4.4 THE SECULAR BEHAVIOR OF X-RAY AND RADIO EMISSION FROM SUPERNOVA REMNANTS*

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Abstract. Continuous injection models for the secular behavior of the radio and X-ray emission from supernova remnants are examined and compared with the observations. Among other things, it is concluded that (1) continuous injection probably occurs for at least 10 yr in every case and about 1000 yr in most supernova remnants, in which case the supernova remnants 3C392, W28, Pup A and IC443 should produce 1–10 keV X-ray fluxes $\approx 10^{-10}$ ergs/cm^2-sec, and (2) the X-ray sources in the Crab Nebula, Cas A and Tycho can be explained in terms of a model wherein continuous injection occurs for 300 yr for the Crab Nebula, much less than 250 yr for Cas A and much longer than 400 yr for Tycho. Finally, it is shown that if Tycho and Cas A contain an X-ray star such as NP 0532, it is quite possible that the X-ray emission from those sources is predominantly due to the X-ray star.

1. Introduction

The purpose of this communication is to discuss the secular behavior of the radio and X-ray flux from supernova remnants which is to be expected on the basis of a model which assumes that relativistic electrons are continuously injected into the source for some time after the initial explosion. Ths results of this analysis, which are discussed in more detail elsewhere (Tucker, 1970), lead to the following conclusions: (1) a continuous injection model is capable of explaining the observed variation of the radio luminosity with the size of the source, if the injection time t_i is of the order of 2000 yr for most sources; (2) the intensity and spectral shape of the X-ray emission from the Crab Nebula, Cas A and Tycho are readily understood on the basis of this model if $t_i = 300$ yr for the Crab Nebula, $\ll 200$ yr for Cas A and $\gg 400$ yr for Tycho; (3) if Tycho is typical, then the supernova remnants 3C392, W28, Pup A and IC443 should produce X-ray fluxes of the order of $\frac{1}{10}$ that of Tycho; (4) if Cas A and Tycho contain a compact X-ray source similar to NP 0532, then it is quite possible that the X-ray emission from those objects is predominantly due to the compact source.

2. The X-Ray and Radio Emission from Relativistic Electrons in Supernova Remnants

The intensity of the synchrotron radiation from supernova envelopes can decrease with time for two reasons: (1) The energy losses suffered by the electrons as a result of adiabatic expansion and radiation and (2) the magnetic field strength can decrease with time. The relative importance of these effects depends on the energies of the electrons, the rate of production of relativistic electrons as a function of time and the evolution of the magnetic field strength with time.

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Assume that relativistic electrons are injected into the emitting region at a rate described by the equation

$$f(t) = 1/(1 + t/t_i)^2 \tag{1}$$

This time dependence is consistent with the predictions of both the oblique rotator model (Gunn and Ostriker, 1969; Cavaliere and Pacini, 1970) and the low density limit of a relativistic stellar wind model (Michel, 1969; Goldreich and Julian, 1969), so that the results discussed below are not dependent on the validity of any particular pulsar model. In fact any law of the form $f(t)=1/(1+t/t_i)^x$ would give essentially the same results in the limits $t \ll t_i$ and $t \gg t_i$.

If it is assumed that the relativistic electrons are produced after the stellar envelope has been ejected, then the effective radius of the source is given by the position of the ejected shell for $t \leqslant t_s$, where t_s is the slowing down time, i.e., the time required for the interaction with the interstellar medium to have a noticeable effect on the motion. This happens in a time corresponding to a radius of the order of 4 parsec. For radii greater than this the ejecta are mixed in with the interstellar medium and the effective radius of the source is given by the position of the shock front which propagates ahead of the ejected shell*.

Since the dependence of r on t is different in the different phases of the expansion, the dependence of the luminosity on r will be different depending on the relative magnitude of the age of the source t, the injection time t_i, and the slowing down time t_s or equivalently r, r_i, and r_s. We know the value of r_s fairly well ($r_s \sim 4$ pc) and the value of r can be determined from the observations by a number of (usually indirect) methods, all of which give roughly the same values (see Minkowski, 1968; Shklovsky, 1968; Poveda and Woltjer, 1968; Westerlund, 1969a, b). The value of r_i or the corresponding time t_i is less certain, since it depends on the model for injecting energy into the nebula. In general if the energy input is due to a rotating neutron star which is slowing down, then $t_i \approx E_{r0}/L_0$ where E_{r0} is the initial rotational energy of the neutron star and L_0 is the initial rate of loss of rotational energy. This implies that in general the brighter sources should have shorter lifetimes, and vice-versa. Pulsar observations, when available, can provide a means for estimating t_i. However, pulsars are observed in only two supernova remnants, so in most cases t_i must be treated as a parameter to be determined indirectly with the help of observations. An estimate of t_i can be obtained by assuming that the luminosity at the maximum of the light curve is a good estimate of L_0, and that E_0 is of the same order as the gravitational binding energy; this implies values for t_i lying somewhere between a hundred and a thousand years. For example, the observations of NP 0532 imply that for the Crab Nebula, $t_i = 300$ yr. Using this value for t_i in Equation (1) yields a spectrum which is consistent with the radio and X-ray observations of the Crab, if we assume a magnetic field $B = 2 \times 10^{-4}$ G.

