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SN1987A supernova: a black-hole precursor?

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The 11+8 neutrino events observed at Kamiokande[1] and IMB[2] detectors have been analysed by several authors[1–12]. The inferred total neutrino luminosity W_ν and its distribution among the various neutrino species, vary between the different analyses depending on the events included in the analysis, the parameterization of the neutrino spectra, the role played by ν_e–oxygen scattering, the distance of the Large Magellanic Cloud (LMC) and other aspects. Most authors find high total neutrino energy, in the range $W_\nu = 3$–6.7×10^{53} erg, and a large flux of prompt neutronization neutrinos $\Phi_{\nu_e}^{\rm prompt}\approx 10^{10}\,{\rm cm}^{-2}$. The Kamiokande collaboration[1] has quoted a value of $W_{\bar\nu_e} = 8\times10^{52}$ erg for the total $\bar\nu_e$ energy. This value is subject to uncertainties in the distance to the LMC, low statistics and other experimental and theoretical factors. From this value we have deduced[8] that $W_\nu \approx 6.7\times10^{53}$ erg which implies a gravitational energy release $\gtrsim 0.37\,M_\odot c^2$. This value is too high for a binding energy of a standard, $1.4\,M_\odot$, neutron star which means that a massive $M \gtrsim 2\,M_\odot$ neutron star or a black hole form. In the following we focus on lepton number conservation and the ensuing limitation on $\Phi_{\nu_e}^{\rm prompt}$. We show that an identification of the first two events in the Kamiokande data as ν_e prompt events requires a mass, $M \gtrsim 6\,M_\odot$, which implies a black-hole formation. This is also consistent with the probable identification of the progenitor[13] as a B3I supergiant of $\sim25 M_\odot$.

Several authors (refs 3, 10; A. Dar and S. Dado, personal communication) attribute the first two forward-directed Kamiokande events ($\theta_1 = 18\pm18°$, $\theta_2 = 15\pm27°$) to ν_e-e scattering. The probability that these events originate from $\bar\nu_e$-p reaction, or from ν-oxygen scattering with an isotropic distribution is, even using the higher limit for the angles, $P = p(\theta_1 \le 36°)p(\theta_2 \le 42°) = 0.012$. As these two neutrino events come within the first 0.1 s it is suggestive to identify them as prompt neutronization neutrinos generated via $e^- + p \rightarrow \nu_e + n$ during the collapse. (Thermalized neutrinos contain equal numbers of $\bar\nu_e$ and ν_e and interpreting the two events as thermal neutrinos scattering on electrons would require—due to the much larger $\bar\nu_e + p \rightarrow e^+ + n$ cross-section, about 50 isotropic events within the first 0.3 seconds[3]). The resulting energy in neutronization neutrinos is then $W_{\nu_e}^{\rm prompt} \approx (1.5\pm0.3)\times10^{53}$ erg with corresponding fluxes $\Phi_{\nu_e}^{\rm promt} \approx 1.2\pm0.2\times10^{10}\,\nu_e\,{\rm cm}^{-2}$ (with average energies $E_{\nu_e}^{\rm prompt} \approx 25$ MeV) are much higher than the predictions of the conventional model calculations involving a neutron star formation[3,10]. Thus if we insist on this natural identification of the first two events, a neutron star formation is inconsistent.

We would like to reinforce this argument in a model-independent way. The prompt neutrino flux is limited (due to lepton number conservation) by the number of electrons in the collapsing core. Numerical simulations[11] show that $\sim0.6\,\nu_e$ prompt per electron are obtained, but even when assuming a 1:1 ratio one still has $\Phi_{\nu_e}^{\rm prompt} \le (M_{\rm core}/M_\odot)\quad({\rm L}/50\,{\rm kpc})^{-2}\quad(0.2\times10^{10})$ $\nu_e\,{\rm cm}^{-2}$. Thus $\Phi_{\nu_e}^{\rm prompt} \approx 1.2\times10^{10}\,{\rm cm}^{-2}$ requires $M_{\rm core} \gtrsim 6\,M_\odot$ implying a black hole. This argument relies on two events and is therefore of limited statistical significance. For a canonical neutron-star mass of $1.4\,M_\odot$, one expects 0.25 prompt neutrinos and the Poisson probability of seeing two neutrinos $P = [(0.25)^2\,e^{-0.25}]/2 = 0.024$. A similar probability of 0.025 is obtained for a standard neutron star taking the first event to be a prompt ν_e and the second a $\bar\nu_e$ event. Even though these probabilities are small and may indicate a black-hole formation, they are not small enough to exclude completely a standard neutron star.

