Cosmic gamma-ray background from Type Ia supernovae revisited: Evidence for missing gamma-rays at MeV

Kyungjin Ahn, Eiichiro Komatsu, and Peter Höflich
Department of Astronomy, University of Texas at Austin

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The observed cosmic γ-ray background at ∼ MeV has often been attributed to Type Ia supernovae (SNIa). Since SNIa is close to a standard candle, one can calculate the γ-ray intensity of SNIa integrated over redshifts fairly accurately, once the evolution of the SNIa rate is known. The latest SNIa rate measured at $z \lesssim 1.6$ (Dahlen et al. 2004) indicates that the previous calculations of the γ-ray background consistently overestimated the SNIa rate. With the new rate, we find that the SNIa contribution is an order of magnitude smaller than observed, and thus new population(s) of sources should be invoked.

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The cosmic X-ray and γ-ray background encodes the most energetic phenomena in the universe. It has widely been accepted that different population of sources contribute to the different energy bands (see [1] for a review). On the low energy side, the intensity spectrum in the X-ray or soft γ-ray region, $\lesssim 0.5$ MeV, has been successfully explained by the integrated counts of obscured Active Galactic Nuclei (AGNs) [2, 3, 4]. At $\gtrsim 0.5$ MeV the spectrum of these AGNs sharply cuts off [4]. On the high energy side, $30$ MeV $\lesssim E \lesssim 10$ GeV, beamed AGNs (blazars) are able to account for the observed background almost entirely [5, 6, 7]. The blazar spectrum appears to break below $\sim 10$ MeV: thus, blazars are unable to account for the low energy spectrum. A natural question to ask is, then, “what are the most dominant sources contributing to the medium energy band, 0.5 MeV $\lesssim E \lesssim 10$ MeV?”

Ever since the first proposal made by Clayton and Silk in 1969 [8], it has often been argued that the γ-ray background at $\sim$ MeV region can be accounted for by Type Ia supernovae (SNIa) [9, 10, 11, 12]. The contribution from core-collapse supernovae at $\sim$ MeV must be much smaller than that of SNIa because the γ-ray photons cannot easily escape the hydrogen envelope of the progenitor (a massive star) [12]. If this is true, the spectrum of the γ-ray background can be used as a powerful probe of the cosmic star formation history. The previous calculations of the γ-ray background from SNIa were, however, subject to uncertainty in the supernova rate (SNR) of SNIa.

In this paper, we present a more robust prediction for the cosmic γ-ray background from SNIa using the observationally determined SNR, thereby avoiding any uncertainty associated with the progenitor model. We show that the previous calculations consistently overestimated the SNR, and the SNIa contributes no more than 10% of the observed level of the cosmic γ-ray background. Our results strongly argue for the existence of new population(s) of sources contributing to the background at $\sim$ MeV.

The spectrum we derive in this paper was already presented in the previous paper [13] where it is shown that the soft γ-ray background at $< 0.511$ MeV may have a substantial contribution from the redshifted 0.511 MeV lines of dark matter annihilation in galaxies distributed over cosmological distances. These signals cannot, however, explain missing γ-rays at $> 0.511$ MeV.

We calculate the background intensity, $I_\nu$, as [14]

$$ I_\nu = \frac{c}{4\pi} \int \frac{dz}{H(z)(1+z)^4} P_\nu \left[ \frac{\nu}{H(z)(1+z)} \right], \quad (1) $$

where $\nu$ is an observed frequency, $H(z)$ is the expansion rate at redshift z, and $P_\nu(\nu, z)$ is the volume emissivity in units of energy per unit time, per unit frequency and per unit proper volume:

$$ P_\nu(\nu, z) = (1+z)^3 \text{SNR}_{1a}(z) \bar{E}_\nu. \quad (2) $$

Here, SNR$_{1a}$ is the SNR of SNIa, which is the number of SNIa per unit time and per unit comoving volume. (Hence $(1+z)^3$ in the front.) The time-averaged γ-ray energy spectrum of each supernova, $\bar{E}_\nu$, in units of energy per unit frequency, depends only on $\nu$ as SNIa is a standard candle to a good approximation. One obtains

$$ I_\nu = \frac{c}{4\pi} \int \frac{dz}{H(z)(1+z)^2} \left[ \nu(1+z) \bar{E}_\nu(1+z) \right] $$

