ON THE NATURE OF THE SUPERNOVA REMNANT 0540-69.3 IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

The implications of the recently discovered x-ray pulsar within the SNR 0540-69.3 in the Large Magellanic Cloud is investigated. It is suggested that the SNR is a shell-plerion combination.

THE x-ray pulsar recently discovered by Seward *et al*[1] appears to be the fourth case of a pulsar supernova remnant (SNR) association, being close to or within SNR 0540-69.3 in the Large Magellanic Cloud (LMC). This SNR has been extensively studied in Radio[2], Optical[3,4] and X-ray[4,5] and appears to be similar to the Crab Nebula. In fact, as we shall outline below, the case appeared to be so convincing that the presence of a pulsar at the centre of the SNR was already conjectured before its discovery[5]. We briefly review below some of the salient features of SNR 0540-69.3.

A radio map at 843 MHz has recently been published by Mills *et al*[2]. Though this is the highest resolution map available, it is still not adequate to resolve the structure within. However, Mills *et al*[2] suggest that this is a centrally filled remnant similar to the Crab. The linear diameter has been estimated to be 9 pc, and the integrated flux density is 1055 mJy[2]. The radio spectral index $\alpha_R = -0.43$, similar to that of most SNRs.

Mathewson *et al*[4] have mapped this remnant using the HRI on board the Einstein Observatory. The map clearly shows that the x-ray emission is centrally condensed and roughly 3 pc in diameter. The x-ray luminosity in the $0.15-4.5$ KeV band is $\sim 1.2 \times 10^{37}$ erg s^{-1}. However, as Mathewson *et al*[4] have commented, a significant fraction of this may be from a central (but unresolved) point source. The x-ray spectrum has been measured by Clark *et al*[5] and they find that it is best fit by a power law of index $\alpha_X = -0.8$, which strongly suggests that the x-ray emission is non-thermal. While pointing out that a featureless spectrum could in principle be produced by a hot plasma at 4×10^7 K, Clark *et al*[5], however, favoured a synchrotron origin for the observed x-rays. The discovery of the pulsar appears to clinch the latter interpretation and lend support to the conjecture that SNR 0540-69.3 is another Plerion, like the Crab Nebula.

IS SNR 0540-69.3 ANOTHER "CRAB NEBULA"?

Let us now examine this possibility more carefully. The observed period of pulsar ($P = 50.2$ ms) and its period derivative [$\dot{P} = (4.84 \pm 0.02) \times 10^{-13}$ ss^{-1}] suggests a characteristic age $P/2\dot{P}$ of 1640 years. The derived surface magnetic field of 4.9×10^{12} Gauss is very close to that of the Crab Pulsar (3.6×10^{12} Gauss). The radio remnant of 9 pc in size is roughly consistent with the radio size of the Crab Nebula[6], given their respective ages. The sizes of the synchrotron x-ray nebula is in rough agreement with that surrounding the Crab Pulsar[6], again given the ratio of their characteristic ages. It now remains to show that the observed x-ray and radio luminosities of 0540-69.3 agree with what one would expect. We first turn our attention to the x-ray nebula.

It is generally believed[7,8] that the relativistic particles emitted by the pulsar and the magnetic field frozen into this wind are contained by filamentary shell in the Crab Nebula, which is expanding at 1700 km s^{-1}. Very convincing arguments have been made that the filaments in the Crab Nebula have been accelerated to their present velocity by the pressure of the Pulsar bubble. In fact, it is through such detailed arguments that it has been possible to deduce an initial period ($P_0 = 16$ ms) for the Crab Pulsar[7-9]. In what follows we shall adopt the point of view that long-lived plerions like the Crab and Vela X are produced only when the cavity boundary is expanding rather slowly compared to a typical supernova blast wave, and that the velocity was imparted by the central pulsar over the initial characteristic slowdown time $\tau_0 = P_0/2\dot{P}_0$. More precisely, the expansion velocity is determined by the relation

$$\frac{1}{2}M_{ej}v^2 \approx \frac{1}{2}E_0^{rot};\ E_0^{rot} = \frac{1}{2}I\omega_0^2 \qquad (1)$$

here M_{ej} is the mass ejected, I the moment of inertia of the pulsar, $\omega_0 = 2\pi/P_0$ and $E_0^{\rm rot}$ the initial stored rotational energy. If the age of 0540-69.3 is equal to the characteristic age of the pulsar, the observed radio size implies an average expansion velocity $\sim 2700\ \mathrm{km\ s^{-1}}$ for the nebular boundary. Assuming the mass accelerated by the pulsar is similar to the mass in the filaments of the Crab, we deduce for the initial period of the x-ray pulsar $P_0 \approx 10$ ms. One can now estimate the spectral luminosity of the nebula in the x-ray region using the formalism developed by Pacini and Salvati[7] (PS):

$$S_X \alpha B_*^{(6-\gamma-4\alpha)/2} P_0^{2(\alpha-2)} v^{3(2-\gamma)/4} t^{(2-\alpha-\gamma)}. \quad (2)$$

(For convenience we have recast the formula derived in PS to explicitly display the parameters of the pulsar). In the above equation

B_* = surface magnetic field of the pulsar,
P_0 = the initial period of the pulsar,
v = the expansion velocity of the nebula, and
t = the age of the nebula.