Here one should note that supporting evidence for a possible black-hole model is also supplied from arguments other than the lepton number conservation. The first is the already mentioned apparent high total neutrino energy[8]. The second is the probable identification of the SN1987A progenitor as Sk-69 202[13], a blue supergiant of spectral type B3I[14,15] implying[16] a mass $\sim25 M_\odot$. This identification is consistent with the observed lower than standard optical luminosity, the higher than standard expansion velocity and the light-curve time behaviour[17–19]. Simulations by Wilson *et al.*[20] indicate that progenitors with masses $\gtrsim 25\,M_\odot$ produce a massive iron core which upon cooling through neutrino emission followed by accretion, form a black hole on a time scale of a few seconds. In this connection it is interesting to note that a $25\,M_\odot$ progenitor[20] implies $W_{\bar\nu_e} = 11\times10^{52}$ erg (ref. 21) leading to $W_\nu = 9\times10^{53}$ erg. Therefore, such a progenitor is consistent with our seemingly high previous estimate[8] of W_ν. The third argument concerns the 7-s gap between the first eight and the last three events of the Kamiokande data. This may be due to a cooling of a neutrino sphere[11,12], however it has recently been argued[22] that it is unlikely that the last three events are the tail of a cooling process, thus suggesting other causes for this gap. For example, a late

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accretion phase, or a rotating collapse leading to two neutron stars which eventually coalesce[23,24]. In these cases a black hole is a probable outcome.

Even though a black-hole outcome seems to be favoured we cannot rule out a standard neutron-star formation. If indeed a neutron star will eventually be inferred from X-ray observations (within the next couple of years), very important hints concerning novel particle physics features of neutrinos can be deduced[8]. We need to minimize effects which diminish W_{ν}^{total} and/or $\Phi_{\nu_e}^{\text{prompt}}$. A ν_e magnetic moment $>10^{-14}\ \mu_e\ (10^{12}\ \text{gauss}/B)$ where B is the magnetic field near the core reduces, by mixing sterile right-handed neutrinos, both W_ν and $\Phi_{\nu_e}^{\text{prompt}}$ by a factor of two. MSW[25,26] or vacuum ν-mixing can enhance the detectability of the thermal component[4,5] but reduce $\Phi_{\nu_e}^{\text{prompt}}$ by mixing ν_μ or ν_τ into the initial pure ν_e neutronization neutrinos. A feature which ameliorates the W_ν problem by enhacing the total $\bar{\nu}_e$ signal and also enhance somewhat $\Phi_{\nu_e}^{\text{prompt}}$ is ν_τ, ν_μ decays, that is $\nu_\tau \rightarrow \nu_e + M^0$ $\nu_\mu \rightarrow \nu_e + M^0$ with M^0 an unobserved majoron[8].

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Photon–photon pair production and the opacity of SN1987A to TeV and PeV γ-rays

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Supernovae have long been considered as likely sites of cosmic-ray acceleration. Interaction of newly accelerated cosmic-ray nuclei with target material within the expanding supernova is expected to produce an observable flux from SN1987A of very high-energy and possibly ultra high-energy γ-rays in the TeV and PeV (10^{15} eV) ranges, and several experiments are being constructed to detect this radiation. The presence of intense infrared emission from the supernova itself will, however, make some regions of SN1987A opaque to TeV and PeV γ-rays due to pair-production interactions. Observations at these energies, combined with a knowledge of which regions of SN1987A could be contributing γ-rays may thus give information about the nature and location of particle accelerators in supernovae. Here I discuss the important question of photon–photon pair-production interactions and calculate from which regions of SN1987A may be observed TeV and PeV γ-rays.

