, it is convenient for the purpose of this discussion to regard the mean density of the Universe as being the product of the average density of galaxies, $n_g = 2 \times 10^{-75}$ cm^{-3} (Allen 1963), and an average galactic mass, $M_g = 7.5 \times 10^{10}\, M_\odot$. We may then characterize the average rate of synthesis of ^{56}Fe within galaxies, which for simplicity are regarded as identical, by some function $f(t)$. For convenience $f(t)$ will be normalized so that

$$\int_0^{t_0} f(t)dt = 1\ ,$$

where t_0 is the present age of the Universe. The gamma-ray source function per unit energy due to each galaxy is then

$$P(E,t) = \sum_i P_i(E,t) = \sum_i K_i \delta(E - E_i) f(t)\ , \tag{5}$$

where the sum is over the lines of rest energy E_i emitted in the ^{56}Ni and ^{56}Co decays and where K_i is the total number of gammas in the ith line emitted by the average galaxy up to the present epoch. The differential flux today due to gamma rays of type i is then given (see, e.g., McVittie 1965) in an evolving Universe by

$$\frac{\partial^2 F_i}{\partial E \partial \Omega} = \frac{c n_g}{4\pi} \int_0^\infty (1 + z) P_i[E(1 + z), t] \frac{dt}{dz} dz\ . \tag{6}$$

The derivative dt/dz depends upon the cosmological model, which specifies the relationship of the cosmic time t to the redshift z. For numerical discussion we consider two cosmological models for which $t(z)$ can be written

$$t(z) = \frac{t_0}{(1 + z)^\gamma}\ . \tag{7}$$

They are (1) a low-density universe ($\rho_0 = 3 \times 10^{-31}$ g cm^{-3}; $q_0 = 0.01$) for which $\gamma \simeq 1$ and (2) an Einstein–de Sitter universe ($\rho_0 = 1 \times 10^{-29}$ g cm^{-3}; $q_0 = 0.5$) for which $\gamma = \frac{1}{2}$. In each case we use the previously mentioned observed density of ^{56}Fe, even though the closed universe demands a much higher density in some form. We take the Hubble constant to be $H_0 = 75$ km sec^{-1} Mpc^{-1} (Sandage 1968). With the aid of equation (7) we obtain

$$\frac{\partial^2 F_i}{\partial E \partial \Omega} = \frac{n_g c K_i}{4\pi} \frac{1}{H_0 E_i} f\left[t_0 \left(\frac{E}{E_i}\right)^\gamma\right] \left(\frac{E}{E_i}\right)^{\gamma - 1}\ . \tag{8}$$

The first factor $n_g c K_i/4\pi$ is just the total flux per unit solid angle of photons having as their source the ith line, just as in equation (1), whereas the remaining factors indicate their distribution in energy due to the redshift. The total flux due to each line is listed in the third column of Table 1 with no correction for absorption. One can easily confirm that the integral spectrum corresponding to equation (8) is in fact

$$\frac{\partial F_i}{\partial \Omega} = \int_0^{E_i} \frac{\partial^2 F_i}{\partial E \partial \Omega} dE = \frac{n_g c K_i}{4\pi} = \frac{c}{4\pi} g_i n(^{56}\mathrm{Fe})\ . \tag{9}$$

One sees from equation (8) that the energy distribution from a given photon line is determined primarily by the shape of the galactic production function $f(t)$, whereas the effects of cosmology enter more weakly through the exponent γ. To illustrate these ideas numerically, we consider models of constant $f(t)$ and of exponentially decreasing $f(t)$.

If nucleosynthesis has occurred within galaxies at a constant rate up to the present time t_0 since it began at some time t_*, then $f(t) = (t_0 - t_*)^{-1}$. In Figure 1, a, we show the profile of the line at 1.24 MeV emitted in 66 percent of the ^{56}Co decays for the specific choice $t_0 - t_* = 7 \times 10^9$ years. The low-density universe yields a rectangular profile for such $f(t)$, whereas the line flux in the high-density universe is progressively weaker at redshifted energies. This particular line has an edge at the rest energy that is slightly greater than the continuum of equation (3), which is shown for comparison. Clearly the best chance of detection for the models of constant $f(t)$ is at that edge, the height of which is

$$\Delta\left(\frac{\partial^2 F_i}{\partial E \partial \Omega}\right)_{E=E_i} = \frac{n_g c K_i}{4\pi} \frac{1}{H_0 E_i (t_0 - t_*)} . \tag{10}$$

For contrast we show in Figure 1, *b*, the line profile for exponentially decreasing nucleosynthesis $f(t) = A \exp[-\lambda(t - t_*)]$, where $A = \lambda\{1 - \exp[-\lambda(t_0 - t_*)]\}^{-1}$. We again take $t_0 - t_* = 7 \times 10^9$ years for purposes of comparison. The choice $\lambda^{-1} = 7 \times 10^9$ years corresponds to a slow decrease in the rate of galactic nucleosynthesis, the present rate being $1/e$ of the initial rate. The edge at the rest frequency is still quite detectable, though smaller than for the case of constant $f(t)$, whereas the edge corresponding to the

