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The gamma-ray signal from type IIP core-collapse supernovae

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The shock wave resulting from the core-collapse of a massive star can accelerate particles up to PeV energies in the first few days to weeks after the explosion. This can lead to the production of a potentially detectable gamma-ray signal. The gamma-ray flux however is strongly affected by the two-photon-annihilation process, where gamma-ray photons interact with photons from the SN photosphere. This process hampers the detection of gamma-rays from core-collapse supernovae at very high energies. In order to probe the detectability of the gamma-rays with current and upcoming gamma-ray facilities, we estimate the gamma-ray flux from typical type IIP core-collapse supernovae (CCSNe). These are the most common type of supernovae, and are presumed to arise from red supergiant progenitors. We include a detailed time-dependent calculation of two-photon absorption. Our results will be very useful in creating a strategic observing program to detect CCSNe with the next generation gamma-ray observatory, such as the Cherenkov Telescope Array (CTA).

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1. Introduction

In the first days and weeks after the explosion of core-collapse supernovae (CCSNe), it has been shown that efficient particle acceleration can energized hadrons up to the \gtrsim PeV range through the first-order Fermi mechanism, diffusive shock acceleration (DSA). The accelerated hadrons can in turn interact with the dense circum-stellar environment and produce gamma rays, through pion creation-decay [1–15]. A naive estimate of the gamma-ray signal thus created shows that a detection of extraGalactic CCSNe located within a few \lesssim Mpc, by next-generation instruments operating in the ~ 10 GeV to ~ 100 TeV range is a priori conceivable. However, the gamma-ray signal from hadronic interactions of accelerated particles with their surrounding can be degraded by interactions with low energy photons from the SN photosphere, leading to the creation of electron-positron pairs. This two-photon process has been shown to be very important in the first days to weeks after the explosion of a CCSN, reducing the gamma-ray signal by several orders of magnitude, and a careful calculation of the level of attenuation is essential in order to investigate the chances of detection in the gamma-ray range with future instruments. The inclusion of time effects, including for instance the time evolution of the photospheric radius and temperature, of the shock radius and the time of flight of photons before interaction is thus crucial in this problem. The importance of these time effects has been shown in the case of the very well studied SN1993J [16, 17]. The case of SN1993J was especially instructive, since it likely corresponded to a type IIb SN, and thus a rather energetic event, and thus would have been a good candidate for the detection with gamma-ray instruments. However, such type of CCSNe is expected to be infrequent, and the bulk of CCSNe might be less luminous in the gamma-ray domain. Using a simple analytical description of the photosphere and shock evolution, we investigate the gamma-ray signal from typical core-collapse type IIP SNe, taking into account the degradation due to the two-photon process. We find that the gamma-ray signal of only nearby objects, typically located within $\lesssim 1$ Mpc is somewhat at the level of the typical sensitivity of next-generation Cherenkov instruments in the ~ 10 GeV, and that above the $\gtrsim 100$ GeV range, the chances of detection are reduced [18].

2. The gamma-ray signal from type IIP CCSNe

As mentioned before, the detectability in the gamma-ray domain is mainly limited by the two-photon process, that we intend to take into account. We rely on an estimate of the gamma-ray signal from the shell around the SN shock wave expanding through the dense wind of its progenitor red super giant (RSG) star [1, 19]:

$$\begin{aligned} \frac{dN}{dE} \approx & 4.8 \times 10^{-14} \left(\frac{\xi_{\text{CR}}}{0.1} \right) \left(\frac{\dot{M}_w}{10^{-6} M_\odot/\text{yr}} \right)^2 \left(\frac{v_w}{10^6 \text{ cm/s}} \right)^{-2} \\ & \times \left(\frac{D}{\text{Mpc}} \right)^{-2} \left(\frac{v_{\text{sh}}(t)}{10^9 \text{ cm/s}} \right)^2 \left(\frac{R_{\text{sh}}(t)}{10^{14} \text{ cm}} \right)^{-1} \left(\frac{E}{1 \text{ TeV}} \right)^{-2} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}, \end{aligned} \quad (1)$$