* This assumes that a shock front does in fact develop. In a direction transverse to the interstellar magnetic field this is surely a good assumption. In a direction parallel to the magnetic field it is not obvious what will happen. (For discussions of the dynamics of supernova envelopes see Spitzer and Tomasko, 1968; Kruskal *et al.*, 1965, Colgate, 1967, and Shklovsky, 1968.)

For the cases of Cas A and Tycho, the radio and X-ray observations imply $t_i \ll 200$ yr and $t_i \gg 400$ yr, respectively (for more details, see Tucker, 1970).

The variation with t of the radio luminosity $L_{\text{rad}}\,(=\nu_{\text{rad}}L(\nu_{\text{rad}}))$ for the Crab Nebula, Tycho and Cas A is shown in Figure 1. Also shown are the positions of those supernova remnants for which the distance is fairly well known, and a broad shaded band having a slope of -0.67. Poveda and Woltjer (1968) have shown that it is probable that most of the other supernova remnants lie within the shaded area of the diagram. To get the curves going through the Crab Nebula, Tycho and Cas A, it was assumed that $r_s = 4$ pc in each case and $r_i = 0.3$ pc for the Crab Nebula and Cas A, and $r_i = 7$ pc

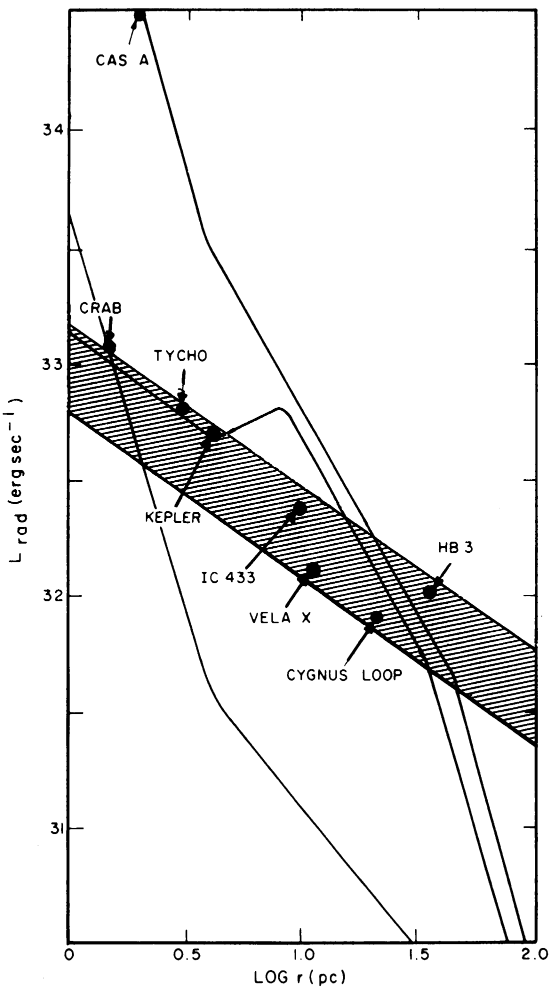

Fig. 1. The radio luminosity of supernova remnants as a function of their radius. Those remnants for which the distance is fairly well known are shown explicitly; the others most probably lie within the shaded area of the diagram. Data are taken from Poveda and Woltjer (1968). Also shown are curves illustrating continuous injection models for Cas A, the Crab Nebula and Tycho.

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for Tycho, values suggested by a comparison of the observed spectra and the predictions of the continuous injection model.

