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Would SN1993J have been detected by next generation Cherenkov instruments?

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ABSTRACT

Already in the first days after the explosion of a supernova, the strong shock expanding forward into the dense wind of the progenitor star can theoretically accelerate particles up to the $\sim$ PeV ($= 10^{15}$eV) range. These accelerated particles, interacting with the dense wind material, should lead to the production of gamma rays in the 1–100 TeV range, through pion production. However, no supernova has yet been detected by current Cherenkov instruments, and the question of the detectability of extragalactic supernovae in closeby galaxies (within a few Mpc) by next generation instruments is still open. The detection in the TeV range is especially hindered by the two–photon annihilation process, in which high–energy gamma rays interact with soft photons from the photosphere to produce electron/positron pairs, thereby degrading the gamma–ray signal from the system. We calculate the temporal evolution of the expected gamma–ray attenuation in the well-studied type IIb SN 1993J, accounting for both temporal and geometrical effects.

Keywords: supernovae — gamma–rays — extraGalactic — particle acceleration

INTRODUCTION

The possibility for core–collapse supernovae (CCSNe) to accelerate particles up to the PeV range has been put forward by several groups (see e.g. reviews by Bykov et al. 2018; Tamborra & Murase 2018, and references therein). In Type IIP, IIL and some IIb SNe, the explosion of the massive stellar progenitor sends a fast shock expanding in the dense wind of a red supergiant (RSG), providing an environment conductive to the excitation of non–resonant streaming instabilities, allowing for the acceleration of PeV particles within the first $\sim$tens of days after the SN explosion (Tatischeff 2009; Marcowith et al. 2018). Simple energetic considerations (Kirk et al. 1995) have indicated that the production of gamma rays subsequent to the acceleration of high–energy particles could be detected by Cherenkov instruments in the TeV range, but so far, no detection has been reported (H. E. S. S. Collaboration et al. 2019). This non–detection may be due especially to one effect, the attenuation through pair production, where gamma rays interact with the dense photon field of the SN photosphere, thereby significantly degrading the gamma–ray signal: $\gamma\gamma \rightarrow e^+e^-$ (Gould

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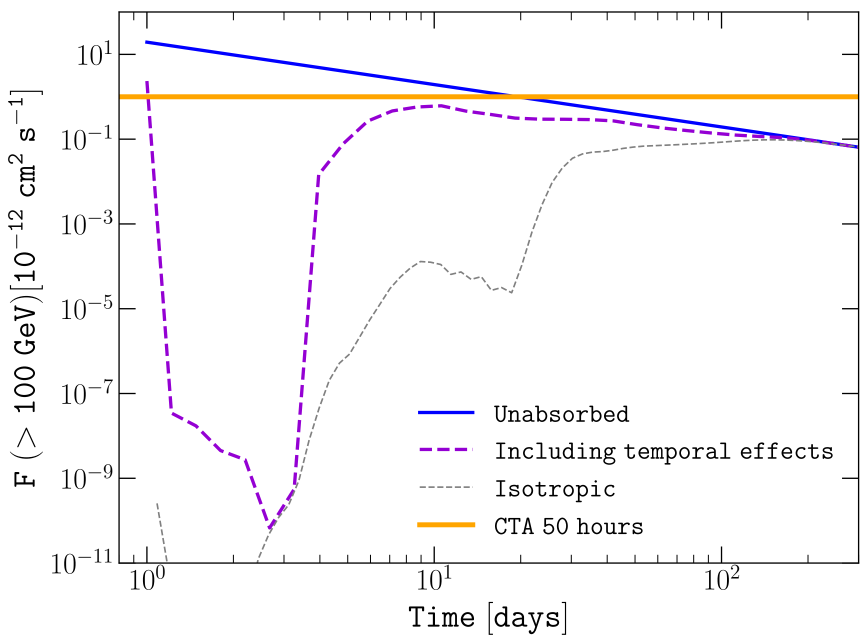

Figure 1. Time evolution of the integrated flux above 100 GeV from SN 1993J. Three cases are shown: Unabsorbed (blue solid), the results of our time–dependent calculation (purple dashed), and the isotropic calculation (grey thin dotted) (Aharonian et al. 2008). The typical sensitivity of CTA in 50 hours at energies above 100 GeV (Fioretti et al. 2016) is shown as the horizontal orange line.

& Schréder 1966, 1967). This effect has already been investigated in different astrophysical contexts (Dubus 2006), and in the case of CCSNe (Marcowith et al. 2014), usually under the assumption of an isotropic problem. However, as recently shown (Cristofari et al. 2020), this effect can be strongly non–isotropic in the early stages (few tens of days after the SN explosion) due to the dissimilar evolution of the radius of the SN photosphere to that of the outer shock.

GAMMA RAYS FROM SN1993J

The case of SN 1993J is particularly instructive, since it is has been extensively studied and observed from the first days after the explosion of the progenitor star. It is one of the brightest optically observed extragalactic SNe, located in M81 (NGC 3031, Ripero et al. 1993) at ≈ 3.6 Mpc. Previous studies (Tatischeff 2009) have indicated that the unabsorbed gamma–ray flux from SN 1993J should typically be of the order of:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = 2 \times 10^{-12} \left(\frac{D}{3.63 \text{ Mpc}}\right)^{-2} \left(\frac{\dot{M}_{\rm RSG}}{3.8 \times 10^{-5} M_{\odot}/\text{yr}}\right)^{2} \times \left(\frac{t}{\text{days}}\right)^{-1} \left(\frac{u_{\rm w}}{10 \text{ km/s}}\right)^{-2} \left(\frac{E}{1 \text{ TeV}}\right)^{-2} \text{TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \, . \tag{1}$$

under the assumption of a steady wind (constant mass-loss parameters) with a temporal efficiency of particle acceleration at the shock $\xi_{\rm CR} = 0.04 \ (t/1\text{day})^{0.17}$. Here, $\dot{M}_{\rm RSG}$ is the mass-loss rate of the RSG progenitor, $u_{\rm w}$ the wind terminal velocity, and D the distance to the object.

The gamma–ray photons interact with low energy (typically eV) photons through pair production processes. The resulting attenuation can be estimated in the case of SN 1993J, for which the photospheric radius and temperature have been well–measured. The details of this calculation are presented in Cristofari et al. (2020) and results are shown in Fig. 1. Compared to previous calculations which rely on the assumption of an isotropic situation, our novel time–dependent calculation indicates improved chances of detection starting a few days after the SN explosion. The typical sensitivity for 50 hours of observations with the next-generation of TeV instrument CTA (Cherenkov telescope array) is shown to be a factor of $\sim$2 above the expected signal for SN 1993J. This result supports the need for further study of the detectability of extragalactic CCSNe with CTA, taking into account the actual instrument response function of the instrument.

Moreover, further studies considering different types of CCSNe and environments are needed to understand which ones would be the most promising targets of interest for instruments operating in the very–high–energy gamma–ray domain.

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