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# THE COSMIC GAMMA-RAY BACKGROUND FROM TYPE Ia SUPERNOVAE

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## ABSTRACT

We present an improved calculation of the cumulative $\gamma$-ray spectrum of Type Ia supernovae during the history of the universe. We follow Clayton & Ward (1975) in using a few Friedmann models and two simple histories of the average galaxian nucleosynthesis rate, but we improve their calculation by modeling the $\gamma$-ray scattering in detailed numerical models of SN Ia's. The results confirm that near 1 MeV the SN Ia background may dominate, and that it is potentially observable, with high scientific importance. A very accurate measurement of the cosmic background spectrum between 0.1 and 1.0 MeV may reveal the turn-on time and the evolution of the rate of Type Ia supernova nucleosynthesis in the universe.

*Subject headings:* cosmology: theory — diffuse radiation — gamma rays: theory — nuclear reactions, nucleosynthesis, abundances — supernovae: general

## 1. INTRODUCTION

Their large stores of radioactivity make supernovae prolific sources of $\gamma$-rays. This old prediction (Clayton, Colgate, & Fishman 1969) has now been given solid footing by observations of $\gamma$-ray lines from supernova 1987A (e.g., Leising & Share 1990 and references therein). Supernovae of Type Ia (SN Ia's) are the most intrinsically radioactive, and it now seems plausible that $\frac{2}{3}$ of the Fe in the universe has been synthesized by them (Thielemann et al. 1991), although estimates as low as 50% exist (Arnett, Schramm, & Truran 1989). Because a large fraction of the $^{56}$Co $\gamma$-rays do escape from such objects, the density of those $\gamma$-rays in the universe must approximately equal the density of Fe in the universe. This old argument (Clayton & Silk 1969) seems today more secure than it then did. Clayton & Ward (1975) provided a more comprehensive treatment of cosmic emission lines for this purpose, deriving the shape of the cosmic continuum for each $^{56}$Ni and $^{56}$Co line for any cosmological model of the Friedmann family. In their treatment, they assumed for simplicity that all of the $\gamma$-rays escaped, and they therefore neglected the Compton continuum resulting from scattering within the supernova (Burrows & The 1990). We address those deficiencies in order to better define the target for $\gamma$-ray astronomy. As discussed by Clayton & Silk, the ultimate detection of this cosmic spectrum will provide a direct measure of the history of SN Ia nucleosynthesis in galaxies, and therefore a measure of the star formation rate at earlier epochs. It will also aid in understanding the evolution of the iron abundances in old Galactic stars.

## 2. THE CONTRIBUTION OF TYPE Ia SUPERNOVAE

The contribution of different types of supernovae to the $\gamma$-rays in the universe depends on the rate of each type and the amount of radioactive $^{56}$Ni produced in each. Evans, van den Bergh, & McLure (1989) using 24 supernovae in Shapley-Ames galaxies derive Type Ia, Ib, and II supernova rates in the approximate ratio 1:1:4. The recent discovery by Muller et al. (1992) that the rate of Type Ib/Ic could be quite large argues for different ratios. Models of SN Ia's eject 10 times more $^{56}$Ni than was ejected in SN 1987A. Type I supernovae are much brighter in $\gamma$-rays (Burrows & The 1990) than are Type II supernovae. Previous calculations of $\gamma$-ray emission from supernovae by many investigators (Burrows & The 1990; Chan & Lingenfelter 1991; Nomoto, Kumagai, & Shigeyama 1991; Pinto & Woosley 1988; The, Clayton, & Burrows 1991) have shown that SN Ia's are much brighter than other types. For example, the maximum flux of the 847 keV line at 1 Mpc from SN Ia's is $\sim 4 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$, compared with Type Ib/Ic $\sim (3\text{–}90) \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$, and with Type II $\sim 3 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$. An order of magnitude estimate of the relative contributions to the background radiation of the various types is $(F_{\rm II}/F_{\rm Ia}) \approx (4/1) \times (3 \times 10^{-6}/4 \times 10^{-3}) = 3.0 \times 10^{-3}$ and $(F_{\rm Ib/Ic}/F_{\rm Ia}) \approx (1/1) \times [(3\text{–}90) \times 10^{-5}/4 \times 10^{-3}] = [(7.2\text{–}220) \times 10^{-3}]$. Because most of the $^{56}$Fe in the universe was synthesized in Type Ia supernovae, and because of the large escape fraction of $\gamma$-rays from them, we consider only the SN Ia contribution to the cosmic $\gamma$-ray background. The spectra from the other types will not be qualitatively different, only weaker.

