# Evidence for Strange Matter in Supernovae?

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With the aim of overcoming the present energetic difficulties in getting type-II supernova explosions, we present a possible scenario based on strange-matter formation. The observational expectations of this picture are discussed and the predictions of the model for SN 1987A neutrinos and remnant pulsar are examined.

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There are two currently favored models proposed to explain type-II supernova explosions[1] (SNII): the prompt-shock and the delayed-shock (neutrino heating) mechanisms. Neither one has been conclusively successful in explaining these spectacular events.

The prompt-shock model[2] is based on the hydrodynamical bounce of infalling matter after core collapse of the star. It has been recently proved[3] that in order to get an explosion able to account for the observed events we have to introduce an equation of state (EOS) for supranuclear densities much softer than the widely believed one. It appears as if the use of the current values for the physical ingredients needed by the model will surely make the shock fail.[4] The actual softness of the nuclear EOS at these extreme regimes is now being intensively investigated by a number of groups, but up to now there is no agreement about the value of this crucial property.

In the delayed mechanism[5] the stalled prompt shock is heated by an intensive neutrino flux coming from the collapsed core, which revitalizes the shock and produces the explosion. This mechanism is strongly dependent on the neutrino transport scheme and it has not been confirmed by all workers.[1] Moreover, even if successful it seems to provide much weaker explosions than the observed ones.[5]

The situation is clearly controversial and there is no final word either in favor or against each mechanism. The simulation of these events is one of the most difficult problems of theoretical physics, perhaps obscuring the correctness of one of the models cited above. However, the present problem might also indicate the incompleteness of the physics included in the simulations, especially when the core gets densities above the nuclear-matter saturation one ($\rho_0$). It is the most important and poorly known stage of its evolution.

In this Letter we discuss some observational consequences of a model for SNII driven by strange-matter (SM) formation,[6] some of them very different from those predicted by the models cited above.

At the moment of bounce we have, according to current simulations, a central density of $(2\text{-}3)\rho_0$ inside the hot and lepton-rich proto-neutron star (proto-NS). While this object is cooling by neutrino emission it suffers a substantial contraction almost reaching its final configuration in a short time (of $\sim$ seconds).[7]

Let us assume that the quoted neutrino emission avoids a recollapse but is unable to produce the ejection of the outer layers of the star. At these moments the core of the proto-NS reach densities for which it is conceivable that a high-strangeness quark-gluon plasma (known as "strange matter") could appear. It is now also believed that this form of deconfined QCD phase might even be energetically preferred[8] to $^{56}$Fe, a possibility that is certainly not excluded by preliminary calculations.[9] Several works following the original suggestion of Witten lend support to the idea that SM might be very important to an understanding of a variety of observations, such as $\gamma$-ray-burst transients[10] and Centauro events,[8] and (more importantly in our case) provides a new hypothetic energy source inside the collapsed core of a SNII.

A number of ways by which a SM seed could appear in a high-density medium has been discussed in Ref. 11. A proto-NS core is a particularly favorable environment for this deconfinement to occur spontaneously, through a variety of fluctuations,[12] or even triggered by strangelets (SM droplets) already present in the pre-SNII star.[13] Once formed, the SM will begin to swallow the nuclear matter in the surroundings because it is, by hypothesis, a lower-energy state. While it has been proposed[12,14] that the combustion corresponds to the slow mode, subsequent work[15] shows that this mode appears to be hydrodynamically unstable and thus it could not occur in these conditions. The conversion of nuclear matter should thus proceed in a *detonation* mode. It is precisely a certain amount of the liberated energy cast into a detonation wave that can be crucial for the ultimate fate of the collapsed star. Some simplified calculations[6] based on this model show that the detonation wave typically carries few foe (1 foe$=10^{51}$ ergs) of energy, depending on the bagged QCD parameters, which is the correct order of magnitude expected for the energetics of a SNII event.[16]

It is worthwhile to note that the propagation of this detonation is easier in an environment filled by chargeless particles: They are easily swallowed when they fall onto the burning front as they do not feel a Coulomb barrier.[8] This constraint sets the time scale at which the detonation is likely to occur. At the time of bounce the matter still has an important fraction of charged particles ($Y_e \sim 0.3$), but after some seconds the neutronization is almost complete,[7] and the collapsed core reaches these favorable conditions.