where $\xi_{\text{CR}} = P_{\text{CR}}/\rho_w v_{\text{sh}}^2$ is the normalised CR pressure, \dot{M}_w the mass-loss rate of the progenitor wind, v_w the wind speed of the progenitor RSG, D the distance, v_{sh} the shock speed, and R_{sh} the shock radius. In the first days/weeks after the explosion, the evolution of the photospheric radius

and photospheric temperature can be described analytically [20]:

$$r_{\text{ph}}(t) = 2.9 \times 10^{14} \left(\frac{f}{0.1} \right)^{-0.062} \left(\frac{E_{\text{SN}}}{10^{51} \text{erg}} \right)^{0.41} \left(\frac{\kappa}{0.34} \right)^{0.093} \times \left(\frac{M_{\text{ej}}}{M_{\odot}} \right)^{-0.28} \left(\frac{t}{\text{days}} \right)^{0.81} \text{ cm} \quad (2)$$

$$T_{\text{ph}}(t) = 1.7 \left(\frac{f}{0.1} \right)^{-0.037} \left(\frac{E_{\text{SN}}}{10^{51} \text{erg}} \right)^{0.027} \left(\frac{R_{\star}}{10^{13} \text{cm}} \right)^{1/4} \left(\frac{M_{\text{ej}}}{M_{\odot}} \right)^{-0.054} \times \left(\frac{\kappa}{0.34 \text{cm}^2/\text{g}} \right)^{-0.28} \left(\frac{t}{\text{days}} \right)^{-0.45} \text{ eV} \quad (3)$$

where f is a numerical parameter found for typical RSG in the range [0.079,0.13], M_{ej} is the ejecta mass, E_{SN} the total explosion energy, R_{\star} the radius of the progenitor star, and κ the opacity, assumed to be time-and-space-independent.

The evolution of the SN shock can be described with self-similar solution [21], and reads, for a slope of the density profile of the envelope of the exploding star $n = 10$:

$$R_{\text{sh}}(t) \approx 4.7 \cdot 10^{14} \left(\frac{E_{\text{SN}}}{10^{51} \text{erg}} \right)^{0.44} \left(\frac{\dot{M}_{\text{w}}}{10^{-6} M_{\odot}/\text{yr}} \right)^{-0.17} \left(\frac{M_{\text{ej}}}{M_{\odot}} \right)^{-0.31} \times \left(\frac{t}{\text{days}} \right)^{0.875} \text{ cm} \quad (4)$$

These quantities are then used to derive the absorption through pair production including time effects, as described in [17], but in the case of type IIP CCSNe.

3. Results

The physical quantities used to describe the type IIP SNe (ξ_{CR} , M_{ej} , \dot{M} , R_{\star} and E_{SN}) can change the level of the gamma-ray emission and the level of the attenuation, but in all case, exploring the parameter space, we find that the gamma-ray signal from a type IIP SN located at 1 Mpc is at most at the level of the expected sensitivity of next-generation instruments. This is illustrated in Fig. ?? . Moreover, we find that the ~ 10 GeV domain will contribute to a potential detection, and that in turn, the detection of gamma-ray above $\gtrsim 100$ GeV in the first month will be very challenging, if possible at all. This strongly limits the possibility of detection of typical type IIP SNe located further than $\gtrsim 1$ Mpc and the possibility of probing particle acceleration to the highest energies using gamma rays. Type IIP SNe represent the most important fraction of CCSNe [22], but are likely to be the worst candidates in terms of detection in the gamma-ray domain, even though other effects, such as enhanced mass loss prior to the explosion might help increase the chances of detection. However, other, more powerful CCSNe (such as type IIb or IIc) might be more promising and could expand the horizon of detectability, thus increasing the chances of detection of gamma rays from SNe in the first days and weeks after the explosion, especially increasing the chances to probe the acceleration up to the PeV range at SNe [23].