## 3. THE SN Ia MODEL EMISSION

We integrate over time the number of emergent photons in the X-ray continuum and in $\gamma$-ray lines per $^{56}$Fe nucleus from a standard Type Ia deflagration model. We use model W7 of Nomoto, Thielemann, & Yokoi (1984) as a representative SN Ia model. The X-ray continuum and $\gamma$-ray line fluxes of this model have been calculated in detail by Burrows & The (1990) and Chan & Lingenfelter (1991). Their results confirm that Type I supernovae give stronger X-ray and $\gamma$-ray fluxes than do Type II supernovae; the $\gamma$-ray lines peak around 70 days with flux of 3–4 $\times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ and X-ray continuum peak flux is $\sim 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at $E \simeq 150$ keV at a distance of 1 Mpc. A more recently evaluated X-ray continuum, the bremsstrahlung emitted by the Comptonized electrons, has been presented by Clayton & The (1991), and we include their results in our calculations of the total spectrum of model W7 and of W7fm, a fully mixed version of W7. For our purpose it is adequate to integrate the $\gamma$-ray emission of model W7fm over the first 600 days. Figure 1 shows that total time-integrated spectrum, consisting of Comptonized X-ray continuum, $\gamma$-ray lines, and bremsstrahlung continuum, represented as number of photons escaping per $^{56}$Fe nucleus ejected. The number of emergent 847 keV $\gamma$-ray line photons per $^{56}$Fe nucleus produced is 0.60 and for the 1238 keV $\gamma$-line is 0.43. We

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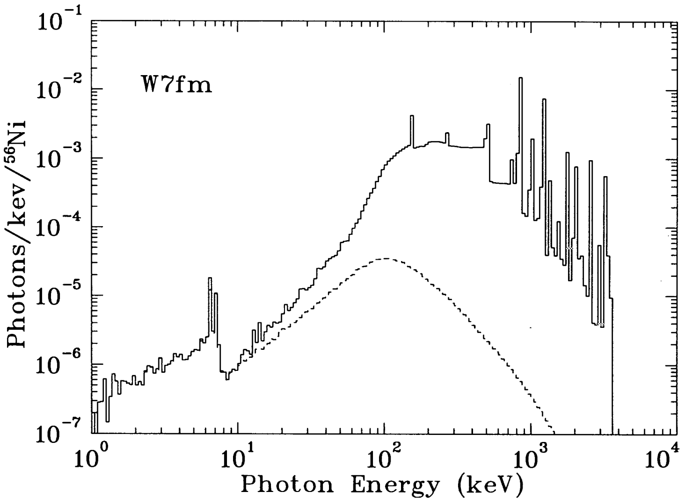

FIG. 1.—The total integrated X-ray continuum and $\gamma$-ray line fluxes per $^{56}$Fe nucleus over the first 600 days of a fully mixed version of model W7 (Nomoto, Thielemann, & Yokoi 1984) of a Type Ia supernova. The dashed line is the integrated bremsstrahlung fluxes from the first 150 days per $^{56}$Fe nuclei (Clayton & The 1991). The solid line is the total integrated flux per $^{56}$Fe nucleus of Comptonized X-ray continuum and $\gamma$-ray lines (Burrows & The 1990) and bremsstrahlung. The emergent fluxes are binned logarithmically in 188 bins between 1 keV and 4 MeV with specific bin boundaries being $E_i(\mathrm{keV}) = 10^{0.02(i-2)}$ for $i > 1$, so line fluxes from $^{56}$Co decays are the product of histogram height and bin energy width $\Delta E_i = E_{i+1} - E_i$.

use Figure 1 as a "standard candle" for the cosmic background estimate to follow.