An important feature of the emerging picture is that the referred detonation does not reach the edge of the compact core, but instead becomes a standard shock from some point $R_c$ outwards, due to the fact that there is a minimum density below which the physical state of matter does not allow the fulfillment of the detonation conditions.[6] For example, for BJ1 nuclear-matter EOS,[17] the minimum density is $\rho_c = 1.859\rho_0$ if the current value $B = 60$ MeV fm$^{-3}$ is adopted for the bagged QCD constant. The later evolution of the core is determined by the fact that the Reynolds numbers are indeed very high $\sim 100$ msec after the hydrodynamical bounce.[15] Thus, we would get a quick intermixing of the strange and nuclear fluids ending with a complete conversion of the core, which may be now called a proto-strange star (proto-SS). The temperature of the just formed SM can be estimated[18] considering the remaining core as isothermal (a good approximation due to the high thermal conductivity of SM) from the equation $\Delta Q = \int Cv\, dT$. Using the $Cv$ of Ref. 19 and assuming $\Delta Q \sim 20$ MeV, $\rho \sim (4\text{-}5)\rho_0$ we obtain the value $T \sim 20$ MeV. Of course this value does not imply that we should expect a neutrino spectrum signal associated with the detonation at such high temperatures.[18] As an example we can look at the calculations of Ref. 7 where it is shown that the core temperature increases even while the neutrino mean energy shows a monotonous decrease. Only detailed models can provide us with a reliable relationship between these quantities.

Let us discuss in some detail the expected neutrino signature from the SM appearance inside the core. The main reactions producing neutrinos in SM are[11]

$$d \rightarrow u + e^- + \bar{\nu}_e\,, \qquad u + e^- \rightarrow d + \nu_e\,,$$

because they are proportional to $\cos^2\theta_C \sim 0.97$. In addition, as the released energy produces chiefly a significative temperature increase, we should have a large thermal neutrino background of all flavors. This would lead to a significant enhancement of neutrino emission.

All of the above considerations can be applied to the case of SN 1987A to see to what extent they are consistent with the observed neutrino signals. The outstanding simultaneous observations of the Kamioka and Irvine-Michigan-Brookhaven (IMB) groups[20] have been intensively analyzed by many authors.[21,22] Because IMB samples the high energy of the distribution, which provides poorer[21] estimations of the extracted quantities, we shall concentrate only on the Kamioka data. This sample shows an apparent bunching in time that could be the result of a few events statistics, but some authors[22] attribute it to an unexpected physical origin. The first neutrino bunch is concentrated in a time interval of $\sim 2$ sec and there is a second one of three neutrinos after a hiatus of $\sim 7$ sec which lasts $\sim 3$ sec. In terms of our model this bunching should be interpreted as follows: The first one is associated with the deleptonization from a proto-NS formed after the emergence of the prompt shock. The hiatus should correspond then to the necessary time to achieve a full neutronization which can make SM form and eases the subsequent propagation of the phase change front. The "late" Kamioka events should thus be interpreted as arising from the deleptonization of the just formed proto-SS.

Quantitatively we can estimate the emission temperature associated with this last bunch following a current approach. We shall employ a Fermi-Dirac expression with zero chemical potential for the neutrino continuum spectra, and infer the effective emission temperature from the mean energy of the late detected neutrinos. We obtain, correcting for detection efficiency and threshold effects, the value $T_{\rm eff} = 1.78^{+0.71}_{-0.51}$ MeV. This temperature in turn implies a total neutrino energy of $\sim 10$ foe carried approximately in equal amounts by the six known neutrino flavors. This last value matches the prediction for the radiated energy in neutrinos that should be nearly equal to the binding energy difference between the proto-NS and the SS. $\Delta E_B = \Delta Q N$, where $\Delta Q$ is the released energy per converted particle ($\sim$10–20 MeV) and $N$ is the total number of converted particles ($\sim 10^{57}$). We note that the deconfinement driven shock holds a comparatively high percent of the total energy released by this process, contrasting to the prompt shock which carries only $\sim 1\%$ from the energy released in the proto-NS formation.

One might naturally wonder why if Kamioka detects late events IMB does not see them at all. We may estimate the expected late events at the IMB counter as

$$n_{\rm IMB} = 2.3 \times 10^{-3} \left(\frac{\epsilon_{\bar{\nu}_e}}{1\ \text{foe}}\right) \left(\frac{\langle\sigma\rangle}{10^{-44}\ \text{cm}^2}\right) \left(\frac{M_D}{5\ \text{kton}}\right) \left(\frac{t_{\rm eff}}{1\ \text{MeV}}\right)^{-1} \left(\frac{D}{50\ \text{kpc}}\right)^{-2},$$

where $\langle\sigma\rangle$ is a temperature-averaged cross section, $M_D$ is the detector mass, $D$ is the distance to the Large Magellanic Cloud, and $\epsilon_{\bar{\nu}_e}$ is the total energy emitted in $\bar{\nu}_e$ neutrinos. Using the values $D = 50$ kpc and $M_D = 5$ kton we obtain a prediction of $n_{\rm IMB} = 0.16$ associated with these late events, showing that it is not surprising to have no events which can signal the referred phase transition. However, in spite of the apparent matching obtained using this model the neutrino observations from SN 1987A alone are insufficient to be considered as evidence in favor of it. Clearly, we must wait for a galactic SNII and/or greatly improved neutrino telescopes in order to get firm experimental arguments.

