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Non Crab-like Plerions?

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Abstract. Several plerionic Supernova Remnants have spectral properties different from the Crab Nebula and do not show the presence of a central observable pulsar. We discuss in particular the cases of CTB87 and 3C58, and show that their properties cannot be fitted in the canonical scenario; a non–standard evolution of the pulsar output seems to be required.

Key words: ISM: supernova remnants – pulsars: general – acceleration of particles

1. Introduction

The Crab Nebula, the prototype of the plerion class, shows a radio spectrum with a spectral index α_r of 0.3. At around 15,000 GHz in the IR the spectrum steepens to an α of 0.8. Such a spectral break due to synchrotron radiation losses was predicted by Kardashev (1962) when electrons with a power law spectrum are injected at a constant rate into a magnetic field in a box. Later Pacini & Salvati (1973, PS) modelled a plerion as a uniformly expanding sphere into which a pulsar injects both magnetic fields and relativistic electrons, and showed that the spectral break is located at about the right frequency.

More recently it has been found that spectral breaks occur in several plerions at much lower frequencies. In 3C58 and G21.5-0.9 breaks are found at about 50 GHz, while CTB87 has a break around 20 GHz. In these objects weak X-ray emission is observed, so weak that the mean spectral index between the radio break and the X-ray point at 2 keV is in the range 0.8–1.0, while the radio spectra are quite flat. Therefore the break appears to be larger than the canonical $\Delta\alpha$ = 0.5.

It is of course true that in the case of the Crab there are also further breaks in the spectrum – at about 1000 Å and again at about 40 keV with $\Delta\alpha$ respectively 0.34 and 0.26; these are not understood and therefore ascribed to the injection spectrum. But in an object like G21.5-0.9, where the mean index between the break and the X rays is 0.8, and the X-ray is index 0.8 $\pm$ 0.1, the simplest interpretation is that the spectrum would be straight after the break. With α_r = 0.0 we therefore would have $\Delta\alpha$ = 0.8. The situation is even clearer in 3C58, where Green & Scheuer (1992, GS) obtained upper limits to the fluxes in the IRAS bands between 100μm and 12μm, which show that $\Delta\alpha$ is at least 0.7 and that the break is remarkably sharp.

These breaks pose two problems. Applying the usual models we would find that stronger magnetic fields are needed to push so low the frequency at which synchrotron losses occur. This leads to uncomfortably high magnetic energies. Furthermore, as shown by GS the sharp steep break in 3C58 forces one to a model where the electron injection more or less ceased rather suddenly sometime ago. The situation of 3C58 is further complicated by the apparent increase in its radio flux. Aller & Reynolds (1985a) found at 8 GHz a brightening of 0.284 ± 0.046 % yr^{-1}, which later was revised to a smaller, but still positive value (Aller et al. 1986). This was confirmed by Green (1987) who obtained at 408 MHz 0.32 $\pm$ 0.13 % yr^{-1}. Such an increase is hard to understand in an expanding supernova remnant fed by an aging pulsar, and even more so when the electron acceleration has virtually ceased. In fact in the Crab Nebula Aller & Reynolds (1985b) found a flux decrease of 0.167 $\pm$ 0.015 % yr^{-1}, in agreement with the 0.18 % yr^{-1} calculated on the PS model by Véron–Cetty & Woltjer (1991).

In the following we shall consider each of these problems in the framework of the PS models. It is to be noted that these are based on the assumption that the relativistic particles and magnetic fields generated by the pulsar are distributed more or less uniformly through the remnant. More elaborate models involving propagation effects in magnetohydrodynamic winds have been discussed by Kennel & Coroniti (1984a, b), who, however were unable to account for the radio emission. Since the relative roles of particle diffusion, large scale flows and instabilities are unclear, and since our main concern in this paper is the understanding of the spectral breaks at radio frequencies, we do not further consider them.