## 4. THE COSMIC BACKGROUND FROM TYPE Ia SUPERNOVAE

Clayton & Ward (1975, hereafter CW) derived the differential flux today due to a line of rest energy $E_i$ emitted at time $t_E$ in a homogeneous and isotropic Friedmann universe as

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

We adopt their notation. The function $f(t)$ is the normalized (in this case to total SN Ia Fe) nucleosynthesis rate. Stated differently, it measures the normalized age $(t_0 - t_E)$ distribution of SN Ia iron. We adopt these cosmological parameters for the universe: Hubble constant $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$ with $h = 0.55$, present matter density $\rho_0 = \Omega_0 \rho_c$ with critical density $\rho_c = 3H_0^2/8\pi G = 1.88 \times 10^{-29} h^2$ g cm$^{-3}$, and the present density parameter of visible baryonic matter to be $\Omega_0 = 0.028$ carrying an Fe mass fraction $X(^{56}\mathrm{Fe})$. We do not present these as our estimates of correct values for these parameters, but for illustration purposes. Once made, their measurement will provide independent evidence for the true values of these quantities.

The photon number $g_i$ is the number of photons $E_i$ emitted per $^{56}$Fe nucleus. Therefore, the differential flux of equation (1) in an expanding universe scales linearly with $h$, $\Omega_0$, and $X(^{56}\mathrm{Fe})$. We choose $\Omega_0 = 0.028$ for easy visual comparison of our results with those of the CW calculation, which adopted that value of $\Omega_0$. A common estimate of luminous matter density is $\leq 0.01$, whereas the visible baryonic matter density based upon primordial nucleosynthesis $0.015 \leq \Omega_B \leq 0.16$ (Kolb & Turner 1990). Moreover, a preliminary estimate of the luminous mass density from the Muenster Redshift Project data derived by Seitter et al. (1988) is 0.023–0.032, in which Seitter et al. use the $(M/L)_B$ mean values derived from pairs of galaxies. Therefore a luminous density $\Omega_0 = 0.028$ is in the range of current expectations, so we adopt it for purpose of display; but clearly our results will have to be scaled to the true cosmic density of Fe from Type Ia supernovae. The $^{56}$Fe density, $n(^{56}\mathrm{Fe})$, is, for purposes of this calculation, estimated by assuming the iron mass fraction in the Sun, $X_\odot(^{56}\mathrm{Fe}) = 1.34 \times 10^{-3}$, holds for all luminous matter and assuming that whatever dark matter exists in the universe does not contain $^{56}$Fe.

The important temporal factors are the choice of a Friedmann model and the rate of nucleosynthesis. We assume that SN Ia nucleosynthesis was started when the redshift $z = 2.5$ at time $t_*$ and note that this corresponds to $(t_0 - t_*) = 1.3 \times 10^{10}$ yr ago in a low-density universe with $q_0 = 0.014$ and $(t_0 - t_*) = 1.0 \times 10^{10}$ yr ago in an Einstein–de Sitter universe of $q_0 = 0.5$. In the matter-dominated universe, the time when photons having redshift $z$ today were emitted is, for a low-density universe ($\Omega < 1$) (Kolb & Turner 1990),

$$t = \frac{1}{H_0}\,\frac{\Omega_0}{2(1-\Omega_0)^{3/2}} \times \left[-\cosh^{-1}\left(\frac{\Omega_0 z - \Omega_0 + 2}{\Omega_0 z + \Omega_0}\right) + \frac{2(1-\Omega_0)^{1/2}(\Omega_0 z + 1)^{1/2}}{\Omega_0(1+z)}\right] \quad (2)$$

