Reprinted from Current Science, June 20, 1982, Vol. 51, No. 12 - 596-599

ON THE IMPLICATIONS OF THE RADIO AND X-RAY PULSAR IN THE SUPERNOVA REMNANT MSH 15-52

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ABSTRACT

Comparison of the X-ray nebulosity surrounding the X-ray and radio pulsar in the shell-type SNR MSH 15-52 with the Crab nebula leads to an initial period for the pulsar ~ 70 ms. The association of the pulsar with the shell remnant confirms the validity of the Σ-t approach in determining the ages of young SNRs using historical calibrators.

THE detection of a radio pulsar with the same position and period as the X-ray pulsar[1] within SNR MSH 15-52 has just been announced by McCulloch *et al.*[2] The importance of these observations can hardly be overemphasized in view of the fact that it is the third pulsar to be found within a supernova remnant, in a sample of over 300 pulsars and over 110 SNRs. The present pulsar, PSR 1509-58, has the fifth shortest period ($P = 0.150$ s), the two other pulsars associated with SNRs having much shorter periods ($P_{\rm Crab} = 33$ ms, $P_{\rm Vela} = 89$ ms). Of the remaining two with shorter periods than PSR 1509-58, one of them, the binary pulsar PSR 1913+16 is not expected to have an associated remnant. Its period (59 ms) is short not because it is young, but rather the result of speeding up due to accretion from its binary companion[3,4]. The other pulsar PSR 1930+22, with a marginally shorter period (144 ms) has no associated extended radio emission down to a limit of 1.4 K in brightness temperature[5].

The X-ray period measured by Seward and Harnden at two different epochs clearly indicated either an intrinsic secular period increase, or an apparent one due to orbital motion in a binary system[1]. The origin of the X-ray pulses (duty cycle $\sim 80\%$) was attributed by them either to accretion, if in a binary system, or to an intrinsic mechanism as in the Crab pulsar. The very fact that radio pulses have now been detected practically rules out the accretion hypothesis for the X-ray pulses, as even a weak stellar wind would be expected to smother normal pulsar activity. Further, the radio period observed by McCulloch *et al.*[2] on February 4, 1982 (a year and a half after the second X-ray observation) is $0^{s}.150212 \pm 1$ μs. The precise agreement with an extrapolation of the X-ray periods which predicts $0^{s}.150210 \pm 4$ μs, leaves little doubt that the period increase of 72 μs in this interval is intrinsic. With this interpretation, the measured $\dot{P} = 1.5 \times 10^{-12}$ ss^{-1} corresponds to a surface magnetic field of 1.5×10^{13} G, about the highest yet inferred field in pulsars. In fact, the only other known pulsar with a slightly higher field is PSR 0154 + 61.

In addition to discovering the X-ray pulsar in MSH 15-52, Seward and Harnden detected diffuse X-ray emission a few arc minutes in size centred on the pulsar. The luminosity of this extended feature is 2×10^{35} erg s^{-1} (0.2–4 keV) which may be compared with that of similar X-ray nebulosities around the Crab ($L_x \sim 3 \times 10^{36}$ erg s^{-1}) and Vela ($L_x \sim 1.8 \times 10^{34}$ erg s^{-1}) pulsars inferred for the same wavelength interval. Because of the presence of this X-ray nebula, Seward and Harnden[1] have noted that this object may be very similar to the Crab. Unlike the Crab and Vela, however, there is no clear radio nebulosity surrounding PSR 1509-58. The recent 1415 MHz map of MSH 15-52 (made with a resolution of 50″) shows no associated feature above a level of ~ 0.05 Jy per beam[6]. We shall show that this difference is the most significant clue to the past history of PSR 1509-58.

Apart from the nebula created by and surrounding the Crab pulsar, there is no evidence for the canonical shell seen in most SNRs. The optical filaments found at the periphery of this centrally concentrated nebulosity are believed to represent the only mass ($\sim 1 M_\odot$) from the parent star ejected in the explosion. The possibility that a greater amount of mass was ejected, but is invisible because of expansion in a very low density medium has been suggested by several authors[7,8]. Murdin and Clark[8] who have found a weak optical halo surrounding the Crab nebula, have in fact argued that this might originate in such a shell. Pending radio and X-ray confirmation, we feel there is no established evidence for any shell around the Crab nebula.