2. The low frequency of the break

This problem is posed most clearly in the case of CTB87, a plerion with a well established distance based on HI absorption measurements (Davelaar et al. 1986). Its radius is surprisingly

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large, 13 pc. The corresponding large volume and the absence of a shell due to interaction with the interstellar medium shows that the local interstellar density must be less than 0.01 cm^{-3}, certainly not impossible in view of its location 240 pc from the Galactic plane. According to the measurements of Salter et al. (1989a,b), the spectrum breaks at 20 GHz. The conventional synchrotron radiation loss break occurs at an age T given by T = $40,000 B^{-3/2} \nu_b^{-1/2}$ yr, with B in mG and ν_b in GHz. If we adopt a constant expansion velocity V_8 in units of 1000 km/s, T = $13,000 V_8^{-1}$ yr, and with ν_b = 20 GHz we have $B = 0.79 V_8^{2/3}$ mG. The total magnetic energy in the remnant then is $6.55 \times 10^{51} V_8^{4/3}$ erg.

For any plausible value of V this is a very large energy indeed. The energy of the expanding supernova shell (mass M) which confines the magnetic field is $10^{49} V_8^2 (M/M_\odot)$ erg. It should be of the same order as or larger than the magnetic energy, and hence $M \geq 655 V_8^{2/3} M_\odot$, which is clearly unreasonable.

The only way to avoid these conclusions is to treat the break as a fossil break, imposed on the electron spectrum in the past when the field was stronger and preserved because thereafter not much electron acceleration has taken place. Suppose that at the time $t = \tau \ll T$ the pulsar suddenly stopped injecting energy. During the following times the expansion (assumed at constant velocity) was adiabatic, therefore $B_T = B_\tau (\tau/T)^2$. At the time τ the spectral break occurred at a frequency $\nu_{b,\tau}$ given by $\tau = 40,000 B^{-3/2} \nu_{b,\tau}^{-1/2}$ yr. If E_b is the particle energy at the break, after the adiabatic phase $E_{b,T} = E_{b,\tau}(\tau/T)$.

Since $\nu_b \propto B E_b^2$ according to standard synchrotron radiation theory, we have $\nu_{b,T} = \nu_{b,\tau}(\tau/T)^4$. Finally we obtain for the relation between the field now and the break now $T = 40,000 B_T^{-3/2} \nu_{b,T}^{-1/2} (\tau/T)^4$ yr. As a consequence the required present day magnetic field is reduced by a factor $(T/\tau)^{8/3}$ and the magnetic energy by $(T/\tau)^{16/3}$. Choosing V_8 = 1 and T/τ = 3.4 the magnetic energy required at present becomes 10^{49} erg, about the equipartition value. The magnetic energy at τ was 3.4 times larger and if this has been transformed into kinetic energy of the shell a few solar masses would suffice.

In the framework of the PS models the situation is not very different. Here it is assumed that the fraction of pulsar energy going into magnetic fields has a fixed value p, that the maximum energy and the exponent of the accelerated electron spectrum are constant and that the pulsar energy input varies as:

$$L = \frac{L_o}{(1 + t/\tau)^s} \qquad (1)$$

with $s = (n+1)/(n-1)$ and n the pulsar braking index. It was shown by PS that in this case the spectral break at time τ splits into two breaks, the lower of which propagates downward in frequency as t^{-4}, while the other moves up as t^{+4}. In the intermediate range the spectral index (if $s > 2\alpha_r + 1$) is equal to $(s + 6\alpha_r - 1)/8$. To obtain the rather steep average radio to X-ray spectra we then would have to have large values for s. If, as it is for CTB87, α_r = 0.25 and α_{r-X} = 0.9, one would need s = 4.7, while for G21.5-0.9 with α_r = 0.0 and α_{r-X} = 0.8 the exponent s should be 7.4, values corresponding to n = 1.5 and 1.3, respectively. Such low values of the braking index are perhaps not excluded since for the Vela pulsar n = 1.4 appears to have been found (Lyne et al. 1996). Beyond the upper break the spectrum should again have $\alpha = \alpha_r + 0.5$, so again a further break in the injection spectrum is needed as it was in the Crab Nebula.

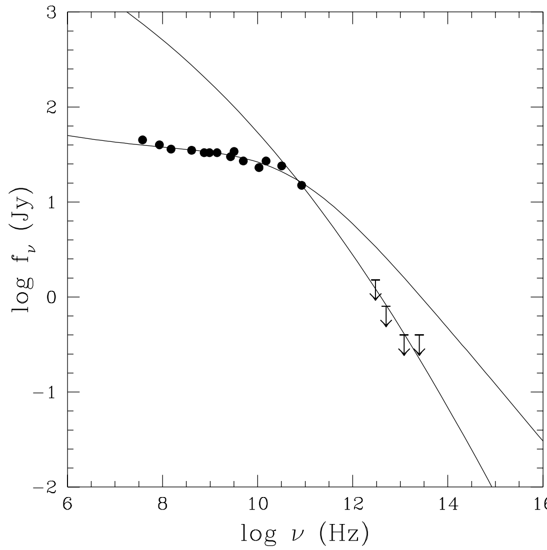

Fig. 1. Two alternate "best" fits with the PS model.

