PHYSICAL REVIEW D **71,** 121301(R) (2005)

Cosmic gamma-ray background from type Ia supernovae reexamined: Evidence for missing gamma rays at MeV energy

Kyungjin Ahn, Eiichiro Komatsu, and Peter Höflich

Department of Astronomy, University of Texas at Austin, 1 University Station, C1400, Austin, Texas 78712, USA

(Received 27 April 2005; published 13 June 2005)

The observed cosmic γ-ray background at $\sim$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.*, Astrophys. J. **613**, 189 (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.

DOI: 10.1103/PhysRevD.71.121301 PACS numbers: 95.35.+d, 95.85.Nv, 95.85.Pw

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) [2–4]. 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 [5–7]. 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) [9–12]. 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_ν, as [14]

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

where ν 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:

$$P_\nu(\nu, z) = (1+z)^3 \mathrm{SNR}_{\mathrm{Ia}}(z) \bar{E}_\nu. \tag{2}$$

Here, $\mathrm{SNR}_{\mathrm{Ia}}$ 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 ν as SNIa is a standard candle to a good approximation. One obtains

$$\begin{aligned} \nu I_\nu &= \frac{c}{4\pi} \int \frac{dz\, \mathrm{SNR}_{\mathrm{Ia}}(z)}{H(z)(1+z)^2} [\nu(1+z)\bar{E}_{\nu(1+z)}] \\ &\simeq 0.50 \text{ keV cm}^{-2}\,\text{s}^{-1}\,\text{str}^{-1} \int \frac{dz}{\mathcal{E}(z)(1+z)^2} \\ &\quad \times \left[\frac{\mathrm{SNR}_{\mathrm{Ia}}(z)}{10^{-4}\text{ Mpc}^{-3}\,\text{yr}^{-1}}\right]\left[\frac{\nu(1+z)\bar{E}_{\nu(1+z)}}{10^{49}\text{ erg}}\right], \end{aligned} \tag{3}$$

where $\mathcal{E}^2(z) \equiv \Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2$. It follows from Eq. (3) that contribution from high redshift SNIa is negligible unless $\mathrm{SNR}_{\mathrm{Ia}}(z)$ grows faster than $(1+z)^{5/2}$ toward higher redshifts. On the other hand, recent observations suggest that $\mathrm{SNR}_{\mathrm{Ia}}(z)$ 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 $\mathrm{SNR}_{\mathrm{Ia}}$ at $z \lesssim 1.6$ based on 25 SNIa observed as part of the Great Observatories Origins Deep Survey (GOODS).

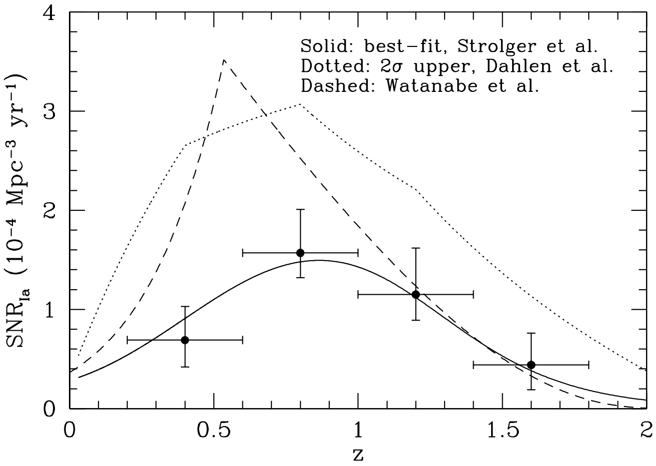

FIG. 1. Type Ia supernova rates (SNR_{Ia}). Observed data from GOODS survey are shown with 1σ statistical error bars (filled circles). The solid line is the best-fit model deduced by Strolger *et al.* [16]. The dashed line is for the rates used in Watanabe *et al.* [12]. The model adopted by The *et al.* [10] gives the SNIa rate of $\simeq 1.6 \times 10^{-3}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$, which is an order of magnitude larger than the best-fit model and is not shown. The dotted line is constructed by connecting the 2-σ upper limits (including systematic errors) of observed rates [15].

