Ultra-high energy radiation from young supernovae

MOST cosmic rays are believed to originate in first-order Fermi acceleration at blast shocks in supernova remnants. The acceleration is fully efficient after about 1,000 years, and is restricted to $E_p < 10^{14}$ eV (ref. 1). There are suggestions[2-5] that cosmic rays with energy up to 10^{18} eV might be accelerated in young supernova remnants for several years after the explosion.

A pulsar inside a supernova would release energy by magnetic dipole radiation or its equivalent at an approximate rate[6]

$$L = 4\times10^{43} B_{12}^2 R_{10}^6 P_{\mathrm{ms}}^{-4} \times (1 + R_{10}^6 B_{12}^2 t/16 P_{\mathrm{ms}}^2\,\mathrm{yr})^{-2}\ \mathrm{erg\,s^{-1}} \qquad (1)$$

where P_{ms}, B_{12} and R_{10} are the initial period (in ms), the surface magnetic field (in 10^{12} G) and the radius (in 10 km) of the pulsar and t is the time since explosion. The time dependence assumes spindown by magnetic dipole losses only. A fraction of the pulsar luminosity might be used to accelerate protons deep inside the supernova shell. The maximum achievable proton energy in the pulsar wind shock model[5] is $E_p^{\max} \simeq 1.9\times10^6 B_{12} P_{\mathrm{ms}}^{-2}$ TeV. Charged particles with energy less than $E_{\mathrm{esc}} \simeq 10^7\, B_{12} u_9^{1/2}/\xi P_{\mathrm{ms}}^2$ TeV, where u_9 is the expansion velocity of the shell in units of $10^9\ \mathrm{cm\,s^{-1}}$ and $\xi > 1$ is a parameter characterizing the diffusion of accelerated particles (G. Auriemma, T.K.G. & P. Lipari, in preparation), are contained in the magnetic field of the shell and interact with the shell material. Neutral secondaries freely leave the shell. These include neutrons with energy $\gtrsim 1$ TeV, which do not decay before leaving the supernova shell. If a young pulsar is born in SN1987A and protons are accelerated to ultra-high energies, the phenomenon might be observed for the first time in very high energy and ultra-high energy (UHE) γ-rays and upward-going, neutrino-induced muons.

Although the acceleration might be (and is indeed expected to be) quite different for the two classes of objects, we can compare the UHE cosmic ray luminosity of SN1987A to that of the well-studied X-ray binary system Cyg X-3, another candidate for UHE proton acceleration[7,8]. The TeV γ-ray flux from Cyg X-3 is 4×10^{-11} TeV/E particles $\mathrm{cm^{-2}\,s^{-1}}$, which corresponds to a source proton luminosity of $\sim10^{39}\ \mathrm{erg\,s^{-1}}$. Such a luminosity could also be accommodated in supernovae containing pulsars with period smaller than 15 ms according to equation (1). If a young pulsar with $P \sim 1$ ms resides in SN1987A, luminosities of $(15/1)^4 = 5\times10^4$ Cygnus luminosity could be achieved for a duration of ~1 yr. The relative loss in luminosity from the fact that the Large Magellanic Cloud (LMC) is five times the 12 kpc Cyg X-3 distance is offset by the fact that the Cygnus accelerator has a duty cycle of only a few per cent[8]. Experiments are contemplated (one is already running in New Zealand) to observe this dramatic emission. For this experiment (JANZOS) to observe SN1987A at 10^{17} eV, it is sufficient to have a rate excess of about 10^3 over Cygnus luminosity, that is, $\sim10^{42}\ \mathrm{erg\,s^{-1}}$. We point out here that this much power is unlikely to be realized because the supernova luminosity in the 10^{15}–19^{17} eV energy range is constrained by the continuous cosmic ray (CR) flux at Earth.

An upper limit on the supernova luminosity in this range can be obtained from the assumption that the total CR flux between 10^{15} and 10^{17} eV is accelerated in young supernovae in our Galaxy. The observed energy flux of such particles at Earth is $7\times10^{-7}\ \mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}}$, which leads to a total energy content in the Galaxy of $\varepsilon_{\mathrm{CR}} = 3\times10^{-16}\, V_{\mathrm{cont}}$ erg, where V_{cont} is the effective containment volume of CR in our Galaxy.

The total contribution of young supernovae to the pool of galactic CR between 10^{15} and 10^{17} eV is $\varepsilon_{\mathrm{YSN}} = \nu\tau_{\mathrm{cont}}\Delta t f_n L_p$, where ν is the frequency of supernovae, τ_{cont} is the containment time of high-energy CR in the Galaxy, Δt is the time during which a typical supernova injects particles into the Galaxy, f_n is the fraction of the accelerated particles that are converted to neutrons with energies $>10^{15}$ eV, and L_p is the luminosity in accelerated protons $>10^{15}$ eV. The fraction f_n depends somewhat on the proton energy spectrum but is ~0.1. We estimate $\tau_{\mathrm{cont}} = 10^5$ yr (ref. 9), $\nu = 0.03\ \mathrm{yr^{-1}}$, $\Delta t = 3$ yr, and $V_{\mathrm{cont}} = 10^{67}\ \mathrm{cm^3}$. Then equating $\varepsilon_{\mathrm{CR}}$ and $\varepsilon_{\mathrm{YSN}}$ gives an upper limit $\nu_{30} L_p \leq 10^{41} V_{67}/\tau_5\ \mathrm{erg\,s^{-1}}$. Here ν_{30} V_{67} and τ_5 are the respective quantities in terms of our chosen estimated values.

There are large uncertainties in these estimated numerical values. Nevertheless the observed galactic CR spectrum places useful upper limits on the product of frequency and power of young supernovae that accelerate particles to energies $>10^{15}$ eV. Clearly, only a small fraction ($<1/100$) can do that with $L_p \simeq 10^{42}\ \mathrm{erg\,s^{-1}}$.

Indeed if this acceleration mechanism works we can turn the argument around and relate the observed CR spectrum above 10^{15} eV to the distribution of initial pulsar periods and magnetic field strengths. This will be a subject of a future paper.

Some other observations can be used to place indirect limits on the power L_p that might be expected from SN1987A. From the fact that no anisotropy of cosmic rays (due to photons) is observed in the direction of the galactic centre one can put a limit ~10 times Cyg X-3 luminosity during the 3 yr period of the experiment[10]. A somewhat weaker upper limit ($L_p \lesssim 10^{41}\ \mathrm{erg\,s^{-1}}$) is implied by the upper limit on neutrinos (upward muons) in deep underground experiments[11] from the direction of the centre of the Galaxy. The neutrino limits apply for a period of 1.5 yr during 1983–84. Recent limits on the pulsar contribution to the optical light curve of SN1987A (W. D. Arnett & S. Woosley; talks at George Mason University Supernova Workshop, October 1987) correspond very roughly to $10^{40}\ \mathrm{erg\,s^{-1}}$, assuming 10% efficiency for converting particle luminosity into visible light.

A luminosity of up to $10^{40}\ \mathrm{erg\,s^{-1}}$ in protons from SN1987A would be quite consistent with all these limits. If the output of SN1987A in ultra-high energy protons is of this order of magnitude, existing VHE and UHE γ-ray detectors in the Southern hemisphere will still be able to see fluxes from the supernova in the LMC provided the spectral index of the accelerated cosmic rays is <2.4. Were such an event to happen in the galactic centre, UHE γ-ray fluxes will of course be stronger by a distance factor of $(50/8)^2 \simeq 30$.

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