WHITE DWARF ORIGIN OF SN 1987a

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ABSTRACT

We argue that the recently discovered supernova in the Large Magellanic Cloud represents the transition of a white dwarf to a neutron star in a binary system. The rapid rise to maximum light, the very subluminous nature and reports of the detection of neutrinos from the event are fully consistent with the proposed model.

Inspector Gregory	: Is there any other point which you would wish to draw my attention?
Sherlock Holmes	: To the curious incident of the dog in the night time.
Inspector Gregory	: The dog did nothing in the night time.
Sherlock Holmes	: That was the curious incident.

SILVER BLAZE

I. INTRODUCTION

THE recent supernova SN 1987a in the Large Magellanic Cloud is very unusual in several aspects:

(i) When it was discovered on 24 February 1987 it was brightening very rapidly (about 0.5 magnitude in 5 hours) and had probably brightened by at least ~ 8 magnitudes since the previous night[1]. The maximum magnitude of 4 was reached within 2 days of the discovery[2]. In fact if the reports of the detection of neutrinos from the supernova on 23 February by the Italian–Soviet team[2a] and the Japanese is confirmed, then one can assert that the light maximum was within 2–3 days of the explosion. This rapid rise should be compared with the typical rise time of a week to 15 days.

(ii) It is a very subluminous supernova—the absolute magnitude at light maximum was only -14.7 mag. This is to be compared with $M_v = -19.7 \pm 0.8$ for Type I supernovae and $M_v = -19 \pm 1.4$ for Type II supernovae[3].

(iii) It is not yet established whether it is a Type I or Type II supernova. The presence of hydrogen in the Spectrum[4] suggests that it may be a Type II SN, although a very subluminous one. However, the velocity of the Hα absorption feature is $\sim 17{,}000$ km s^{-1}, which is about a factor of two larger than in a typical Type II supernova. Also very strong emission lines corresponding to Hα and Hβ are seen and their strength was increasing during February 25.0–26.1.

(iv) This supernova has been very "subluminous" in the radio wavelength also. Based on the radio luminosities of the recent supernovae[5], the radio flux from SN 1987a should have been in the range of 30–3000 Jy at 5 GHz. However, the maximum flux observed was only 100 mJy at 843 MHz, 1.4 GHz and 2.3 GHz[6]. Interestingly, the maximum flux was observed on 26 February when the optical continuum appears to have reached the maximum.

In this note we wish to suggest a scenario for this very unusual supernova.

II. THE STANDARD MODELS

The most popular model at present[3] for a Type I SN is a C–O white dwarf accreting from a companion in a binary. The companion could be a main sequence star or another degenerate dwarf. Under suitable conditions the mass of the accreting white dwarf will grow to 1.4 $M_\odot$ and when this happens carbon ignites resulting in the disruption of the white dwarf. Several observed properties of Type I supernovae are in reasonable agreement with the predictions of this model.

The progenitors of Type II SN are believed to be massive stars[3]. In these stars a degenerate iron core forms at the centre, and when the mass of this core reaches the Chandrasekhar Limit it collapses in a dynamical timescale. This results in the formation of a neutron star and the expulsion of the extended, hydrogen-rich envelope in an explosive manner.

Clearly, neither of these standard models is a satisfactory starting point for the supernova under discussion.

III. REQUIREMENTS OF THE MODEL

Any model of this supernova should explain the rapid rise to maximum light and the subluminous nature. Both these are consistent with much less mass ejected than in standard supernovae. This may be seen as follows:

Diffusion theory predicts[7] that the maximum luminosity will be reached approximately when the photon diffusion length is about one third the radius of the expanding sphere. This implies that the photon diffusion velocity should be one third the expansion velocity of the surface:

$$V_{\text{diff}} = \tfrac{1}{3} V_s. \tag{1}$$

In a time t the photons would have diffused through a length R_{ph} given by $R_{\text{ph}}^2 = Dt$, where D is the diffusion constant. Substituting $D = lc/3$, where l is the mean free path of the photon and c is the velocity of light, one gets

$$\frac{R_{\text{ph}}}{l} = \frac{1}{3}\frac{c}{V_{\text{diff}}} = \frac{c}{V_s}. \tag{2}$$

