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Galactic Supernova Remnants: Radio Evolution and Population Characteristics

J. L. Caswell[A] *and I. Lerche*[A,B]

[A] Division of Radiophysics, CSIRO, P.O. Box 76, Epping, N.S.W. 2121.
[B] Permanent address: Department of Physics, University of Chicago, Chicago, Illinois 60637, U.S.A.

Abstract

Shell SNRs show a systematic gradient of radio surface brightness normal to the galactic plane, and a measured scale height for this effect has been obtained. The progenitor distribution and birth rate are significantly modified when allowance is made for this effect. The galactic height dependence of radio surface brightness satisfactorily accounts for the otherwise anomalous high-latitude SNR AD 1006. It also provides a crucial clue to the origin of the radio emission, suggesting that the interstellar magnetic field is dominant over internally generated fields in shell SNRs. Recently we have independently reached the same conclusion from a consideration of the cumulative number count of shell SNRs.

Introduction

The majority of supernova remnants (SNRs) exhibit a shell structure in their radio emission, and the following discussion deals solely with *shell* remnants (which represent a homogeneous class of objects). By contrast the radio emission from the Crab Nebula peaks at the centre and falls steadily to the edge with *no enhanced shell* (a 'filled' object). Other sources of the Crab Nebula type have recently been recognized (Lockhart *et al.* 1977), and the statistics and evolution of such 'Crab-like' sources require a separate study (see Caswell 1978).

Discussion

Because shell SNRs comprise swept-up interstellar matter, an understanding of their interaction with the interstellar medium is of prime importance. An observable property of SNRs revealing this interaction was investigated qualitatively by Caswell (1977), who found that, on average, the shells are brighter on the side closer to the galactic plane. A quantitative analysis of this effect has now been completed using 33 shell SNRs, and details have been given by Caswell and Lerche (1978*a*; hereafter referred to as CL). The z dependence (where z is the galactic 'height' or distance from the plane) of the brightness across individual remnants also describes the z dependence of the mean brightness of SNRs of a given age. We then find that for typical shell SNRs the surface brightness Σ at 408 MHz (in $\mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$) is well represented by

$$\Sigma = 1\cdot 25\times 10^{-15}\, t^{-6/5} \exp(-\,|z|/110)\,, \tag{1}$$

where t is the age in years and z is measured in parsecs.

The measured $\Sigma(z)$ dependence (equation 1) confirms earlier suspicions that sources at high z evolve more rapidly than those near the plane. Thus the scale height of the distribution of surviving SNRs (which is observed to be ~ 80 pc) does not represent that of the progenitors. A correction factor is directly calculable from the observational result (1) and, as shown by CL, leads to a local scale height of 200 pc for supernovae producing shell remnants. The uncorrected rate of occurrence of SNRs is correspondingly smaller than that of the total number of supernova explosions in the ratio of the uncorrected to corrected scale heights. For supernovae forming shell radio remnants our best estimate (CL) of the mean interval between events is 80 years, significantly smaller than the uncorrected value (~ 150 yr; see Clark and Caswell 1976). If, in addition, allowance were made for supernovae which leave Crab-like remnants, the interval would drop still further, although probably by less than a factor of two.

Some interesting consequences are as follows:

(i) No longer do the progenitors of shell SNRs have a scale height corresponding to a thin disc population. Indeed shell SNRs may have resulted predominantly from type I supernovae.

(ii) The progenitor scale height (200 pc) is now more akin to that of the observed pulsars whose $\langle |z| \rangle$ is 260 pc (Taylor and Manchester 1977). This is especially so when it is remembered that there is an indication that younger pulsars have a slightly smaller scale height than the mean.

(iii) The rate of occurrence of supernovae giving rise to shell radio remnants, although not as great as current estimates of the occurrence rate for pulsars (which range from 1 per 6 yr to 1 per 40 yr, depending on several assumptions; see Taylor and Manchester 1977; Manchester 1979, present issue pp. 1–7), is not as discrepant as was formerly thought. Indeed, allowing for the uncertainties in the pulsar birth rate, it is possible that the two rates are now compatible. This interesting possibility strongly suggests that a new, more sensitive, search for pulsars in the nearby SNRs is likely to be productive and worth while.

We now consider the cause of the dependence of surface brightness on galactic height and its relevance to our understanding of the evolution of the radio emission of SNRs.