The location of PSR 1509-58 is reasonably close to the centre of the shell SNR MSH 15-52. The determination of the true centre of a remnant without a pronounced circular symmetry is a difficult and questionable exercise. It is well known that variations in the density of the interstellar medium into which the shell is expanding cause variations in both the retardation of the different parts of the ejecta as well as in their radio brightness. Considering all this, since PSR 1509-58 is within a few minutes of the approximate centroid of this 30′ diameter remnant, we shall assume in the following that the pulsar and the shell were produced in the same explosion.

Seward and Harnden have noted[1] that if the change in the period of the pulsar were intrinsic, then it would imply a characteristic age ($P/2\dot{P} = 1677$ y) which would be grossly discrepant with the standard age estimate of over 10^4 y for MSH 15-52. Since, as we discussed above, the period change is in fact intrinsic, the characteristic time of $\sim$1700 years represents an absolute maximum age for the pulsar, and also for MSH 15-52 if they are associated as we have assumed.

Age calculations in the 'standard model' explicitly or implicitly assume that most SNRs have decelerated sufficiently to be described well by the Sedov solution. In addition, a knowledge of the linear diameter, D, of the source is needed. This requires a reasonable distance estimate which is possible only for a fraction of the known SNRs. For the remaining, one resorts to the empirical Σ-D relationship (here Σ is the surface brightness) which, as yet, does not have a firm theoretical basis.

In view of the above, some doubts have been cast recently on the "standard" method of age determination of shell-type SNRs. As an alternative method, one can use the secular decrease of the surface brightness which is independent of the distance to the source, and which can be calibrated using the historical shell-SNRs whose ages are precisely known[9,10]. Figure 1 illustrates this method. Srinivasan and Dwarakanath[10] have argued in their paper that the secular decrease of the surface brightness of the calibrators is best fit by a line of slope between 2.5 and 3.5, whereas the 'standard model' predicts a slope of 1.2. On this basis, one obtains a considerably smaller age for MSH 15-52 of 900–1250 years. This corresponds to an average expansion velocity of 12,000 km s^{-1} for the shell and an energy of 1.4×10^{51} ergs per solar mass of material ejected. It is interesting that the above age estimate is now *less* than the pulsar characteristic age, suggesting that PSR 1509-58 may, in fact, be even younger than 1700 years. If true, this would imply that the initial period, P_0, of this pulsar was substantially longer than that of, say, the Crab pulsar.

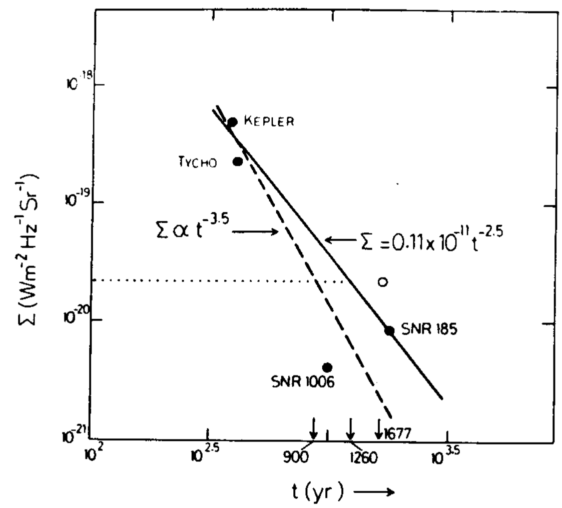

Figure 1. Estimation of the age of shell-type SNRs using the secular decrease of the surface brightness (Σ) and calibrating with the historical shell remnants. The dashed line of slope -3.5 is a least square fit using all the four calibrators shown. The solid line of slope -2.5 excludes SNR 1006 for reasons discussed by Srinivasan and Dwarakanath[10]. The dotted line shows the measured surface brightness[12] of MSH 15-52. Ages corresponding to its intersection with the two slopes are indicated by arrows on the age axis. The open circle marks the position that MSH 15-52 would have in this diagram if its age corresponded to the maximum age ($P/2\dot{P} = 1677$ y) of the pulsar. The age estimated by the "standard" methods leads to $\sim 10^4$ y.