Most sources appear to lie in the region traced out by the curve through Tycho, implying that $r_i \sim 7$ pc or $t_i \sim 2000$ yr for most sources. This would explain why the observed L_{rad} vs r curve does not exhibit any dependence on the radio spectral index α_r. If most sources are in the region $r_s < r \sim r_i$, the dependence of their radio luminosity on α_r is weak. Any spread in the values of r_s and r_i should wash out this dependence leading to a curve of the type observed. The observation of an increase of the radio intensity with time for sources having radii in the range 5–10 pc would lend support to this model.

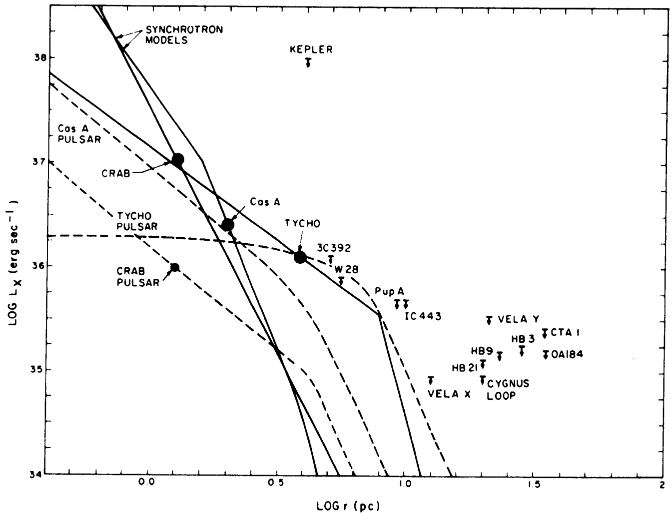

Fig. 2. The 1–10 keV X-ray luminosity as a function of the radius of the radio source for known supernova remnants (Gorenstein *et al.* 1970). Curves illustrating the models discussed in the text are also shown.

The variation with r of the 1–10 keV luminosity L_x for the Crab Nebula, Tycho, and Cas A are shown in Figure 2 together with observational data (Gorenstein *et al.*, 1970). Of course the curves for the Crab and Cas A must flatten for small r since at all times we must have $L_x < L_0$, where L_0 is the total power input of the central source.

The model that fits the observations from Tycho predicts a decrease with r according to $r^{-1.7}$, which suggests that at least one of the sources, 3C392, W28, Pup A or IC 443 should have an intensity at least $\frac{1}{10}$ that of Tycho.

It is well known that the Crab Nebula is not a uniform extended source. Rather, it is a complex source of the core-halo type, where in this case the core source is the pulsar NP 0532, which accounts for about 10% of the X-ray emission between 1 and 10 keV (Kellogg, 1970). Since this radiation is produced essentially at the site of the energy source of the nebula, we might expect the luminosity of the pulsar to follow rather closely the time dependence of the central energy source, which is given approximately by Equation (1). This implies that the luminosity of the pulsar X-ray source varies approximately as $1/r^2$ which is less steep than the $r^{-4.7}$ dependence for the extended source. The evolution of the pulsar X-ray source is shown by the dotted line in Figure 2, which shows that the pulsar X-ray source should become dominant for $r \gtrsim 3$ pc, or $t \geqslant 2000$ yr. It is of interest to speculate whether a compact source (it may not be pulsing) dominates the emission from Cas A and Tycho. An estimate of the intensity of these hypothetical compact sources can be made as follows: If we extrapolate the luminosity of the Crab pulsar back in time according to Equation (1), an initial 1–10 keV luminosity $\sim 2 \times 10^{37}$ erg/sec is obtained. If we now assume that (i) the ratio of the initial 1–10 keV luminosity of the pulsar $L_{px}(0)$ to the initial total power output of the central source L_0 is a constant for all sources, and (ii) $L_0 t_i =$ constant for all sources with $t_i \sim 25$ yr for Cas A and 2500 yr for Tycho then the initial 1–10 keV compact source luminosities for Cas A and Tycho are of the order of 2×10^{38} erg/sec and 2×10^{36} erg/sec, respectively. An evolution in time according to equation (1) then leads to secular behavior of the compact sources as shown by the dotted curves in Figure 2.

These curves show that, if the assumptions are correct, a significant fraction of the emission from Cas A and Tycho is due to a compact pulsar-like source. Angular diameter measurements should provide a test of this hypothesis in the near future.

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Discussion

J. E. Grindlay: Have you been able to estimate the current injection rate in Cas A and thus the present energy that may be put into high energy particles?

E. M. Kellogg: Cas A is assumed still to have electrons being injected. No absolute estimate of the injected energy or flux is made.