If n is so small the pulsar rotation rapidly declines after $t = \tau$ and the energy output becomes negligible. As a consequence no such pulsars should be observable among the older pulsars in the field. Perhaps the difference in magnetic field structure could also account for the lack of detectable pulses in these plerions.

3. The sharpness of the break

The preceding considerations allow us to understand most of the plerions with a spectral break at low frequencies and a steep spectrum beyond. However the sharpness of the break in 3C58 poses particular problems. We have tried and failed to fit PS models to this break. While there is no problem with low n values to obtain the $\Delta\alpha > 0.7$ found by GS, the models always give too smooth a break. If we choose a model that respects the GS limits in the infrared then the radio spectrum below 50 GHz is too soft (see Fig. 1). We therefore confirm the conclusion of GS that a more sudden reduction in the particle injection rate is required, though a priori there is no reason why this should have happened as recently as assumed by GS: a break once made travels downwards in frequency $\propto t^{-4}$ while preserving its shape.

We shall now consider two options: a sudden decrease in the overall energy output of the pulsar – for instance, because of a rearrangement of its magnetic field; or, alternatively, a case where the pulsar energy loss continues according to the same law, but where the ratio of the input of magnetic and particle energy suffers a sudden change – for instance, because of the closure of the sparking gaps in the pulsar magnetosphere during the slowing down of the rotation.

In the first case we essentially come back to the GS model, except that by regarding the break as fossil we may lower the magnetic energy requirement. According to the discussion of GS the equipartition energy in 3C58 is around 10^{48} erg, while the field requirement for a current synchrotron break at 50 GHz corresponds to 10^{51} erg. Placing the near cessation of the energy input at approximately 250 years after the supernova event of 1181 AD these values could be brought to equality. The implication would be that we are now in a fully adiabatic phase and according to the early results of Shklovskii (1960) the radio flux of 3C58 should decrease by 0.30 % yr^{-1}.

The alternative option of a change in p, the fraction of energy going into magnetic fields, is not all that different if it happened long ago, except for the fact that the magnetic field in the object would decline more slowly. However if the change occurred rather recently interesting effects could result. Let us consider a case where $\tau \gg T$, with T the present age of 3C58. In this case we have essentially $L = L_o$. Let the "phase change" occur at $t = T^*$, and $p = p_1$, $p = p_2$ before and after T^*, respectively. The evolution of the magnetic energy $\mathscr{M}$ in the object is given by

$$\frac{d\mathscr{M}}{dt} = pL_o - \frac{\mathscr{M}}{t} \quad (2)$$

where we have taken V = constant. Before T^* we then have

$$\mathscr{M} = \frac{1}{2}p_1 L_o t \quad (3)$$

and after T^*

$$\mathscr{M} = \frac{1}{2}p_2 L_o t + \frac{1}{2}(p_1 - p_2)L_o \frac{T^{*2}}{t} \quad (4)$$

Since $\mathscr{M} = (1/6)B^2V^3t^3$ we find

$$\frac{dB^2}{dt} = \frac{6L_o}{V^3t^3}\left[-p_2 + 2(p_2 - p_1)\left(\frac{T^*}{t}\right)^2\right] \quad (5)$$

This is positive at $t = T^*$ if $p_2 > 2p_1$; it remains positive as long as $(t/T^*) < [2(1 - p_1/p_2)]^{1/2}$, which for $p_2/p_1 = 4$ amounts to $t/T^* < 1.22$. At $t = T^*$ we have

$$\frac{1}{B}\frac{dB}{dt} = \frac{1}{T^*}\left(\frac{p_2}{p_1} - 2\right) \quad (6)$$

and for $T^* = 800$ yr and the assumed p_2/p_1 we obtain 0.25 % yr^{-1}. The radio luminosity is proportional to B when $\alpha_r = 0$ and no new electrons are injected, hence it would also increase by 0.25 % yr^{-1}. Fig. 2 shows a fit to the spectral data obtained within this scheme: one could have a sharp break together with an increase of the radio flux, but the problem of a large magnetic energy would remain. It would be of much importance to be absolutely certain that the claimed increase of the radio flux is, in fact, real.