It is most interesting that a similar conclusion can be arrived at by an independent method relating to the nebula surrounding the pulsar. Pacini and Salvati[11] have given a theory for the evolution of a nebula produced and maintained by an active pulsar. The rotational energy lost by the pulsar goes into building the nebular magnetic field as well as the spectrum of particles which radiate in it. We give below the formulae for the spectral luminosity appropriate to the radio and X-ray wavelengths; the dependence on P_0, the initial period and B_*, the surface magnetic field of the pulsar are explicitly displayed.

$$S \propto B_*^{(5+\gamma)/2} \; P_0^{-(5+\gamma)} \; \nu^{(1-\gamma)/2} \qquad \text{Radio (1)}$$

$$S \propto B_*^{(2+\gamma)/2} \; P_0^{-(2+\gamma)} \; \nu^{-\gamma/2} \qquad \text{X-Ray (2)}$$

where γ is the energy spectral index of the particles emitted by the pulsar. This is customarily deduced from the radio spectral index of the nebula, α_R through the relation $\gamma = 1 + 2\alpha_R$; for the Crab $\gamma = 1.6$. In eqs. (1) and (2) we have assumed a dipole braking index of 3 for the pulsar. In these equations we have suppressed the temporal behaviour of the luminosity since we shall be comparing the nebula around PSR 1509-58 with the Crab nebula of roughly the same age. Equations (1) and (2) correspond to eqs. (5.3) and (5.4) of Pacini and Salvati[11]. Since the age of the pulsar is of the order of its initial characteristic time $\tau_0 = P_0/2\dot{P}_0$, we feel that these are the appropriate formulae rather than eqs. (5.7) and (5.10) of Pacini and Salvati[11] which refer to the asymptotic regime $t \gg \tau_0$. For example, in this asymptotic regime the nebular magnetic field (eqs. (2.5) of Pacini and Salvati[11]) would be *independent* of the initial period of the pulsar, and therefore of the rotational energy lost by the pulsar. This, we feel is an unphysical result for $t \sim \tau_0$ since adiabatic losses are not expected to be severe at this stage. It turns out that the use of their formulae appropriate for $t \gg \tau_0$ does not alter our conclusions in any significant way.

The ratio of the X-ray luminosity (0.2–4 keV) of the nebula surrounding this pulsar to that of the Crab is $\sim 1/15$. From eq. (2), we can now obtain the initial period of PSR 1509–58, and find $P_0 \sim 4.3\, P_0$(Crab). Assuming an initial period for the Crab pulsar of 16 ms, we are led to the conclusion that $P_0 \approx 68$ ms for PSR 1509–58.

This initial period implies a $\tau_0 \sim 345$ yr and an age for the pulsar of 1333 yr. Thus the approximation used in deriving eq. (1) and (2), *viz.*, $t \sim \tau_0$ is now justified. With this estimate for the age, we can in principle restore the temporal dependence which was suppressed in eqs. (1) and (2) and refine the age and initial period estimates. The marginal change so obtained in these quantities is of no real significance however, considering the other assumptions made in the comparison.

We shall now estimate the radio flux from this nebula at 1415 MHz. From eq. (1) we obtain

$$F_{1415}\,(d/d_{\rm Crab})^2 \approx (1/143)\, F_{1415}({\rm Crab}) \qquad (3)$$