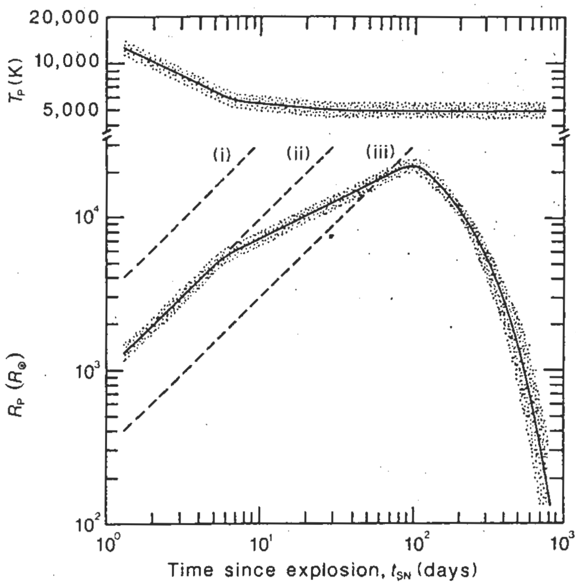

Fig. 1 Approximate photospheric radius and temperature of SN1987A based on observations and expected behaviour (see text). Dashed lines indicate shells expanding ballistically at (i) 25,000 km s^{-1} (fastest material detected), (ii) 8,000 km s^{-1} (shell containing most of the matter), and (iii) 2,400 km s^{-1} (probable boundary between H envelope and He layer).

Because of the relatively close location of SN1987A in the Large Magellanic Cloud[1] (LMC), if only a small fraction of the $\sim 10^{51}$ erg released during a typical type II supernova explosion[2,3] were converted to very energetic particles then SN1987A could be observable at TeV energies with existing southern hemisphere detectors. Several possible mechanisms for acceleration in supernovae are discussed in ref. 4. If $\sim 10^{39}$ erg s^{-1} was used to accelerate protons with a spectrum extending up to 10 TeV then the supernova could be observable even now above 1 TeV (ref. 5). If the particle spectrum extends beyond 10 PeV then existing air shower experiments might also detect the supernova and data from the Buckland Park air shower array[6] at Adelaide have been examined for a burst of PeV γ-rays arriving within a short time interval of the observed neutrino burst[7,8]. This search is continuing for delayed PeV emission from SN1987A.

From mid-latitudes SN1987A is viewed at large zenith angles and this increases the effective energy threshold of a typical air shower array to >1 PeV. Interaction of γ-rays with photons of the cosmic microwave background radiation, however, severely reduce the flux of γ-rays from LMC at energies $\gtrsim 10^{14}$eV (see ref. 9 and refs therein). Air shower observations from particle arrays at much more southerly latitudes and higher altitudes, such as from the particle array under construction at the South Pole[10,11], making observations possible at 10^{14} eV, or below, are therefore highly desirable. To observe ultra high-energy γ-rays from SN1987A, new particle detectors are being installed at Mount Chacaltaya, Bolivia, and by a Japan–New Zealand–Australia collaboration in New Zealand, but it is doubtful whether their energy thresholds for air showers from SN1987A will be much <1 PeV.

Observations were carried out by the Adelaide group in April 1987 using the White Cliffs Solar Power Station[12], Australia, as a γ-ray telescope operating at ~ 5 TeV and these will resume in September; attempts are being made to speed up development of a new telescope to be located at Woomera[13], Australia. Other detectors which may be used to search for γ-ray emission from SN1987A are the University of Durham telescope[14] at Narrabri, Australia, and the telescope of Potchefstroom University[15], South Africa, both of which operate in the TeV energy range.