In this type of model the high frequency part of the spectrum beyond the break is reduced by a factor $(1 - p_2)/(1 - p_1)$ compared to what a standard PS model would have yielded. In Fig. 2 we have taken $1 - p_2 = 5.410^{-4}$ so as to reproduce the observed X-ray flux, under the assumption that the injected particle spectrum maintains all the way a constant slope of 1.2. However, the case of the Crab Nebula shows that intrinsic changes of slope may well occur at energies below the X-ray range; if so, the value of p_2 would not have to be so extreme.

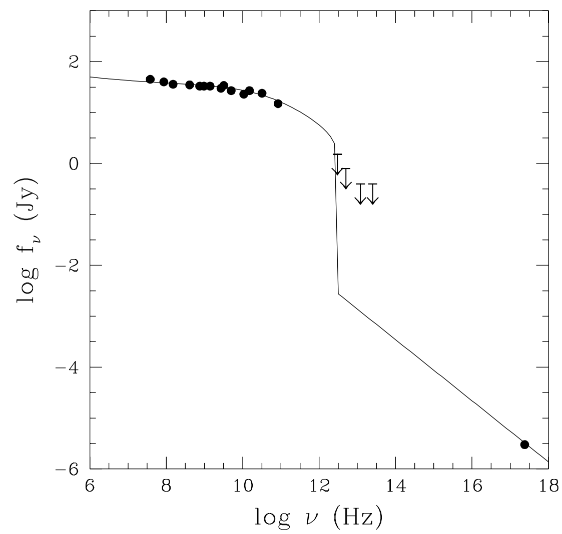

Fig. 2. The model assumes a "phase change" with $p_2/p_1 = 4$, $1 - p_2 = 5.410^{-4}$ at time $T^* = 0.94 \times T = 750$ yr.

Another way to cause an increase in the radio flux is to slow down the expansion. However, the total absence of a shell–like radio source makes this unlikely. If 3C58 were not the remnant of SN1181 its age could be larger. In fact, the largest velocities observed in some filaments amount to 900 km/s (Fesen 1983) which with a mean radius of about 3 pc would correspond to an age of 3300 years. In proper motion studies Fesen et al. (1988) and Van den Bergh (1990) failed to find filaments with proper motions larger than 0.07 arcsec/yr, which also would be compatible with a higher age. However the filaments are very faint and the presence of larger velocities cannot be excluded. On the other hand the luminosity of SN1181, corresponding to $M_V = -14$ if at the distance of 3C58, always seemed rather low and thus weakened the indentification. If the age were 4 times larger then the magnetic field needed for a non–fossil synchrotron break would be 2.5 times lower and the magnetic energy 6 times lower. But large values of p_2/p_1 would be required to obtain much of an increase in the radio flux. Another way to change the energy requirements would be to decrease the distance which has been determined from HI absorption at a velocity of –34 km/s (Green & Gull 1982). Non circular motions in the Galactic gas could therefore have some importance.

4. A separate class of plerions?

The Crab Nebula has alway been considered the prototype of the plerionic class. The discovery of its twin 0540-69 in the LMC seemed to confirm this. However in the mean time a rather numerous class of plerionic objects have been identified which

Table 1. Pure plerions of the second kind with the Crab Nebula for comparison. Listed are the distance, D; the radius of the radio source, R; the flux density at 10 GHz, S_{10}; the X-ray luminosity between 0.2 and 4 keV, L_X; the frequency of the lowest break, ν_b; the radio spectral index, α_r; the average spectral index between 10 GHz and 2 keV, α_{r-X}; and the X-ray spectral index, α_X.