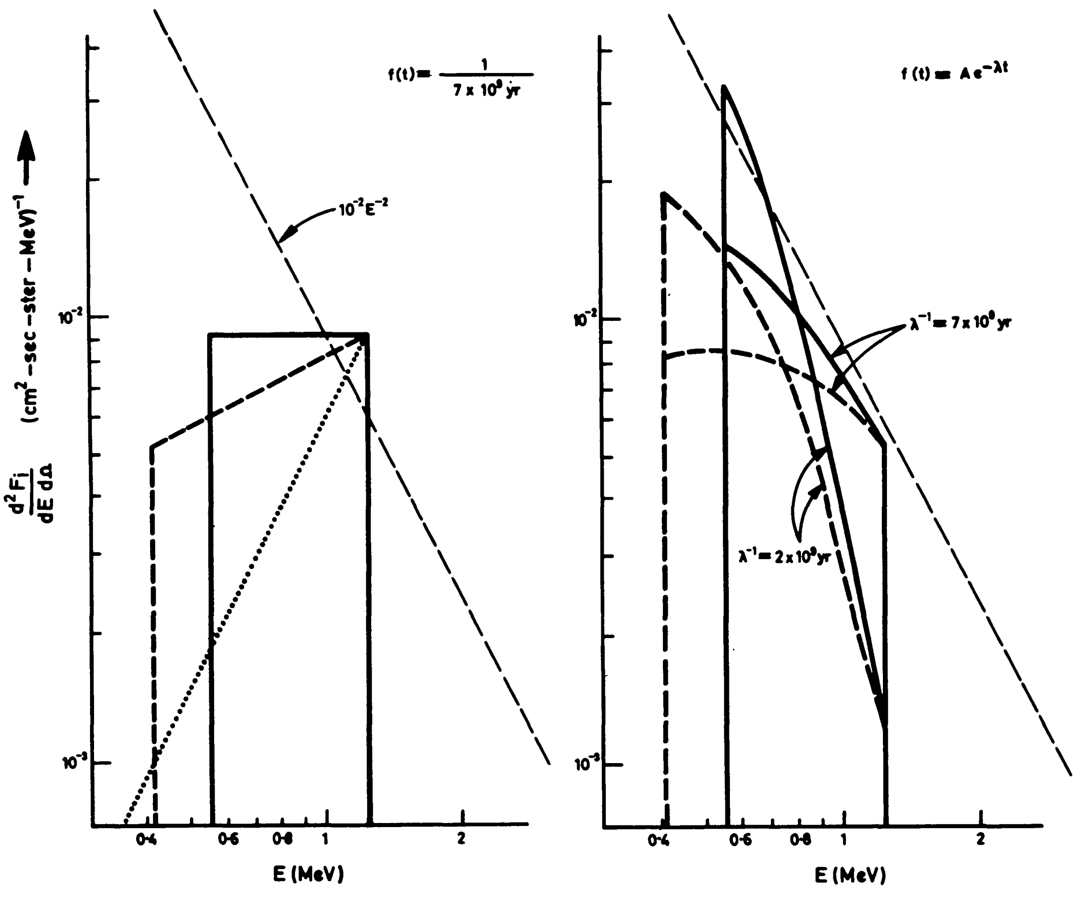

FIG. 1.—Differential flux due only to the ^{56}Co line at 1.24 MeV. Models of constant production of ^{56}Fe over a period of 7×10^9 years are shown on the left, and models of exponentially decreasing production over a period of 7×10^9 years are shown on the right. Contrasting cosmological models corresponding to a low-density universe (*solid line*) and an Einstein–de Sitter universe (*dashed line*) are shown in each case. The steady-state universe (*dots*) is shown on the left; however, the line profile is in this case actually independent of $f(t)$. The approximation of equation (3) to the diffuse background is shown for comparison.

epoch t_* (when nucleosynthesis began) is now larger than in the case of constant $f(t)$ and is also potentially detectable. A rate of nucleosynthesis more strongly peaked at t_* is obtained with the choice $\lambda^{-1} = 2 \times 10^9$ years. The edge at the rest frequency is now only about 15 percent of the continuum, but the edge at the epoch of commencement is correspondingly larger, and there would seem to be a reasonable chance to detect both edges. Detection of an edge at the rest frequency could provide sure evidence that nucleosynthesis is occurring today, and its value

$$\Delta \left(\frac{\partial^2 F_i}{\partial E \partial \Omega} \right)_{E=E_i} = \frac{n_g c K_i}{4\pi} \frac{f(t_0)}{H_0 E_i} \tag{11}$$

is directly proportional to $f(t_0)$, the value of the galactic production rate at the present epoch. For the exponential models $f(t_0) = \lambda\{\exp [\lambda(t_0 - t_*)] - 1\}^{-1}$.