Figure 1 shows the data (symbols) as well as the best-fitting model of Strolger *et al.* [16] (the solid line). The $SNR_{Ia}(z)$ reaches $1.6 \times 10^{-4}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$ at $0.6 < z < 1.0$ and then drops at $z > 1$. It thus follows from Eq. (3) that the expected intensity of the γ-ray background is $\nu I_\nu \sim 0.5\ \mathrm{keV\,cm^{-2}\,s^{-1}\,str^{-1}}$, as $\mathcal{E}(z)(1+z) \sim 2$ at $z = 0.8$.

As a comparison, we also plot in Fig. 1 the $SNR_{Ia}(z)$ 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 $SNR_{Ia}(z)$ 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 $SNR_{Ia}(z)$ 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 γ-ray background by a factor of 2 to 3 (Fig. 5 of [12]). (The longer delay time reduces the amplitude.) The SNR_{Ia} used by [10] is even larger ($SNR_{Ia} \simeq 1.6 \times 10^{-3}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$) and is not shown in Fig. 1. They used an analytic model of the $SNR_{Ia}(z)$ 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 $SNR_{Ia}(z)$ 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 $SNR_{Ia}(z)$.

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 produces the wide range in masses of radioactive ^{56}Ni between 0.08 to $\approx 0.8 M_\odot$ needed to explain both "normal-bright" and subluminous SNIa, and the brightness decline relation [18], a cornerstone of modern cosmology. For recent reviews, see [19,20]. 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 x-ray spectra, avoiding potential problems caused by the uncertainties in the rate of subluminous SNIa [22]. By using a SNIa at the bright end of the distribution, we may overestimate the SNIa contribution to x rays.

As a reference model for the γ-ray spectrum and the light curve of SNIa, we have chosen the delayed-detonation model, *5p0z22.23*, of [24] 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 [25]. The calculations are based on a Monte Carlo code for γ rays [23] but with updated bound-free opacities and nuclear branching ratios [28,29].

Figure 2 shows the time-averaged γ-ray spectrum of SNIa. The lines correspond to various γ-ray emission lines from radioactive decays of $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co}$ and $^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$. The line energies and branching ratios are summarized in Tables 1 and 2 of [23]. 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 0.846 78 MeV are due to ^{56}Ni.

Figure 3 shows the predicted spectrum of the cosmic γ-ray background from SNIa as well as the observational data from HEAO-1 A4 MED [30] and COMPTEL [31] experiments. The AGN contribution [4], 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-σ upper limit of $SNR_{Ia}(z)$ [15] (including systematic errors), finding that the 2-σ limit is still a factor of 6 smaller than observed. Therefore, we conclude that SNIa cannot account for the observed γ-ray background at $\sim$MeV, and other sources should be invoked. Similar results were obtained independently by [27], 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 γ-ray background in this energy region. We thus argue that there should be new population(s) of sources accounting for the "missing γ-rays" at $\sim$MeV. What

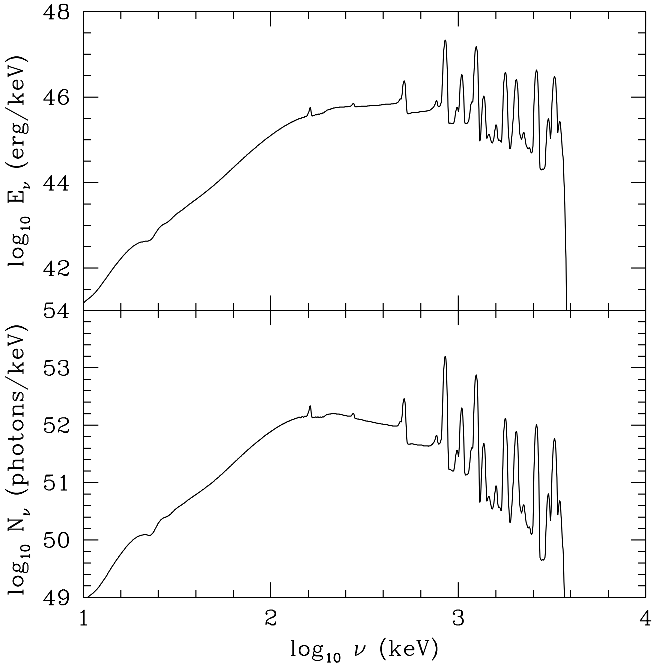

FIG. 2. (top) Time-averaged supernova spectrum, E_ν, of a proto-type SNIa. (bottom) The same spectrum expressed in differential photon number [$= E_\nu/(h\nu)$].