$$ \simeq 0.50 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ str}^{-1} \int \frac{dz}{E(z)(1+z)^2} $$

$$ \times \left[ \frac{\text{SNR}_{1a}(z)}{10^{-4} \text{ Mpc}^{-3} \text{ yr}^{-1}} \right] \left[ \frac{\nu(1+z) \bar{E}_\nu(1+z)}{10^{49} \text{ erg}} \right]. \quad (3) $$

where $E(z) \equiv \Omega_m h^2 (1+z)^3 + \Omega_k h^2$. It follows from equation (3) that contribution from high redshift SNIa is negligible unless SNR$_{1a}(z)$ grows faster than $(1+z)^{5/2}$ toward higher redshifts. On the other hand, recent observations suggest that SNR$_{1a}(z)$ peaks at $z \sim 1$ and drops at higher redshifts; thus, the most dominant contribution must come from lower redshifts. Dahlen et al. [15] have determined the SNR$_{1a}$ at $z \lesssim 1.6$ based on 25 SNIa observed as part of the Great Observatories Origins Deep Survey (GOODS). Figure 4 shows the data (symbols) as...
The SNR \( \gamma \)-ray background is \( \nu I \sim 0.5 \) keV cm\(^{-2}\) s\(^{-1}\) str\(^{-1}\), as \( \mathcal{E}(z)(1+z) \sim 2 \) at \( z = 0.8 \).

As a comparison, we also plot in Figure 1 the SNR\( I_a \)(z) used by the previous work\[12\]. The latest determination by\[15\] lies below it essentially because their estimate was based upon indirect determinations. They used an empirical analytic function for the SNR\( I_a \)(z) normalized to the local determination of the star formation rate at \( z = 0 \), assuming a Type II supernova rate per unit stellar mass of 0.007 \( M_\odot \)^{-1} and Type Ia to Type II ratio of 1/3. Another uncertainty comes from an adopted progenitor model of SNIa. Observations suggest that SNR\( I_a \)(z) follows the star formation rate with a delay time. This is where significant uncertainty in the progenitor model comes in. They showed that the uncertainty in the delay time easily affects the amplitude of the predicted \( \gamma \)-ray background by a factor of 2 to 3 (Figure 5 of\[12\]). (The longer delay time reduces the amplitude.) The SNR\( I_a \) used by\[10\] is even larger (SNR\( I_a \sim 1.6 \times 10^{-3} \) Mpc\(^{-3}\) yr\(^{-1}\)) and is not shown in Figure 1. They used an analytic model of the SNR\( I_a \)(z) for which it was assumed that all the baryons in the universe were converted into stars. This led to a gross overestimation of the star formation rate by an order of magnitude. Now that SNR\( I_a \)(z) has been determined up to \( z \sim 1.6 \), we can circumvent all of these theoretical uncertainties in the star formation rate and the progenitor model, by taking observationally determined SNR\( I_a \)(z).

Currently, the most favored scenario for SNIa is the explosion of a single degenerate White Dwarf close to the Chandrasekhar mass, in which the ignition occurs close to the center. Initially, the nuclear burning front propagates as a deflagration front and, after burning of about 0.2 to 0.3 \( M_\odot \), turns into a detonation\[17\]. This so-called “delayed-detonation” model allows to explain both the optical and infrared light-curves and spectra. This class of models produce the wide range in masses of radioactive \( ^{56}\)Ni between 0.08 to \( \approx 0.8M_\odot \) needed to explain both “normal-bright” and subluminous SNIa, and the brightness decline-relation\[18\], a cornerstone of modern cosmology. For recent reviews, see\[13, 20\]. As a typical feature of these models (and consistent with late time spectra\[21\]), the mean \( ^{56}\)Ni velocities increase with the \( ^{56}\)Ni mass and, thus, the relative contribution of SNIa with high \( ^{56}\)Ni masses dominate the \( \gamma \)-ray spectra, avoiding potential problems caused by the uncertainties in the rate of subluminous SNIa\[23\]. By using a SNIa at the bright-end of the distribution, we may overestimate the SNIa contribution to \( \gamma \)-rays.