and for the Einstein–de Sitter universe,

$$t = \frac{2}{3H_0}\,\frac{1}{(1+z)^{3/2}} , \quad (3)$$

with the present age of the universe, $t_0$, given by the above expressions with $z = 0$. We evaluate two different rates of nucleosynthesis (following CW) for each model of the universe; one is a constant rate of nucleosynthesis of

$$f(t) = \frac{1}{(t_0 - t_*)} , \quad (4)$$

and the other one is an exponentially decaying rate of nucleosynthesis

$$f(t) = \frac{2\lambda}{\{1 - \exp[-2\lambda(t_0 - t_*)]\}}\, e^{-2\lambda(t - t_*)} \quad (5)$$

with $\lambda = 1/(t_0 - t_*)$ and normalized such that $f(t)dt$ is the fraction of present Fe nuclei that was synthesized between $t$ and $t + dt$; that is, $\int_{t_*}^{t_0} f(t)dt = 1$.

The constant case might be more relevant because it is possible that the rate of Type Ia supernovae was not as much greater in the past as was the mean nucleosynthesis rate used for chemical evolution of galaxies. Arnett et al. (1989), among others, have made this point. We reemphasize it because the $\gamma$-ray background directly measures the SN Ia rate rather than the total nucleosynthesis rate. A question which remains is of the evolution time for SN I progenitor configurations. This can be shorter than $10^9$ yr for double intermediate-mass binaries, but could be as long as several Gyr for the average SN I. In that case the initial time $t_*$ might fall at redshifts less than that of initial star formation. This uncertainty affects the derivation of the initiation of general nucleosynthesis from observations of the beginning of SN Ia explosions. Our arbitrary choice of $z = 2.5$ for the first SN Ia is for the direct comparison which it enables with the CW calculations, which thus illustrates the differences in SN I emission rather than cosmological differ-

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ences. A major objective of the measurement will be to determine this time of the beginning of (SN Ia) nucleosynthesis.

An escaping photon of energy $E_i$ in an expanding universe is redshifted to observed energy $E$ with

$$z = E_i/E - 1\ . \tag{6}$$

Each photon number $g_i$ of energy $E_i$ in Figure 1 contributes to each observed energy bin $E$ as written in equation (1) due to the expansion of the universe and also due to the evolution of the nucleosynthesis rate $f(t_E)$, with $t_E$ being evaluated by equations (2) or (3), (4) or (5), and (6). The X-ray continuum is treated in like manner by dividing it into a large number of narrow energy bins, each of which is then treated as a single energy. The sum of all contributions from all emission energies $E_i$ in Figure 1 to the observed energy bin $E$ is shown in Figure 2 as

$$\frac{\partial^2 F}{\partial E\, \partial\Omega} = \sum_i \frac{\partial^2 F_i}{\partial E\, \partial\Omega}\ . \tag{7}$$

Figure 2 differs from the result in CW, who included $\gamma$-ray lines from both $^{56}$Ni and $^{56}$Co decay but no continuum. Furthermore, we use the calculated emerging $\gamma$-ray line fraction from a specific numerical standard model of a Type Ia supernova, whereas CW assumed that all escaped. Most important in that regard are the $^{56}$Ni lines, which mostly do not escape. The inclusion of the continuum increases appreciably the differential flux below 200 keV, as can be seen by comparing Figure 2 with Figures 1 and 2 of CW. There is no longer such a pronounced minimum between 100 and 200 keV, an evident feature in Figures 1 and 2 of CW. Lack of escape of the $^{56}$Ni line at 158 keV is one big alteration of that feature from the CW calculation, where that rest edge provided the low-energy border of the 200 keV dip. One important feature of the spectrum in Figure 2 is the sudden drop near 250 keV due to the redshifted 847 keV $\gamma$-ray line from the turn-on time of galaxian nucleosynthesis. This feature is the best indicator from the $\gamma$-ray background for the onset time of SN Ia's in the universe. We have also done the same calculation for the unmixed version of model W7 and find the result to be very close to what we show in Figure 2, but with slightly lower intensity (typically only about 10% less).