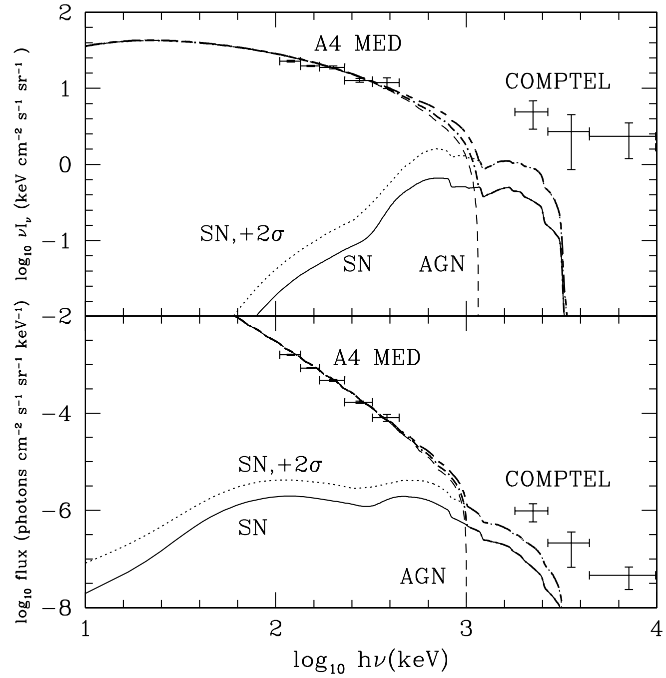

FIG. 3. Predicted γ-ray background from type Ia supernovae. The solid line is the prediction from the best-fit SNR_{Ia} by [16], while the dotted line is the one using the 2-σ upper limit (including systematic errors; see also Fig. 1). The data points with error bars are from the HEAO-1 A4 MED [30] and COMPTEL experiments [31]. The AGN contribution [4], which explains the HEAO data, is also plotted in the thin dashed line. The sum of the SNIa and AGN contributions is plotted in the thick lines. The top and the bottom panels use different units.

could these sources be? Perhaps the most straightforward possibility would be a population of blazars emitting in ~MeV region. These ''MeV blazars'' [32] cannot, however, be the primary candidate; otherwise one must require *all* of the regular blazars to be the MeV blazars, contrary to observations [33].

If one had to abandon ''ordinary'' astronomical sources such as AGNs and SNIa (which we argue we should) as an explanation to the MeV γ-ray background, then more exotic sources would be required. Of potential candidates would be γ 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 γ-ray background [34]. 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 [35] that such light dark matter is a promising explanation to the 511 keV lines detected at the center of our Galaxy [36,37]. 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 γ-ray background at $<$0.511 MeV substantially [13]. 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 [38], might also contribute substantially at ~MeV [39]. Although much is uncertain, the MeV γ-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 γ-ray background is currently not very well constrained (see Fig. 3). Given the importance of this region of the spectrum, it seems urgent to carry out more precise measurements of the MeV γ-ray background.

We would like to thank D. E. Gruber for providing us with the observational data plotted in Fig. 3, Y. Ueda for providing us with the AGN predictions plotted in Fig. 3, and T. Dahlen for providing us with the 2-σ statistical and systematic errors of the supernova rate (which are non-Gaussian) plotted in Fig. 1. We would like to thank P. R. Shapiro for helpful discussion. K. A. was partially supported by NASA Astrophysical Theory Program Grants No. NAG5-10825, No. NAG5-10826, No. NNG04G177G, and Texas Advanced Research Program Grant No. 3658-0624-1999. The gamma-ray calculations have been performed on 11 nodes of the Beowulf cluster at the Department of Astronomy which has been financed by the John W. Cox Fund in 1999, and maintained by the NASA Grants No. NAG5-7937, NASA Grants No. HST-GO-10118.05 and No. HST-GO-10182.47 to P. A. H. This work was supported by NSF Grant No. AST0307312 and LBNL 6711032 to P. A. H.