The detection of a peak at a redshifted epoch would provide, if it exists, a unique measure of the commencement of nucleosynthesis. The redshifted edge would not be expected to be as sharp as we have drawn it in Figure 1, because all galaxies have probably not begun nucleosynthesis at exactly the same epoch, and a small time difference early in the evolution of the Universe corresponds to a larger spread in redshift than it does at the present epoch. These edges should certainly be sought with high-resolution detectors, however, because of their great theoretical importance.

In a steady-state universe an average over galactic ages within each volume element must be performed, and the resulting line profile is proportional to $(E/E_i)^2$ independent of the shape $f(t)$ of the galactic production function. In Figure 1, *a*, we have included such a profile for the 1.24-MeV line normalized so that the production rate of ^{56}Fe is equal to $(7 \times 10^9 \text{ years})^{-1}$ per ^{56}Fe nucleus. The interesting feature is the relatively sharp decrease of the line profile on the long-wavelength side—a feature that could, in principle, offer evidence of a steady-state universe because it persists even for decreasing $f(t)$. A radiation-dominated evolving universe can produce a profile as steep as (E/E_i) if $f(t)$ is constant, but the line profiles in evolving universes should resemble Figure 1, *b*, if, as seems likely, $f(t)$ is a decreasing function.

It is also evident from Figure 1 that gamma rays originating as these lines may constitute a major fraction of the diffuse background in this energy region. The figure shows the effect of one line only, whereas the total flux available, if no photons are absorbed, is roughly 7 times as great as that in the line illustrated there.

The total fluxes in these lines may be even greater than the number listed in Table 1 if the Universe contains substantial hidden matter containing ^{56}Fe. If the hidden iron were synthesized at early epochs (corresponding, for example, to the epoch $z \simeq 2$, at which the density of quasi-stellar sources is a maximum [Schmidt 1969]), we might see a somewhat stronger series of lines peaking at about $E_i/3$. The gamma rays from ^{56}Ni synthesized in compact massive objects may not escape, however. A uniform sphere of matter will be partially opaque to nuclear gamma rays if its dimension is less than $R \leq [M(R)/10^{11} M_\odot]^{1/2}$ kpc.

It is of interest to note that the observations of Vette *et al.* (1969) showing an excess gamma-ray flux in the range 0.5–6 MeV already suggest an effect similar to the one under discussion here. Nuclear gamma rays are one of the few physical mechanisms capable of producing a gamma-ray excess near 1 MeV. We cannot propose a detailed explanation of the results of Vette *et al.*, because their channel from 3.5 to 6.0 MeV apparently contains too many counts for a ^{56}Co spectrum, for which the last intense line is at 3.26 MeV. Nonetheless we believe that future experiments in this energy range should be designed in such a way as to be sensitive to the features of the ^{56}Co spectrum, especially to the ledge expected at the rest frequency for models of continuous nucleosynthesis.

In concentrating on the universal background, we have ignored the emission from our own Galaxy. Due to the short half-life of ^{56}Co, the emission from the Galaxy will fluctuate enormously, reflecting primarily the time of the last supernova. If we take the production model used by Clayton *et al.* (1969), the omnidirectional flux near 1 MeV will increase by a factor of several thousand at the time of a galactic supernova and will decrease with a 77-day half-life. The excess flux measured by Vette *et al.* (1969) would, except for their top energy channel as noted above, be approximately accounted for by a supernova about 2–3 years ago at a distance near 10^4 pc. If this anomaly is due to a galactic supernova, however, it will decay with the 77-day half-life.

One very interesting feature of the ^{56}Co spectrum is the 511-keV annihilation line emitted in 40 per cent of the ^{56}Co decays. (The e^+-emission branch is 20 percent.) By the reasoning used previously, the total flux of such photons irrespective of redshift is expected to be

$$\frac{\partial F(e^+ + e^- \rightarrow 2\gamma)}{\partial\Omega} = 3.7 \times 10^{-3}\ \mathrm{cm^{-2}\ sterad^{-1}\ sec^{-1}}\,,$$

which is approximately a factor of 2 greater than the upper limit set on this line by Metzger *et al.* (1964). In setting that limit, however, those authors have apparently assumed a monoenergetic line superimposed on a smooth background, in contrast to our expectation of a redshift-smeared line in the presence of many other lines. The most favorable frequencies for setting upper limits to the fluxes under discussion here are probably to be found at the steps expected at the rest energies of other ^{56}Co lines, especially those at 3.26, 1.24, and 0.847 MeV.

All of these issues can be resolved with a high-resolution gamma-ray telescope in space. Either the ^{56}Co spectrum should be detectable, or the current set of ideas suggesting its presence must be wrong. If it can be detected, its intensity and redshift distribution contains unparalleled information. The opportunity seems to us to warrant special effort.

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