The sketched model allows us to foresee some other physical consequences. One is the production and ejection of strangelets,[13] suggested to be excellent candidates for Centauro event primaries.[8,23] Since it has been shown that all primordial strangelets must have already decayed today,[24] contemporary production is needed to supply the primaries flux of about $10^{-2}$ $m^{-2}yr^{-1}$ onto the Earth. The strangelets ejection could proceed as outlined in Ref. 13, providing a spectrum of Centauro primaries. These charged strangelets could be further accelerated by recently proposed mechanisms[25] in supernova remnants. While detailed modeling remains to be done, it seems remarkable that the SM occurrence to SNII's can potentially give a natural explanation for the Centauro-primaries source, while other less frequent physical events might also contribute.[8]

Another bonus of this model is related to the heavy isotopes born in SNII events.[1] Up to now, the necessary fine-tuned conditions for production and ejection of neutronized heavy isotopes beyond the iron peak (a feature shared by $M > 20M_\odot$ stars) leave little room for an easy explanation of the observed abundances. The narrow zones where these heavy isotopes are thought to be produced by means of the $r$ process at densities $\sim 10^{10}$ g cm$^{-3}$ cannot be ejected unless unlikely strong prompt shocks occur.[26] We conjecture that a detonation starting deep inside the core could eject all the matter from some separation radius at the edge of the compact core on, helping then to overcome this problem in a completely new fashion.

Finally, it is worthwhile to remark that in this scenario the SNII compact remnant is a SS, not a NS. Moreover, if it is correct NS's should not exist. The structure of these new objects has been discussed by many authors.[11,27] It has been shown that for models between $1M_\odot$ and $2M_\odot$ the radius and gravitational red shifts are almost indistinguishable from those expected for a NS, but have profound differences regarding their outer layers' structure and properties. It has been argued that the presently accepted SS structure is at odds with the formation of a magnetosphere[11] and could not explain the glitch phenomenon.[28] However, if some bound states of SM in fact exist (some of which have been recently proposed[29]) it is conceivable that their inclusion in SS models can help to overcome these objections.[30] Interestingly, there has already been a possible identification of a strange compact remnant from a supernova explosion: the young supernova remnant N49 in the Large Magellanoc Cloud where the ultraenergetic 5 March 1979 $\gamma$-ray burst has been detected.[31] There is a model[10] for this event consisting of a SS struck by a small lump of SM (a NS is not likely to be able to account for this emission). If we accept the remnant-$\gamma$-ray-event association and the SS-projectile model, then we should conclude that the compact remnant associated to N49 is a SS, as predicted by this picture.

After the completion of this work we become aware of the discovery of an unexpectedly fast pulsar in the remnant of SN 1987A.[32] The reported rotation rate ($\Omega = 1968.629$ Hz) is at least 3 times faster than the fastest pulsar known up to now, implying in turn that the structure of the underlying object that produces the emission does not correspond to any realistic known neutron-matter EOS in the mass range around $1.4M_\odot$[33] currently expected from formation considerations. In fact, there are stiff EOS models that can support such a rotation state but only for large masses ($M > 2M_\odot$). On the other hand, the soft EOS that could also explain this observation is not successful if required to explain simultaneously, for example, the binary pulsar 1913+16 mass (or even worse the more massive pulsar 4U0900−40) in the weakly rotating limit. This may indicate that neutron matter behaves completely different than previously expected, or than the compact object is made up of some other material. The natural alternative resulting from the presented model is that SN 1987A pulsar is also a SS. One might indeed conjecture that SM could support a rotation rate like the observed one because, in addition to the gravitational binding, there is an important contribution to the total binding due to strong interactions (that even dominates the structure for small-mass SS's as pointed out in Ref. 27). We must require the angular velocity of the pulsar to be less than the Kepler frequency $\Omega_k$ (corresponding to a particle in a circular orbit at the equator of the star). The value $\Omega_K$ is an absolute upper limit for a uniformly rotating object.[33] Because of the very different mass-radius relationship that holds for relatively low-mass SS's ($M \propto R^3$ which follows from $\rho \sim 4B$ in these models,[11,27] a substantially different behavior than that of NS's (where $M$ is a complicated decreasing function of $R$) concerning rotation can be expected. For example, in the Newtonian limit we have $\Omega_K \propto B^{1/2}$ independent of the radius $R$. The ability of SS's to support high rotation rates must be confirmed by performing fully relativistic, rapidly rotating structure calculations and the important analysis of the stability of nonaxisymmetric modes. If stability of SS's at these rotation rates is proved and no other physical picture of a compact star sharing these features arises, the observation of the SN 1987A pulsar might provide firm evidence about the plausibility of the presented model.