Here R_{ph}/t has been identified with the diffusion velocity. The above equation essentially says that the radius of the photosphere, measured in units of the mean free path of the photon, is c/V_s. The mean free path l is related to the density ρ through the usual relation

$$l = (\kappa\rho)^{-1}, \tag{3}$$

where κ is the mass absorption coefficient (the Compton opacity in the present case). Combining equations (1)–(3) one can express the mass in the expanding sphere in terms of the radius of the surface *at the time of the light maximum* as follows

$$\begin{aligned} M &= \frac{4\pi}{3}(\rho R_s) R_s^2 \\ &\sim \frac{4\pi}{\kappa}\left(\frac{c}{V_s}\right)^2 R_s^2, \end{aligned} \tag{4}$$

where R_s is the radius of the expanding surface at light maximum. Thus, the rise to the maximum in three days as opposed to the typical ten to fifteen days implies that the mass ejected must be ~ ten times *less* than in a typical supernova.

It was mentioned in the introduction that if this supernova is of Type II, as suggested by the presence of hydrogen, then the expansion velocity is almost a factor of two larger than what is normally observed. This, again, fits in with the mass ejected being only a fraction of a solar mass.

Another unusual feature of SN 1987a is that hydrogen has been seen in emission and the strength was increasing within two days after the explosion. Since emission lines will be seen only after the emitting region becomes optically thin, this is also in agreement with an unusually small amount of mass ejected. It might be remarked that the strength of the Hα emission line (for example) is not inconsistent with the above remark. It will be recalled that the line to continuum intensity ratio in Hα is very large for Novae though the mass ejected $\sim 10^{-5} M_\odot$.

A rapid rise to maximum luminosity is also consistent with the supernova being subluminous. Given that the black body temperature of the continuum is roughly the same for most supernovae[3], the luminosity at maximum will scale as the surface area of the photosphere, i.e. as t_{max}^2. Thus, the fact that SN 1987a is subluminous by about four magnitudes, is in agreement with the maximum in light occurring ~ 3 days after the explosion.

Besides the low mass in the ejecta, the other important fact to be borne in mind while constructing a model is the detection of neutrinos. This detection, if confirmed, is perhaps a strong signature that a neutron star has been born in the supernova event!

In the next section we present a model in which the above two features appear naturally.

IV. SN 1987a: ACCRETION-INDUCED COLLAPSE OF A WHITE DWARF

We wish to suggest that the subluminous supernova in LMC represents the transition of a white dwarf to a neutron star in a binary system. This scenario first suggested by Whelan and Iben[8] has been invoked by several authors to explain the observed properties of the recently discovered binary pulsars, in particular the two millisecond pulsars in binaries[9, 10].

Whether or not an accreting white dwarf in a binary will collapse to form a neutron star depends on several factors[9]: (i) the composition of the white dwarf (ii) the accretion rate (iii) the initial mass of the white dwarf etc. It is generally believed that C–O white dwarfs will evolve to degenerate carbon ignition resulting in its disintegration. On the other hand, stars in a narrow mass range (around 10 $M_\odot$) will produce bare O–Ne–Mg white dwarfs. If these are able to grow in mass they can collapse to form a neutron star.

The accretion rate is probably the most important factor that determines whether or not the white dwarf will grow to the Chandrasekhar mass. If the accretion rate is $< 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$ the accreted matter is likely to be blown off in Nova eruptions. Higher accretion rates are required for a net growth in mass. This is possible in a fairly wide binary.

van den Heuvel has argued[9] that in wide binaries ($P \gtrsim 0.5$ d) in which the companion is $\sim 1\ M_\odot$ and in which the mass transfer is driven by the nuclear evolution of the normal star, the accretion rate will satisfy the above criterion. Accretion from the stellar wind of a non-Roche lobe-filling companion is also possible, but since low mass stars do not have strong winds it would have to be a red supergiant. But as we will argue later, the low radio luminosity of SN 1987a suggests that the accretion was not from a wind. The evolution of binaries in which the mass donor is a low-mass giant has been studied extensively by Webbink *et al*[11] and Taam[12]. It is clear from their studies that given the right initial orbital parameters it is easy to obtain self-stabilizing mass transfer at a high rate. van den Heuvel has argued that the binary pulsars PSR 0820+02 and PSR 1953+29 were born in such accretion-induced collapse of white dwarfs. The 5.4 ms pulsar (PSR 1855+09), also in a binary, may have had a similar birth.