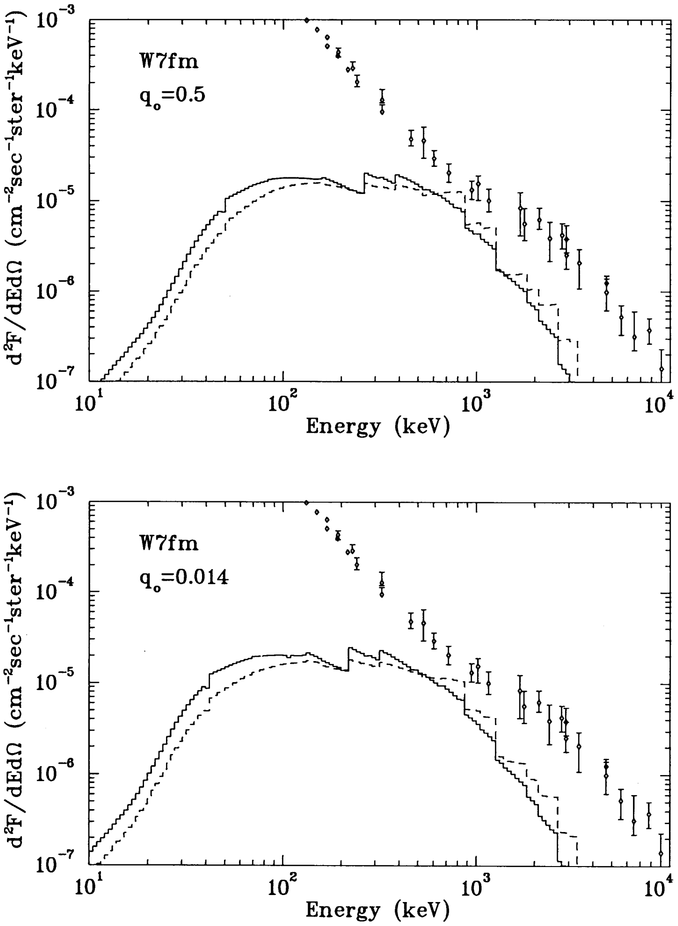

FIG. 2.—The differential flux of cosmic Type Ia supernovae in the Einstein–de Sitter ($q_0 = 0.5$ *top*) universe and in the low-density ($q_0 = 0.014$, *bottom*) universe. The solid line is the differential flux for exponential model of galactic nucleosynthesis that began $1.0 \times 10^{10}$ yr ago ($1.3 \times 10^{10}$ yr for low-density universe) and decays as $\exp[-2(t - t_*)/1.0 \times 10^{10}$ yr] {or $\exp[-2(t - t_*)/1.3 \times 10^{10}$ yr] for low-density universe}. The short-dashed curve is the differential flux for a constant rate of nucleosynthesis that begun at $1.0 \times 10^{10}$ yr ago ($1.3 \times 10^{10}$ yr for low-density universe). For comparison, data taken from Fig. 8 of Schönfelder (1989) are shown.

## 5. SPREADING THE $z = 2.5$ TURN-ON

The sudden drops with decreasing energy in Figure 2 (e.g., at about 250 keV) reflect the assumption that nucleosynthesis began abruptly at $z = 2.5$. This onset cannot be expected to be so well orchestrated, because different galaxies will commence star formation at different times, and the intrinsic spread of evolution times of SN Ia binaries could also be quite large. In this section we spread the turn-on time of SN Ia's in the universe in a normalized Gaussian, and we will show that the sudden drop feature of the 847 keV redshifted energy from supernova $\gamma$-ray background is not completely washed out.