γ and α have the same meaning as in PS, namely, the spectral index of the injected particles ($\gamma = 1.6$ for the Crab) and the slowdown index for the pulsar respectively. In the standard model of pulsars $\alpha = 2$. Eqn (2) can be normalised to the spectral luminosity from the Crab Nebula. This yields $S_{X,0540} \simeq 0.3\, S_{X,\mathrm{Crab}}$ or for the x-ray luminosity in the 0.15–4.5 KeV band $L_X \simeq 0.7 \times 10^{37}\ \mathrm{erg\ s^{-1}}$ (We have used a value of $2.3 \times 10^{37}\ \mathrm{erg\ s^{-1}}$ for the x-ray luminosity of the Crab Nebula[6]). This estimate of the x-ray luminosity is consistent within a factor of two of the observed luminosity from 0540-69.3. Since we do not yet have a number for the *pulsed* x-ray luminosity one cannot make a more detailed comparison. To summarise, the observed nebular x-ray luminosity is in good agreement with what one would expect from a nebula produced by a central pulsar whose initial period was ~ 10 ms and whose surface magnetic field is 4.9×10^{12} Gauss.

We now turn to an estimate of the expected radio luminosity from the pulsar bubble. Once again, we use the appropriate formulae derived in PS[7]. The expression for the spectral luminosity in the radio region reads as follows.

$$S_R \alpha B_*^{(3-5\gamma)/2} P_0^{2(\gamma-2)} v^{-3(1+\gamma)/4} t^{-2\gamma}. \quad (3)$$

Again normalizing it to the Crab, one would predict

$$S_{R,0540} \approx 0.04\, S_{R,\mathrm{Crab}}.$$

The observed flux, however, implies a Radio luminosity $\sim 75\%$ that of Crab Nebula, grossly discrepant with the above estimate.

One of the first assumptions that has gone into the above estimates, and which may now be questioned, is that the expansion velocity is tied to the initial period of the pulsar and, that the mass ejected is the same in both the cases, 0540-69.3 and the Crab Nebula. The inferred expansion velocity of $\sim 2700\ \mathrm{km\ s^{-1}}$ could be consistent with a much shorter initial period than 10 ms provided the mass ejected is much larger than in the Crab. We see from (3) that keeping all other parameters the same, a shorter initial period would lead to a larger radio luminosity (assuming, of course, $\gamma < 2$ as in the Crab Nebula). We now estimate the expected radio spectral luminosity by assuming that the newly born pulsar was spinning *maximally*. It has been argued that the rotation period of a canonical neutron star cannot be much less than 1.5 ms[10,11]. Using this value, one finds the expected flux at 843 MHz can at most be $\sim 26\%$ of the observed value. Thus, one is forced to the conclusion that the observed radio flux is far in excess of what one would expect from a plerion of the observed size and 1600 years of age.

A MODEL FOR SNR 0540-69.3

Faced with the above difficulty we wish to suggest that the SNR under consideration is, in fact, a shell remnant with a central nebula produced and maintained by an active pulsar. One can estimate the flux from a shell 9 pc in diameter by using Σ-D relation for radio SNRs in LMC[2]. Within the uncertainties of the Σ-D relation, we find that the expected flux from the shell could account for *almost all* of the radio emission observed from 0540-69.3—the central plerion contributing only a few percent to the observed flux. An attractive feature of the above suggestion pertains to the observed radio spectral index[2]. The value of $\alpha_R = -0.43$ fits in much better with a typical shell rather than a plerion which usually has a very flat spectrum ($\alpha_R = -0.26$ for the Crab and $\alpha_R = -0.08$ for Vela X).

A natural question that would arise is the following. If one is going to postulate a radio shell which is unresolved, why is there no attendant x-ray shell which could surely be resolved by the HRI? This can easily be understood with the use of the *X-ray* Σ-D relation for SNRs in LMC[4]. One expects a surface brightness $\Sigma_X \approx 7.8 \times 10^{-4}\ \mathrm{erg\ cm^{-2}\ s^{-1}\ sr^{-1}}$ for a shell of diameter 9 pc. But the average surface brightness of the observed centrally condensed (D $\sim$ 3 pc) x-ray nebula is $\Sigma_X = 0.12\ \mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}}$. Thus the expected surface brightness of the x-ray shell is ~ 1/150 of that of the plerion, and hence will not be pronounced in the HRI image.

We conclude, therefore, that SNR 0540–69.3 is a shell-plerion combination like MSH 15-52[12, 13].