V. COMPARISON WITH OBSERVATIONS

What are the predictions of such a scenario and how do they compare with the observations of SN 1987a?

(a) In the model proposed above the formation of a neutron star is the cause of the supernova. This is consistent with the reports of the detection of neutrinos on 23 February.

(b) The mass ejected is expected to be very small 0.1–0.2 $M_\odot$. This would result in a subluminous supernova. Also, the maximum in light would be reached much more rapidly than in standard supernovae in which one to several solar masses are ejected.

(c) Since part of the blown-off matter will be unprocessed accreted matter, the spectrum will show hydrogen.

(d) *Radio emission*: Basically two models have been proposed for radio emission. According to Pacini and Salvati[13] and Bandiera *et al*[14] the observed radiation is from a mini Crab nebula produced by the central pulsar. On the other hand, Chevalier[15] has suggested that the radio emission results from the interaction of the ejecta with the circumstellar gas. The latter model has gained a little more credence since radio emission has been detected from two type I supernovae which are not expected to produce pulsars. If one accepts the model due to Chevalier, then the very low radio luminosity of SN 1987a is easily understood in the scenario outlined in the last section. If the mass transfer onto the white dwarf is due to Roche lobe overflow driven by nuclear evolution, then one does not expect much circumstellar matter, and consequently very little radio radiation. In this connection it is worth remarking on the suggestions made[2,16] that a 12th magnitude star of spectral type B3I may have been the presupernova star. In our opinion the rapid rise of the light curve and the subluminous nature is inconsistent with a massive star being the progenitor of SN 1987a. It is equally unlikely to be the mass-donating binary companion of the white dwarf that collapsed. If it were, then one expects considerable amount of circumstellar matter. This is not consistent with the low radio luminosity if Chevalier's model is correct.

VI. DISCUSSION

We have suggested that the recent supernova in LMC (SN 1987a) is one of those rare events in which a white dwarf in a low mass binary is pushed over the Chandrasekhar Limit, resulting in the formation of a neutron star. The observed optical and radio properties of this supernova are in good agreement with this model. We summarize below some of the predictions that follow naturally from this model:

(a) What will be the characteristics of the new born neutron star? The only thing one can say with confidence is that it will be quite hot! It has been argued by several people that the surface layers of the neutron star will cool to $T \sim 10^9$ K in a few thousand seconds[17]. Such a hot star will be a copious emitter of thermal x-rays and gamma rays which should be easily detectable. In the early days the x-ray flux will be highly attenuated by photoelectric absorption in the supernova ejecta. But as the ejecta expands the column density of the absorbing atoms will decrease (column density $\propto 1/t^2$ in the free expansion phase) and the x-rays should soon be easily detectable. In fact, continued x-ray observations will give us a unique opportunity to monitor the cooling of this very young neutron star.

(b) Will this neutron star be functioning as a pulsar? Most likely it will be, although it may not necessarily be beamed towards us. Whether or not there is pulsar activity depends on the spin period and the magnetic field. If the magnetic field of the white dwarf was $\sim 10^6$ G then the neutron star will be endowed with a field $\sim 10^{12}$ G. Even though the majority of white dwarfs have fields $\sim 10^5$ G, a few per cent do have much stronger magnetic fields. In any case, if PSR 0820+02 was born this way then it provides indirect support to the conjecture that this pulsar, too, will have the canonical field.