We assume that the "turn-on time" $t'$ for SN I nucleosynthesis was spread about $t_*$ in a normalized Gaussian:

$$\frac{dG}{dt'} = Ae^{-(t'-t_*)^2/2\Delta t^2} \tag{8}$$

This introduces a 1 $\sigma$ width $\Delta t$ for the commencement of SN I's in galaxies. It is a new parameter that will diffuse the more redshifted edge of each line. The constant $A$ normalizes $\int (dG/dt')dt' = 1$. Clearly $\langle t' \rangle = t_*$ as before. The fraction of galaxies that has turned on at time $t$ is then

$$G(t) = \int_0^t Ae^{-(t'-t_*)^2/2\Delta t^2}\, dt' \tag{9}$$

Our procedure is as before except that the previous function $f(t)$ is replaced by

$$f(t) \rightarrow G(t) f(t) \tag{10}$$

so that, for example, in the constant nucleosynthesis case, the rate $f(t) = (t_0 - t_*)^{-1}$ between $t_*$ and $t_0$ becomes $f(t) = G(t)(t_0 - t_*)^{-1}$, now defined for all values of $t$. Figure 3 shows some comparisons, highlighting the drop near 250 keV of Figure 2 for an Einstein–de Sitter universe. In this figure the exponential nucleosynthesis rate, equation (5), is spread at its commencement with a normalized Gaussian, equation (8), with $\Delta t = 0.1 \times t_*$ and $0.2 \times t_*$. The drop near 250 keV becomes smoother but still can be seen. However the drops near 50 keV (not shown in Fig. 3) and near 400 keV become smooth curves. Therefore the best marker of the onset of SN I nucleosynthesis is an edge near 250 keV [actually $847/(z + 1)$ keV; $z$ is the redshift of the turn-on of SN Ia's] of the cosmic background

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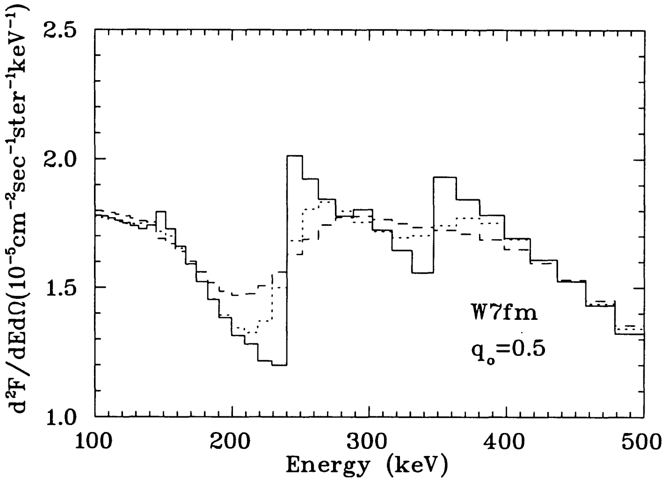

FIG. 3.—The differential flux of cosmic Type Ia supernovae in the Einstein–de Sitter ($q_0 = 0.5$) universe with SN I nucleosynthesis spread in a normalized Gaussian eq. (8) with $\Delta t = 0$ (*solid line*), $0.1t_*$ (*dotted line*), and $0.2t_*$ (*dashed line*) and $t_* = 1.8 \times 10^9$ yr.

spectrum. Although the current data of the cosmic background between 1 and 200 keV are the most firmly established (Kinzer, Johnson, & Kurtess 1978; Marshall et al. 1980), improvement is still needed. It is quite interesting that a dip or break between 300 and 2000 keV does appear in the few hundred keV region (Kinzer et al. 1991) as has been suggested by measurements (Fukada et al. 1975; Trombka et al. 1977).

## 6. FLUCTUATIONS NEAR $z = 0$ (TODAY)

The most distinguishing features of the $\gamma$-ray spectrum are the abrupt decreases near the rest energies of the lines. These steps occur because we have extended the integration to $z = 0$. This is not strictly correct, because the nucleosynthesis of Fe is smooth in neither time nor space near the present. Consider for example an energy bin just below 847 keV, extending from energy $E$ to $E + dE = 847$ keV. The number of supernovae contributing 847 keV photons to this interval at any one time is approximately

$$N_{\rm SN} = 1.1 \times 10^{11} \tau_{56}\, n_{\rm gal}\, R_{\rm SN} (dE/Eh)^3 \ , \qquad (11)$$