G name	21.5-0.9	54.1+0.3	74.9+1.2	130.7+3.1	291.0-0.1	184.6-5.8
Name			CTB87	3C58	MSH11-62	Crab
D(kpc)	4.4	(10)	12	3.2	(2)	2
R(pc)	0.8	2.2	1.3	3.3	1.4	1.7
S_{10}(Jy)	6.7	0.32	5.0	25	10	520
$L_X(10^{35}$erg/s)	2.2	0.6	1.5	0.20	0.03	240
ν_b(GHz)	50	(>5)	20	50	(>8)	15,000
α_r	0.00	0.13	0.25	0.09	0.28	0.30
α_{r-X}	0.75	0.74	0.87	0.92	0.92	0.64
α_X	0.8	...	...	1.0	...	1.14
D^2S_{10}	130	30	720	260	40	2100
$100L_X/D^2S$	1.7	2.0	0.21	0.08	0.08	11.4

Notes to Table 1. The values of R, S_{10}, and α_r have been determined from maps and fluxes in the literature, the values of L_X from Seward (1989) scaled to our distances, and the other independent quantities as indicated. To compute the X-ray flux at 2 keV from L_X we have adopted α_X = 1 in all cases. If no break has been observed in the radio spectrum, the highest frequency at which radio data exist is given as a lower limit in parentheses.

Distances have been determined from HI absorption (scaled to a flat Galactic rotation curve, with 220 km/s, 8.5 kpc to center) for G21.5-0.9 (Davelaar et al. 1986), CTB87 (Green & Gull 1989), and 3C58 (Green & Gull 1982, Wallace et al. 1994). Extremely uncertain distances have been obtained from ill determined X-ray column densities by Seward (1989) for G54.1+0.3 and by Wilson (1986) for MSH11-62. The break frequencies are from Salter et al. (1989a,b) for G21.5-0.9, Morsi & Reich (1987) for CTB87, and Salter et al. (1989b) and Green & Scheuer (1992) for 3C58. For the remaining two sources S_{10} has been obtained by a slight extrapolation.

The X-ray spectral index for G21.5-0.9 is from Davelaar et al. (1986; 2–10 keV, $\alpha_X = 0.72 \pm 0.12$) and Asaoka & Koyama (1990; 1.2–17 kEV, $\alpha_X = 0.88 \pm 0.0.05$). For 3C58 the latter authors give $\alpha_X = 1.19 \pm 0.0.12$, Davelaar et al. (1986) α_X =1.04–1.56, and Helfand et al. (1995) $\alpha_X = 0.7 \pm 0.3$. The data for the Crab Nebula are from Woltjer (1987).

Other objects that could belong to the same class include G20.0-0.2 and G27.8+0.6. The distances to these sources are unknown and neither has been detected as an X-ray source. The former has α_r = 0.0 and a radio flux of 10 Jy (Odegaard 1986), while the latter (Reich et al. 1984) is a large, 40 arcmin source. There is much HII emission in its general area and only part is strongly polarized. As a result the source parameters remain in doubt.

have no observable pulsars, radio spectra generally flatter still than the Crab, frequently breaks at relatively low frequencies, and rather steep mean spectra between radio and X-ray wavelengths. They would presumably be powered by short lived pulsars with either very small braking indices or they would undergo some “phase change” following which the acceleration of relativistic particles is drastically reduced. In Table 1 we list the pure plerions with reliable data. It is seen that the non–Crab like class is relatively the more numerous. More accurate data especially on the spectral shapes above the break would be desirable.

5. Composite Supernova Remnants

Many Supernova Remnants are composites with a plerionic bubble inside an expanding shell source. Unfortunately this frequently makes it difficult to obtain reliable radio spectra. Some of these may well belong to the class considered in this paper.

The data on the plerionic component of G11.2-0.3 were fitted by Bandiera et al. (1996) to a PS model with a fossil break, to reduce the very large magnetic energy inferred by Vasisht et al. (1996). Since the radio spectrum of the source is unknown and since $\alpha_{r-X} \approx 0.7$, it is not clear that at the lowest break $\Delta\alpha > 0.5$. In G0.9+0.1 Helfand & Becker (1987) found a plerionic component with α_r = 0.1 and a very weak X-ray flux corresponding to $\alpha_{r-X} \approx 0.9$, so this is undoubtedly a plerion of the second kind.

Some other composites are very different. The source 0540-69 in the LMC with a pulsar at its centre has α_r = 0.25 and α_{r-X} = 0.55, and appears to have an overall spectrum similar to that of the Crab Nebula. A particularly intriguing case is G29.7-0.3 (Kes 75). With α_r = 0.2 and α_{r-X} = 0.53 it is surprisingly similar to 0540-69, but no pulsar has (yet?) been found inside it. An in–depth search would certainly be worthwhile.

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