where F is the flux in Janskys and d is the distance to PSR 1509–58. In the above we have used the fact that $B_* = 4\, B_*$(Crab). The flux from the Crab nebula at 1415 MHz is 900 Jy (assuming a spectral index of + 0.3). This implies a flux of 1.4 Jy from the nebula, assuming a distance of 4.2 kpc for MSH 15–52 and 2 kpc for the Crab[12]. It now remains to compare this prediction with the observation made by Caswell *et al*[6]. If we assume that the linear dimensions of this nebula are the same as those of the Crab because the ages are comparable, it would imply an angular size of $\sim 2'.4$ at 4.2 kpc. (We have assumed a mean angular diameter of $5'.2$ for the Crab[12].) As the beam size at 1415 MHz was $50''$ (Caswell *et al.*[6]), we expect an average surface brightness of ~ 0.2 Jy/beam which is roughly four times the measured value in the vicinity of the pulsar. In all of the above discussion, we have assumed that the various parameters of PSR 1509–58 such as its moment of inertia, radius, the fraction of the rotational energy lost that goes into building the nebula, the expansion velocity, etc. are identical to those of the Crab pulsar. In view of this, we do not consider the discrepancy between the predicted and observed radio fluxes as significant. Of all these assumptions the most serious one we feel concerns the expansion velocity of the nebula. In the present case it is quite conceivable that the relevant velocity is that of the expanding shell SNR MSH 15–52. Since the lifetime of the radio electrons is expectd to be very long they will fill the entire cavity swept by the shell. Consequently the radio brightness will be much smaller than what was estimated above. On the other hand, since the lifetime of the X-ray electrons will be very short the spatial extent of the X-ray nebula may be rather small, determined essentially, by the distance it diffuses within its radiative (in X-rays) lifetime. A detailed investigation of this is in progress.

The conclusion that PSR 1509–58 was born with an initial period of ~ 70 ms as discussed above has several significant implications. The picture according to conventional wisdom, based on conservation of angular momentum and other considerations, is that all neutron stars are born with very short periods (~ 10 ms). According to this picture, the early history of all pulsars should be similar to that of the Crab pulsar, with its attendant and spectacular nebula. This belief has persisted in spite of the observational evidence that the birth rate of objects similar to the Crab nebula is roughly one in 500 years—a frequency which is derived simply by considering the age, luminosity and expected evolution of the Crab nebula, together with the number of such objects seen in the galaxy[13]. All estimates of the birth rate of pulsars on the other hand have been very much higher, some as high as one in less than ten years[14,15]. One of the most recent such estimates[16] taking into account various selection effects gives one in 20 to 25 years. These two widely different birth rates taken together,force one to the firm conclusion that only a small fraction of all radio pulsars could have had an early history similar to that of PSR 0531 + 22.

So far, the only estimate from observations that we have had for the initial period of a pulsar is that for the Crab; as the accompanying explosion was historically recorded, the age is not in question,and a backwards extrapolation from its present spin-down rate leads to P_0(Crab)~ 16 milliseconds. If our estimate of $P_0 \simeq 70$ milliseconds for PSR 1509–58 is correct, then this is clear evidence that the initial period can vary significantly from pulsar to pulsar. Much more important is that it shows that the initial period can be long enough to substantially decrease the X-ray and radio fluxes from any nebula that the pulsar creates.

Independent evidence that a large fraction of radio pulsars appears on the scene with the initial periods of the order of hundreds of milliseconds has been provided by Vivekanand and Narayan[16] from a study of the current in the P–$\dot{P}$ diagram. But their results cannot be used to choose unambiguously between a long period for neutron stars at birth, or an interval of radio quiescence after birth until the neutron star has slowed down through dipole radiation. Neither can we make this choice in the present case. While we can say with reasonable confidence that particle production to fill the X-ray nebulosity began only around a period of ~ 70 ms, we cannot with the same precision estimate the age of the shell remnant. From the point of view of the ambiguity mentioned above, MSH 15–52 could well be around 1600 years old and the neutron star may have turned on as a pulsar, only after a few hundred years. In this connection, a very sensitive search for a pulsar in G 326.3–1.8 would be of great importance, as it is one of the rare shell-type remnants with a small radio concentration in the middle. Its age derived as illustrated in figure 1 is also $\sim$1600 years.

To summarise, the radio and X-ray observations put together have led us to the following important conclusions:

1. The pulsar PSR 1509–58 has an age of (around) 1300 years and started to function with an initial period of $\sim$ 70 ms.
2. Other pulsars may have even longer initial periods and thus explain the relative rarity of pulsar-created nebulae like the Crab.
3. The association of PSR 1509–58 with MSH 15–52 is evidence that the standard method of age determination of shell-type SNRs leads to overestimates, which can be serious in the case of the younger remnants.
4. There is almost certainly a pulsar in G 326.3–1.8 with age $\sim$1500 yr.

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* Note added in proof

Since this manuscript was submitted we have learnt that the radio pulsations have also been detected by a second group (Manchester *et al.* CSIRO preprint RPP 2639, 1982).