where $\tau_{56}$ is the lifetime of $^{56}$Co in yr, $n_{\rm gal}$ is the local number density of galaxies, and $R_{\rm SN}$ is the frequency, yr$^{-1}$, of SN Ia's per galaxy. For example, if we take $\tau_{56} = 0.305$ yr, $n_{\rm gal} = 0.03$ $h^3$ Mpc$^{-3}$ (Allen 1973), $R_{\rm SN} = 0.01$ yr$^{-1}$, and $dE = 40$ keV then roughly 1260 supernovae contribute to the step at that energy. So averaged over that large energy bin, the $\gamma$-ray flux should be nearly isotropic and constant; but clearly over some smaller interval so few events contribute to the step at any one time that this is no longer true. Within 15 keV of 847 we expect only about 60 supernovae to contribute at any particular time. Over this interval the clustering of galaxies will begin to appear, and the step amplitudes will vary with direction and in time. This interval is also comparable to the Doppler widths of the lines owing to their ejection velocity from SN Ia's, so this effect, and indeed the steps themselves, will be somewhat smeared out. We have not included that Doppler width in our calculations because our large bin size (39 keV at 847) renders it superfluous at that resolution. Clearly the sharp steps shown near the rest energies in the figures are unrealistic.

The Virgo cluster, because it is such a large number of galaxies so nearby, will always provide an enhancement over the general cosmic background near the $^{56}$Co decay rest energies (Clayton 1982). These relatively narrow lines will give us the best handle on the average Fe nucleosynthesis at low $z$. An experiment with even moderate angular resolution and sufficient sensitivity can detect this component which must then be removed from the absolute measurement of the isotropic background flux.

## 7. DISCUSSION AND CONCLUSIONS

We have presented the total time-integrated spectrum of a SN Ia which we use as a "standard candle" for the cosmic-background from SN Ia's. We confirm the result of Clayton & Ward (1975) that the $\gamma$-rays from supernovae contribute significantly to the universal $\gamma$-ray background near 1 MeV. Specific features of the model are the steps near $^{56}$Co $\gamma$-ray line rest energies, which might be consistent with the currently available observational data. This model predicts that a very accurate measurement of background X-ray continuum between 0.1 and 1.0 MeV may reveal the turn-on time and the evolution of Type Ia SN nucleosynthesis in the universe.

Among different models of the general cosmic $\gamma$-ray background, the most promising is the unresolved emission from large numbers of active galaxies (Strong, Wolfendale, & Worrall 1976; Bignami et al. 1979). Other models such as radiation from normal galaxies, clusters of galaxies, Galactic cosmic-ray leakage, primordial cosmic rays, and primordial black holes are less likely on the basis of the energy spectrum and intensity (Fichtel & Trombka 1981). The decay of (unspecified) unstable particles produced in the early universe can in principle fit the MeV excess in the spectrum (Daly 1988). The spectrum from Type Ia supernovae has several unique features, including its differential flux peak between 20 and 80 keV and no flux at energies larger than 3.6 MeV. A high-quality measurement from 1 to 5 MeV might be able to identify this dropoff and confirm that SN Ia's do indeed provide a major component of the cosmic background.

Many of our assumptions in these calculations might be challenged, e.g., that SN Ia's synthesized $\frac{2}{3}$ of Galactic Fe. Because our computed results in Figures 2 and 3 must be multiplied by the fraction of Fe from SN Ia's, it is clear that a much lower SN Ia fraction would lower the expected observability of this signal. This renormalization can be done by inspection as future work clarifies the Fe parentage. However, that uncertainty is not as great as these three: (1) What is the true Fe mean density of the universe? (2) How typical of the universe is our Galaxy's (and our solar neighborhood's) history of nucleosynthesis? and (3) When did SN Ia nucleosynthesis become greater than SN II nucleosynthesis? This work makes no attempt to resolve those questions. They are cosmological issues which will be addressed by future measurements of this cosmic background. Our purpose has been to provide a more realistic calculation of what to expect from future observations and to point out the issues involved in interpreting those observations.