In our opinion, the SM appearance might close the global understanding of the evolution of massive stars: From their birth to death, these stellar objects undergo a chain of quantum tunnelings ending at the matter absolute energy minimum. We believe that a refined SNII theory based on this hypothesis would have a good chance for successfully accounting simultaneous observational data in this field.

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[1] S. E. Woosley and T. A. Weaver, Annu. Rev. Astron. Astrophys. **24**, 205 (1986).

[2] G. E. Brown, H. A. Bethe, and G. Baym, Nucl. Phys. **A375**, 481 (1982).

[3] E. Baron, J. Cooperstein, and S. Kahana, Phys. Rev. Lett. **55**, 126 (1985).

[4] A. Burrows and J. M. Lattimer, Astrophys. J. Lett. Ed. **318**, 288 (1987).

[5] H. A. Bethe and J. R. Wilson, Astrophys. J. **295**, 14 (1985).

[6] O. G. Benvenuto, J. E. Horvath, and H. Vucetich, Int. J. Mod. Phys. A **4**, 257 (1989).

[7] A. Burrows and J. M. Lattimer, Astrophys. J. **307**, 178 (1986).

[8] E. Witten, Phys. Rev. D **30**, 272 (1984).

[9] E. Farhi and R. L. Jaffe, Phys. Rev. D **30**, 2379 (1984).

[10] C. Alcock, E. Farhi, and A. Olinto, Phys. Rev. Lett. **54**, 2088 (1986).

[11] C. Alcock, E. Farhi, and A. Olinto, Astrophys. J. **310**, 216 (1986).

[12] G. Baym *et al.*, Phys. Lett. **160B**, 181 (1985).

[13] O. G. Benvenuto and J. E. Horvath, Mod. Phys. Lett. (to be published).

[14] A. Olinto, Phys. Lett. B **192**, 71 (1987).

[15] J. E. Horvath and O. G. Benvenuto, Phys. Lett. B **213**, 516 (1988).

[16] This value is estimated to be ~2 foe for SN 1987A in W. D. Arnett, Astrophys. J. **319**, 136 (1987).

[17] H. A. Bethe and M. B. Johnson, Nucl. Phys. **A230**, 1 (1974).

[18] T. Hatsuda, Mod. Phys. Lett. **2**, 805 (1987).

[19] N. Iwamoto, Ann. Phys. (N.Y.) **141**, 1 (1982).

[20] K. Hirata *et al.*, Phys. Rev. Lett. **58**, 1490 (1987); R. M. Bionta *et al.*, Phys. Rev. Lett. **58**, 1494 (1987).

[21] J. M. Lattimer, Nucl. Phys. **A478**, 199c (1988).

[22] S. W. Bruenn, Phys. Rev. Lett. **59**, 938 (1987); K. Sato and H. Suzuki, Phys. Rev. Lett. **58**, 2272 (1987).

[23] J. D. Bjorken and L. McLerran, Phys. Rev. D **20**, 2353 (1979).

[24] C. Alcock and E. Farhi, Phys. Rev. D **32**, 1273 (1985).

[25] R. Blandford and D. Eichler, Phys. Rep. **154**, 1 (1987).

[26] W. Hillebrandt, in *Progress in Particle and Nuclear Physics*, edited by A. Faessler (Pergamon, New York, 1986), Vol. 17, p. 215.

[27] P. Haensel, J. L. Zdunik, and R. Schaeffer, Astron. Astrophys. **160**, 121 (1986).

[28] M. A. Alpar, Phys. Rev. Lett. **58**, 2152 (1987).

[29] F. C. Michel, Phys. Rev. Lett. **60**, 677 (1988); H. Lipkin, Phys. Lett. B **195**, 484 (1987).

[30] O. G. Benvenuto, J. E. Horvath, and H. Vucetich (to be published).

[31] W. D. Evans *et al.*, Astrophys. J. Lett. Ed. **237**, 7 (1980).

[32] J. Middleditch *et al.*, International Astronomical Union Circular No. 4735 (1989).

[33] J. L. Friedman, J. R. Ipser, and L. Parker, Astrophys. J. **304**, 115 (1986).