Let us now turn to the spin period of the young neutron star. There is mounting evidence that the majority of pulsars are born as slow rotators[18]. This might be because angular momentum may be lost to the envelope, and this may, indeed, be responsible for the supernova explosion[19]. But in the case of a neutron star born from the collapse of a white dwarf, the spin period will be determined by the angular momentum of the white dwarf prior to collapse. The rotation period of a white dwarf in a binary will be determined by two competing mechanisms. The first is the tidal torque due to the companion and the second is the spin-up of the white dwarf due to the accretion of matter which brings with it specific angular momentum. A rotation period ~ 2 hours will result in a neutron star with a period of ~ 10 milliseconds. If tidal torques were not present then accretion will spin-up the white dwarf to an equilibrium period determined by the accretion rate and the magnetic field[20]. An accretion rate $\sim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ and a magnetic field $\sim 10^6$ G will result in an equilibrium period ~ 200 s. Thus it seems quite plausible that the white dwarf was spinning fast enough to give birth to a fast pulsar.

(c) If the above conjecture is true then there may be a good chance of detecting optical pulses from it. If the Crab Pulsar were placed at the distance to LMC then the peak brightness will be ~ 21 mag. The optical pulses from this young pulsar could be even brighter than this. It would also be worth looking for x-ray pulses.

(d) In the scenario presented above, the pulsar will still be in a binary and since the mass ejected is expected to be only $\sim 0.1\ M_\odot$ the orbit will be very nearly circular. Concerning the orbital period, one can only say that it will be $\gtrsim 1$ day. Curiously, the ultimate fate of such a pulsar depends on its present orbital period. If it is ~ 100 days then it will evolve to be another PSR 0820+02. On the other hand, if the present orbital period is $\sim$ a few days then it will find its peace eventually as a millisecond pulsar. It might be mentioned that even if the neutron star is not functioning as a pulsar the existence of the binary may be inferred if the companion could be detected.

(e) We do wish to draw attention to one possible reason why the neutron star may not function as a pulsar even though it might be spinning fast and is endowed with a strong field. This will happen if the companion star continues to transfer mass. If the accretion rate onto the neutron star is sufficiently large then it can suppress the mechanism by which relativistic particles are produced, and there will be no "pulsar activity". If the mass transfer is weak then the pulsar itself may not be "smothered", but the radio radiation from it may be absorbed by the matter surrounding the pulsar. We feel, however, that such a continued mass transfer is unlikely for the following reason: When there is a sudden mass ejection (like in a supernova) the binary separation will increase, and along with it the radii of the Roche lobes. As a result the mass-donating star will no longer fill its Roche lobe and hence mass transfer will cease till the star evolves further and grows in size[21].

(f) Finally, we would like to comment on the importance of continued radio observations of this supernova in the near future. As was remarked earlier, in our scenario one doesn't expect any radio emission à la Chevalier. On the other hand, the rapid decline in the observed radio emission is not what one would expect in the Pacini-Salvati model. One is therefore tempted to speculate that the *observed* radio emission might not have been due to either of these two mechanisms, but due to the relativistic electrons created in the explosion itself radiating in the magnetic field frozen in the ejected matter. But if there is a fast pulsar in the centre then it will pump the supernova cavity with relativistic particles and magnetic field and radio emission will build up. One of the main criticisms levelled against this model for radio supernova is that even if there is such a mini Crab Nebula, it would be obscured by the ejecta till it breaks up into filaments. In the present case, since the mass ejected is very small that difficulty may not be there. In fact if the period of the central pulsar is 20 ms and its magnetic field $10^{12.5}$ G the radio flux (at, say, 5 GHz) could build up to ~ 50 Jy in a few months. The synchrotron x-ray emission from such a nebula should also be detectable once the optical depth for x-rays becomes small. According to the standard calculations the x-ray luminosity could be ten times larger than that of the Crab Nebula[14,18].

An alternative scenario?: We wish to mention in passing a variant of the model outlined in section IV which may also be consistent with the optical observations of SN 1987a that have been reported so far. It has been suggested[22,23] that under some special circumstances an accreting white dwarf may neither collapse to form a neutron star nor be totally disrupted, but only its outer layers will be blown off leaving behind a white dwarf core. However, in view of the reports of the detection of neutrinos from this supernova we do not favour this alternative.

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