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1993ApJ...403...32T

## REFERENCES

Allen, C. W. 1973, Astrophysical Quantities (London: Athlone)

Arnett, W. D., Schramm, D. N., & Truran, J. W. 1989, ApJ, 339, L25

Bignami, G. F., Fichtel, C. E., Hartman, R. C., & Thompson, D. J. 1979, ApJ, 232, 649

Burrows, A., & The, L.-S. 1990, ApJ, 360, 626

Chan, K. W., & Lingenfelter, R. E. 1991, ApJ, 368, 515

Clayton, D. D. 1982, in Essays in Nuclear Astrophysics, ed. C. A. Barnes, D. D. Clayton, & D. N. Schramm (Chicago: Univ. of Chicago Press), 40

Clayton, D. D., Colgate, S. A., & Fishman, G. 1969, ApJ, 155, 75

Clayton, D. D., & Silk, J. 1969, ApJ, 158, L43

Clayton, D. D., & The, L.-S. 1991, ApJ, 375, 221

Clayton, D. D., & Ward, R. A. 1975, ApJ, 198, 241 (CW)

Daly, R. A. 1988, ApJ, 324, L47

Evans, R., van den Bergh, S., & McClure, R. D. 1989, ApJ, 345, 752

Fichtel, C. E., & Trombka, J. I. 1981, Gamma Ray Astrophysics, New Insight Into the Universe (NASA SP-453) (Washington, DC: NASA)

Fukada, Y., Hayakawa, S., Kasahara, I., Makino, F., & Tanaka, Y. 1975, Nature, 254, 398

Kinzer, R. L., Johnson, W. N., & Kurfess, J. D. 1978, ApJ, 222, 370

Kinzer, R. L., Matteson, J., Gruber, D., Nolan, P., Rothschild, R., Knight, F., Baity, W., & Peterson, L. E. 1991, preprint

Kolb, E. W., & Turner, M. S. 1990, The Early Universe (Reading: Addison-Wesley)

Leising, M. D., & Share, G. H. 1990, ApJ, 357, 638

Marshall, F. E., Boldt, E. A., Holt, S. S., Miller, R. B., Mushotzky, R. F., Rose, L. A., Rothschild, R. E., & Serlemitsos, P. J. 1980, ApJ, 235, 4

Muller, R. A., Marvin, H. J., Pennypacker, C. R., Perlmutter, S., Sasseen, T. P., & Smith, C. K. 1992, ApJ, 384, L9

Nomoto, K., Kumagai, S., & Shigeyama, T. 1991, in Gamma-Ray Line Astrophysics, ed. N. Prantzos & P. Durouchoux (New York: AIP), 236

Nomoto, K., Thielemann, F.-K., & Yokoi, K. 1984, ApJ, 286, 644

Pinto, P. A., & Woosley, S. E. 1988, ApJ, 329, 820

Schönfelder, V. 1989, in Proc. Gamma Ray Observatory Science Workshop, ed. W. N. Johnson (Greenbelt: NASA), 3–24

Seitter, W. C., Ott, H.-A., Duemmler, R., Schuecker, P., & Hortsmann, H. 1988, in Morphological Cosmology, ed. P. Flin & H. W. Duerbeck (Berlin: Springer-Verlag), 3

Strong, A. W., Wolfendale, A. W., & Worrall, D. M. 1976, J. Phys. A: Math Gen., 9, 1553

The, L.-S., Clayton, D. D., & Burrows, A. 1991, in IAU Symp. 143, Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies, ed. K. A. van der Hucht & B. Hidayat (Dordrecht: Kluwer), 537

Thielemann, F.-K., Hashimoto, M., Nomoto, K., & Yokoi, K. 1991, in Supernovae, ed. S. Woosley (New York: Springer-Verlag), 609

Trombka, J. J., Dyer, C. S., Evans, L. G., Bielefeld, M. J., Seltezer, S. M., & Metzger, A. E. 1977, ApJ, 212, 925

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