From an assessment of published data, CL concluded that the *diffuse* galactic medium shows a density dependence

$$\rho(z) = \rho(0)\exp(-|z|/180)\,. \tag{2}$$

Since the mean diameter D of a shell SNR centred on z is proportional to $\{\rho(z)\}^{-1/5}t^{2/5}$ during the adiabatic expansion phase, we have (CL)

$$D = 0\cdot 93\,t^{2/5}\exp(|z|/900)\,, \tag{3}$$

where D is measured in parsecs and t in years. Some scatter in this relationship occurs because not all supernovae have *precisely* the same initial energy input E_0. However, a scatter in E_0 leads to a much smaller scatter in D, since $D \propto E_0^{1/5}$. We also assume, of course, that E_0 does not vary systematically with z. Eliminating t between equations (1) and (3) yields the relationship

$$\Sigma = 10^{-15} D^{-3} \exp(-|z|/175). \qquad (4)$$

If equation (4) had shown no z dependence we could have concluded that the z dependence of Σ in equation (1) arose solely from the z dependence of D in equation (3) (through the dependence of Σ on D). However, the presence of the term $\exp(-|z|/175)$ in equation (4) indicates the presence of an additional z-dependent effect, which we call the intrinsic z dependence of Σ.

The relationship (4), a generalization of $\Sigma \propto D^{-3}$ (proposed by Clark and Caswell (1976) for the brighter remnants), is applicable to the faintest known remnants. Indeed it can even account for the galactic loops as being SNRs which are simply old but nonetheless typical in other respects. Earlier results for faint remnants raised the question of whether the $\Sigma(D)$ relation might be steeper for faint remnants (Clark and Caswell 1976; in particular, see the paragraph preceding Section 6). These observations now seem attributable partly to the z-dependence of Σ (equation 4) and partly to the large errors inherent in the distance estimates of faint nearby remnants.

Striking corroboration of the z dependence (4) is provided by the high-z SNR G327·6+14·5. This is the remnant of a supernova observed in AD 1006, so that its age is known: the historically recorded observations indicate a distance of $\sim 1 \cdot 3$ kpc. Clark and Caswell (1976) found that application of their $\Sigma(D)$ relationship (which is identical to equation (4) with z set to zero) to AD 1006 yielded an expected distance of 4 kpc, a diameter of 39 pc and an age (from equation (3) with $z = 0$) exceeding 7000 yr! Equations (3) and (4), which allow for the z dependence, yield a distance of 2·2 kpc, a diameter of 22 pc and an age of ~ 600 yr for AD 1006—in satisfactory agreement with the independently known and estimated values.

Alternatively, equation (4) shows that, in principle, it is possible to use the mean surface brightness of SNRs to estimate the scale height of the $\Sigma(z)$ dependence (Milne 1979, present issue pp. 83–92). The analysis should be restricted to shell SNRs whose distances are known with confidence. Unfortunately, apart from AD 1006, suitable SNRs occur only at quite small $|z|$ (typically less than ~ 100 pc; see Table IV of Clark and Caswell 1976). The intrinsic scatter in the surface brightness and diameter estimates of individual SNRs then tends to mask any systematic trend with z. Accordingly, the error in the scale height determined in this way could be large and is difficult to assess.

The existence of the z dependence of Σ over and above that due to the density of the interstellar medium is, of course, a vital clue to understanding the origin of the radio emission. It suggests that shell SNRs rely on the interstellar medium as the origin of either the relativistic electrons or the magnetic fields which are needed for the synchrotron process. In our opinion the compressed interstellar field is the origin of the field required for the synchrotron emission. This conclusion is, of course, strictly applicable to those SNRs showing the brightness gradient effect: predominantly the old remnants. The fact that the otherwise anomalous SNR of AD 1006 is accounted for by equation (4) argues that quite young remnants also rely for their emission on the compressed interstellar magnetic field.

The general problem of the *origin and evolution* of the relativistic electrons and magnetic fields (whose existence is implied by the synchrotron radio emission) is of fundamental importance to any detailed understanding of SNRs. Therefore we have also attacked the problem from a different viewpoint, described in detail elsewhere (Caswell and Lerche 1978*b*). We considered a large family of theoretical models in which the electron energies, the magnetic field strength and the emitting volume were allowed to vary as different functions of the SNR diameter. We compared predicted evolutions of these models with the evolution implied by the observational statistics, in particular with the cumulative number counts as a function of brightness. Very few combinations of parameters can account for the observations. The most plausible of these requires that the magnetic field B, averaged over any remnant, should not change with increasing age of the remnant. This situation would naturally obtain if the source of the SNR magnetic field is galactic in origin but compressed and enhanced by a constant factor, as is expected to occur across the shock front of an expanding SNR.

To summarize:

(i) The observational statistics (of cumulative number counts) favour an interstellar origin for the magnetic field in 'middle-aged' remnants (the age range to which the statistics are applicable).

(ii) The surface brightness gradients measured across faint SNRs suggest that the magnetic field in this 'old' phase is interstellar in origin.

(iii) The SNR AD 1006 is a young SNR with an anomalously low surface brightness. This can be accounted for by assuming that the $\Sigma(z)$ dependence found for old SNRs is applicable to young SNRs.

(iv) A single z-dependent $\Sigma(D)$ relation appears to represent the evolution of both young and old SNRs.

On the basis of these four points we suggest that throughout most of the lifetime of SNRs the compressed interstellar magnetic field is dominant over fields originating in SNRs.

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