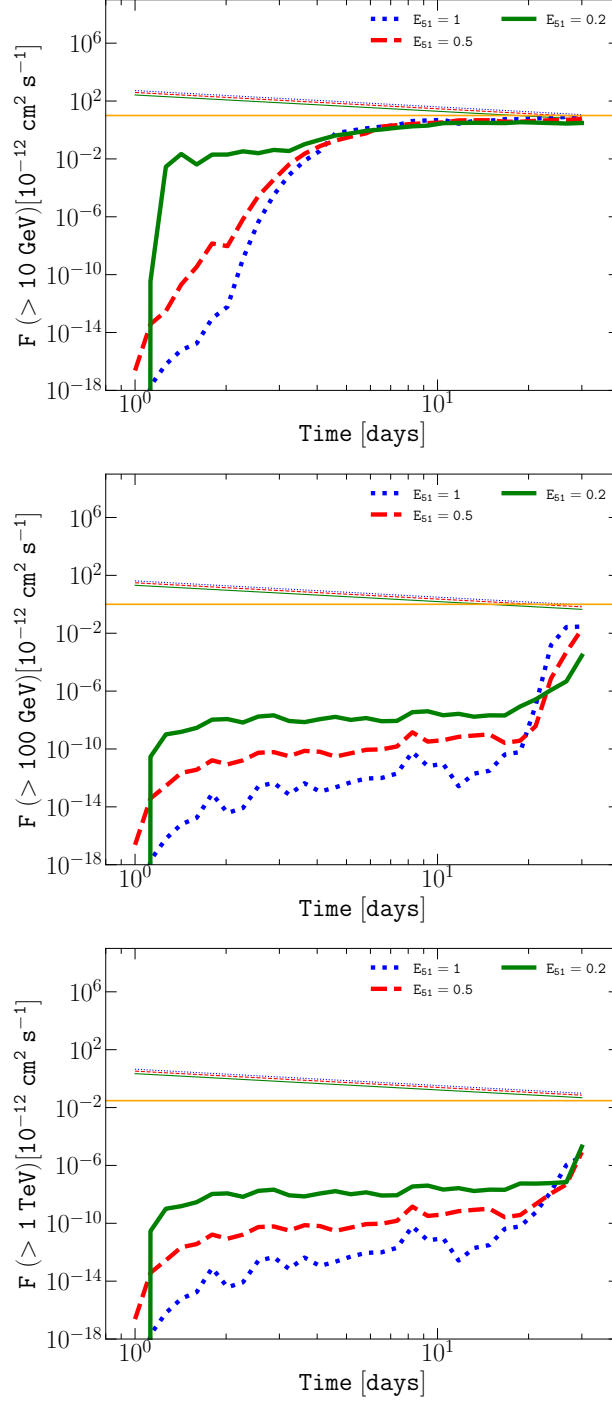


Figure 1: Time evolution of the integrated gamma-ray signal from a type IIP SN located at 1 Mpc, $M_{\text{ej}} = 10 M_{\odot}$, $\dot{M} = 10 M_{\odot}/\text{yr}$. The unattenuated signal is shown (thin lines) and the integrated signal above >10 GeV, >100 GeV and >1 TeV are shown (from top to bottom), for a total explosion energy $E_{\text{SN}} = 0.2$ (green solid), 0.5 (red dashed) and 1 (blue dotted) $\times 10^{51}$ erg. The typical sensitivity of CTA (orange horizontal line) for 50 hours is shown as a guiding-eye for the reader [24], a 5 hours integration curve would be roughly shift by a factor upward.

4. Conclusion

We have calculated the high energy gamma-ray signal expected from type IIP cc-SNe, the most common objects in this category. The calculation account for the effect of time-dependent anisotropic gamma-gamma absorption effect over the soft photon field produced by the supernova photosphere. We find that due to this effect type IIP SNe can hardly be detected above 100 GeV beyond one Mpc but the flux between 1-10 GeV is largely unattenuated. However, enhanced mass loss by the SN progenitor star a few years before the explosion could allow to shift this limit. The detectability horizon of Cherenkov telescopes could be larger for other cc-SNe such as type IIb or IIc.

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