[1] F. W. Stecker and M. H. Salamon, in *Gamma 2001*, edited by S. Ritz, N. Gehrels, and C. R. Schrader, AIP Conf. Proc. No. 587 (American Institute of Physics, New York, 2001), p. 432.
[2] A. Comastri, G. Setti, G. Zamorani, and G. Hasinger, Astron. Astrophys. **296**, 1 (1995).
[3] A. A. Zdziarski, W. N. Johnson, C. Done, D. Smith, and K. McNaron-Brown, Astrophys. J. Lett. **438**, L63 (1995).
[4] Y. Ueda, M. Akiyama, K. Ohta, and T. Miyaji, Astrophys. J. **598**, 886 (2003).
[5] M. H. Salamon and F. W. Stecker, Astrophys. J. Lett. **430**, L21 (1994).
[6] F. W. Stecker and M. H. Salamon, Astrophys. J. **464**, 600 (1996).
[7] V. Pavlidou and B. D. Fields, Astrophys. J. Lett. **575**, L5 (2002).
[8] D. D. Clayton and J. Silk, Astrophys. J. Lett. **158**, L43 (1969).
[9] D. D. Clayton and R. A. Ward, Astrophys. J. **198**, 241 (1975).
[10] L.-S. The, M.D. Leising, and D. D. Clayton, Astrophys. J. **403**, 32 (1993).
[11] A. A. Zdziarski, Mon. Not. R. Astron. Soc. **281**, L9 (1996).
[12] K. Watanabe, D. H. Hartmann, M. D. Leising, and L.-S. The, Astrophys. J. **516**, 285 (1999).
[13] K. Ahn and E. Komatsu, Phys. Rev. D **71**, 021303(R) (2005).
[14] J. A. Peacock, *Cosmological Physics* (Cambridge University Press, Cambridge, United Kingdom, 1999), pp. 91–94.
[15] T. Dahlen *et al.*, Astrophys. J. **613**, 189 (2004).
[16] L.-G. Strolger *et al.*, Astrophys. J. **613**, 200 (2004).
[17] A. M. Khokhlov, Astrophys. J. **245**, 114 (1991).
[18] M. M. Phillips, Astrophys. J. Lett., **413**, L105 (1993).
[19] D. Branch, Annu. Rev. Astron. Astrophys. **36**, 17 (1998).
[20] P. Höflich, C. Gerardy, E. Linder, and H. Marion, Lect. Notes Phys. **635**, 203 (2003).
[21] P. A. Mazzali, E. Cappellaro, I. J. Danziger, M. Turatto, and S. Benetti, Astrophys. J., **499**, L49 (1998).
[22] We note that the emerging γ-ray spectrum, when averaged over time, is similar for all scenarios which produce bright SNIa [23].
[23] P. Höflich, A. Khokhlov, and E. Müller, Astron. Astrophys. **259**, 549 (1992).
[24] P. Höflich, C. L. Gerardy, R. A. Fesen, and S. Sakai, Astrophys. J. **568**, 791 (2002).
[25] Note that, with respect to the amount and distribution of ^{56}Ni, DD models for the ''normal-bright SNe'' are similar to the classical deflagration model W7 of [26], which was used in most of the previous work on the cosmic γ-ray background [10–12,27].
[26] K. Nomoto, F.-K. Thielemann, and K. Yokoi, Astrophys. J. **286**, 644 (1984).
[27] L. E. Strigari, J. F. Beacom, T. P. Walker, and P. Zhang, J. Cosmol. Astropart. Phys. 04 (2005) 017.
[28] H. Jundo, Nuclear Data Sheets **86**, 315 (1999).
[29] M. J. Berger, J. H. Hubbell, S. M. Seltzer, J. S. Coursey, and D. S. Zucker, Report No. NBSIR-87-3597.
[30] D. E. Gruber, J. L. Matteson, L. E. Peterson, and G. V. Jung, Astrophys. J. **520**, 124 (1999).
[31] S. C. Kappadath *et al.*, Astron. Astrophys. Suppl. Ser. **120**, 619 (1996).
[32] J. J. Blom *et al.*, Astron. Astrophys. **298**, L33 (1995).
[33] F. W. Stecker, M. H. Salamon, and C. Done, astro-ph/9912106.
[34] D. Elsaesser and K. Mannheim, Astropart. Phys. **22**, 65 (2004).
[35] C. Boehm, D. Hooper, J. Silk, M. Casse, and J. Paul, Phys. Rev. Lett. **92**, 101301 (2004).
[36] P. Jean *et al.*, Astron. Astrophys. **407**, L55 (2003).
[37] J. Knödlseder *et al.*, Astron. Astrophys. **411**, L457 (2003).
[38] J. F. Beacom, N. F. Bell, and G. Bertone, Phys. Rev. Lett. **94**, 171301 (2005).
[39] K. Ahn *et al.* (unpublished).