THE CURIOUS OPTICAL RING

Mathewson *et al*[3,4] have observed a pronounced oxygen rich annulus of mean diameter ~ 1.6 pc, which must also be explained. It is tempting to suggest that this is, in fact, the boundary of the pulsar bubble. However, it would be very difficult to reconcile such an interpretation with the fact that the x-ray nebula is almost twice the size of the annulus. It is, therefore, attractive to think of the following alternative, namely that the progenitor of the pulsar was a massive star and that mass ejection occurred in two stages. There could have been a standard shock wave which accelerated the mantle of the star to high velocity ($\sim 10^4\ \mathrm{km\ s^{-1}}$) and some of the uncollapsed core material was later pushed out and accelerated by the pressure of the pulsar bubble[14, 15]. In this picture, the very extended and symmetrically placed radio emission ~ 50 pc in diameter seen in the map of Mills *et al*[2] could also be accommodated as due to the fast-moving material (velocity $\sim 15{,}000\ \mathrm{km\ s^{-1}}$!). The inner "shell" of 9 pc diameter would then represent the core material swept up by the expanding pulsar bubble. This would naturally be rich in heavy elements such as oxygen. If in the process of being accelerated by the pressure of a relativistic fluid it breaks up into filaments[16], then one may expect to find them at all distances from the pulsar like in the Crab Nebula[17]. Mathewson *et al*[4] have in fact pointed to an [OIII] emitting filament at a distance of ~ 5 pc from the centre and speculated that this may be associated with the SNR. This would fit in nicely with our picture. But if the material is distributed throughout the nebula, then the observed optical annulus of diameter ~ 1.6 pc could only be due to enhanced excitation at this radius, for example by a standing shock located there. A natural explanation for a standing shock inside a pulsar bubble was suggested a long time ago[8]. There will be a shock located at a radius where the ram pressure of the relativistic wind from the pulsar equals the built up ambient pressure in the bubble. In fact, Rees and Gunn[8] associated the wisps in the Crab Nebula with such a shock front. A simple estimate of the shock radius R_s gives

$$R_s \simeq R_{\mathrm{neb}}\left(\frac{2\dot{R}_{\mathrm{neb}}}{c}\right)^{1/2} \qquad (4)$$

where R_{neb} is the radius and $\dot{R}_{\mathrm{neb}}$ is the expansion velocity of the nebular boundary. (This formula differs from the one given by Rees and Gunn by a factor of $\sqrt{2}$ because we have taken into account the severe radiation losses by the high energy particles and consequently a reduction in their contribution to the ambient pressure, which now derives mainly from the built up magnetic field). Using $R_{\mathrm{neb}} \simeq 4.5$ pc and $\dot{R}_{\mathrm{neb}} \simeq 2700\ \mathrm{km\ s^{-1}}$ we estimate a diameter of ~ 1.2 pc for this standing shock. Thus the observed size of the optical annulus is consistent with the presence of an enhanced excitation ring located at R_s. This feature must in fact be filamentary, as otherwise the relativistic particles could not have propagated beyond it. A high resolution optical image could test this prediction. One would naturally ask if there is a corresponding feature in the Crab Nebula. In the recently published photograph of the Crab Nebula taken in [OIII] emission by Gull and Fesen[18], for example, it is difficult to discern any such feature. It would be worthwhile to look for it in a short exposure image.

SUMMARY AND CONCLUSIONS

1. It is our view that SNR 0540-69.3 is a shell-plerion combination like MSH 15-52 and possibly G326.3 – 1.8[12,13,19]. The plerion contributes only a few percent of the radio emission but dominates the x-ray emission. Future high resolution observations of the polarization pattern as well as spectral index variation over the SNR should confirm or contradict our hypothesis. But if confirmed, it would still leave the interesting question as to why there is not a similar shell at the boundary of the Crab Nebula.

2. Given the above scenario the radio and x-ray observations are consistent with an initial period of 10 ms for the recently discovered pulsar. The initial period has been derived assuming a similar amount of mass ejected as in the Crab and an expansion velocity of $2700\ \mathrm{km\ s^{-1}}$ (as suggested by the radio size and the characteristic age).

3. Although nearly 200 SNRs are known (in the Galaxy and the Magellanic Clouds put together) objects like the Crab Nebula remain extremely rare. The most remarkable thing about the Crab Nebula is its very low expansion velocity compared to the observed and inferred velocities of the ejecta in most supernovae. The plerionic component of 0540-69.3, though weak in radio emission compared to the shell we have postulated, is still a fairly bright nebula. It is interesting to note that the average expansion velocity in this case is also small. This lends support to the

possibility that long-lived plerions are produced only in those rare cases when the ejecta expands relatively slowly. This, of course, raises the fundamental question as to what governs the expansion speed. A discussion of this question, the lifetime of Pulsar-produced nebulae, and their birthrates will be published by us elsewhere[20].

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ANNOUNCEMENT

NATIONAL SEMINAR ON TEACHING METHODS AND TECHNOLOGIES IN TEACHING OF SCIENCES

The National Seminar on Teaching Methods and Technologies in Teaching of Sciences, sponsored by Government of India, Department of Science and Technology, New Delhi, will be held during 24–29 May 1984, at Dehra Dun.

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