As a reference model for the \( \gamma \)-ray spectrum and the light curve of SNIa, we have chosen the delayed-detonation model, \( 5p0z22.23 \), of\[22\] which produces 0.561 \( M_\odot \) of \( ^{56}\)Ni and represents a “typical” SNIa, i.e., at the bright end, where most SNIa are observed\[39\]. The calculations are based on a Monte Carlo code for \( \gamma \)-rays\[22\] but with updated bound-free opacities and nuclear branching ratios\[26, 27\].

Figure 2 shows the time-averaged \( \gamma \)-ray spectrum of SNIa. The lines correspond to various \( \gamma \)-ray emission lines from radioactive decays of \( ^{56}\)Ni \( \rightarrow ^{56}\)Co and \( ^{56}\)Co \( \rightarrow ^{56}\)Fe. The line energies and branching ratios are summarized in Table 1 and 2 of\[22\]. All lines above 1 MeV except one at 1.5618 MeV are due to the decay of \( ^{56}\)Co, whereas all lines below 1 MeV except one at 0.84678 MeV are due to \( ^{56}\)Ni.

Figure 3 shows the predicted spectrum of the cosmic \( \gamma \)-ray background from SNIa as well as the observational data from HEAO-1 A4 MED\[28\] and COMPTEL\[29\] experiments. The AGN contribution\[2\], which explains the HEAO-1 data at lower energy, is also shown. It is quite clear that the predicted SNIa signal falls short of the COMPTEL data by at least an order of magnitude. We also plot the 2-\( \sigma \) upper limit of SNR\( I_a \)(z)\[15\] (including systematic errors), finding that the 2-\( \sigma \) limit is still a factor of 6 smaller than observed. Therefore, we conclude that SNIa cannot account for the observed \( \gamma \)-ray background at \( \sim \) MeV, and other sources should be invoked. Similar results were obtained independently by\[28\], using their “concordance star formation rate”.

To the best of our knowledge, there are no confirmed sources which could produce a substantial amount of the cosmic \( \gamma \)-ray background in this energy region. We thus argue that there should be new population(s) of sources accounting for the “missing \( \gamma \)-rays” at \( \sim \) MeV. What could these sources be? Perhaps the most straightfor-
ward possibility would be a population of blazars emitting in $\sim$ MeV region. These “MeV blazars” cannot, however, be the primary candidate; otherwise one must require all of the regular blazars to be the MeV blazars, contrary to observations.

If one had to abandon “ordinary” astronomical sources such as AGNs and SNIa (which we argue we should) as an explanation to the MeV $\gamma$-ray background, then more exotic sources would be required. Of potential candidates would be $\gamma$-rays from dark matter annihilation, although popular dark matter candidates (e.g., neutralinos) are usually very heavy (dark matter mass of $m_\chi \gtrsim 30$ GeV) and it is unlikely that such heavy dark matter particles contribute to the MeV $\gamma$-ray background. Much lighter dark matter ($1$ MeV $\lesssim m_\chi \lesssim 100$ MeV), on the other hand, is more promising, and it has recently been shown that such light dark matter is a promising explanation to the $511$ keV lines detected at the center of our Galaxy. We have shown in the previous paper that the redshifted $0.511$ MeV lines from other galaxies distributed over cosmological distances contribute to the cosmic $\gamma$-ray background at $< 0.511$ MeV substantially. Although these lines do not produce any flux at $> 0.511$ MeV, it may not be so surprising that any other associated continuum emission, such as the internal bremsstrahlung, might also contribute substantially at $\sim$ MeV. Although much is uncertain, the MeV $\gamma$-ray background would certainly be a potential window to the new physics.

Finally, we emphasize the fact that the precise shape of the spectrum of the MeV $\gamma$-ray background is currently not very well constrained (see Figure 3). Given the importance of this region of the spectrum, it seems urgent to carry out more precise measurements of the MeV $\gamma$-ray background.

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We note that the emerging $\gamma$-ray spectrum, when averaged over time, is similar for all scenarios which produce bright SNIa [22].

Note that, with respect to the amount and distribution of $^{56}\text{Ni}$, DD-models for the "normal-bright SNe" are similar to the classical deflagration model W7 of [24], which was used in most of the previous work on the cosmic $\gamma$-ray background [10, 11, 12, 25].