# THE EVOLUTION OF SUPERNOVA REMNANTS AS RADIO SOURCES

R. Cowsik & S. Sarkar *
Tata Institute of Fundamental Research, Homi Bhabha Road,
Bombay 400005, India.
*now at Department of Astrophysics, University of Oxford,
South Parks Road, Oxford OX1 3RQ, England.

## ABSTRACT

The acceleration of relativistic electrons by hydromagnetic turbulence in shell-type supernova remnants (SNRs) is examined within the framework of previous studies of their structural evolution through interaction with the interstellar medium. The predicted evolution of the synchrotron radio emission by the electrons is in agreement with a wide variety of observations.

## 1. INTRODUCTION

Gull (1973, 1975) has suggested that the relativistic electrons and magnetic field in young SNRs are generated during the transition from free expansion to the adiabatic phase of evolution, thus avoiding the severe expansion energy losses associated with an origin in the supernova explosion itself. His hydrodynamical calculations show that the excitation of a Rayleigh-Taylor instability in the decelerating ejecta results in the formation of a shell-shaped convection zone, in which $\sim 1\%$ of the blast energy is transferred through turbulence into magnetic field, relativistic electrons and hydromagnetic waves.

We treat the relativistic electrons as a collisionless plasma coupled to the magnetic field and to the thermal plasma through collective interactions. The transport equation governing the electron energy spectrum is analytically solved and the transport coefficients estimated from the hydrodynamic calculations. The evolution of the synchrotron radio spectrum can then be followed. We present a brief summary below of the results that are detailed elsewhere (Cowsik & Sarkar, 1982).

*J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 187–192.*

## 2. RADIO EMISSION FROM SNRs

### 2.1 Evolution of the Electron Energy Spectrum

The relativistic electrons undergo adiabatic energy changes due to the time variation of the magnetic field and the confinement volume, as well as stochastic energy changes (2nd order 'Fermi' accelertion) by scattering against magnetosonic waves. In addition, gyro-resonant interactions with Alfven waves rapidly isotropize the particle trajectories, thereby ensuring both the continuation of stochastic acceleration as well as the spatial confinement of the electrons (see Kulsrud, 1979).

The electron spectrum naturally evolves towards a power law shape from any steep form at injection under the combined effects of such convection and diffusion in energy. Figure 1 illustrates the flattening of the spectrum with time, t, for monoenergetic injection with $E = E_0$, both impulsively at $t = t_0$, and continuously from $t_0$ onwards. The power law shape, becomes better defined in the latter case, but the spectrum evolves more slowly than for impulsive injection. The corresponding synchrotron spectra evolve in a similar manner.

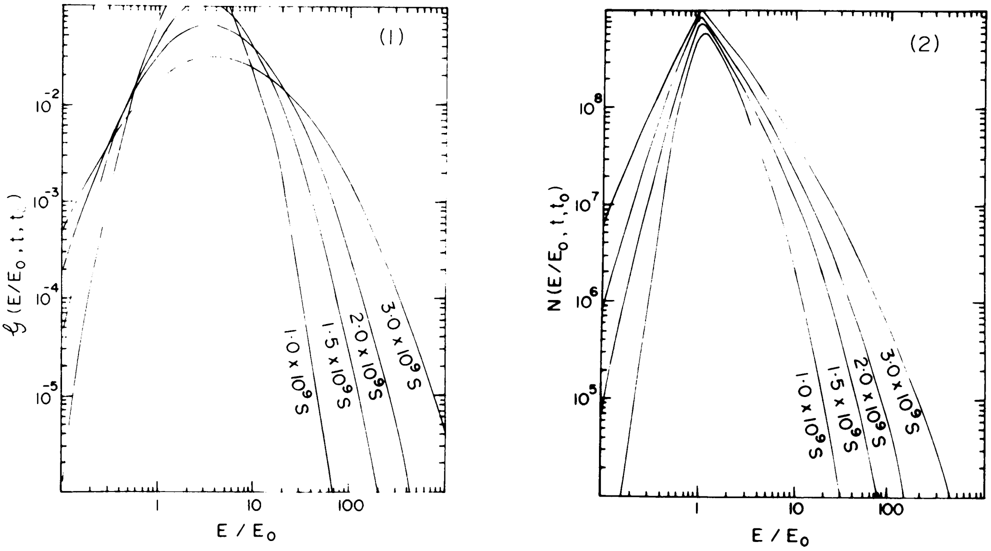

Fig.1. Evolution of the electron energy spectrum corresponding to, (1) Impulsive injection of 1 electron, and (2) continuous injection of 1 electron/s.

### 2.2 The 'Turn-on' of Radio Emission

We find that $\sim$ 30-100 yr after the supernova explosion the build up of the magnetic field is sufficiently rapid that the concommitant betatron acceleration overcomes the effect of expansion energy losses. The correlated increase of the field and electron energies thus leads to a sudden turn on of the radio emission, with peak luminosity being reached at

$$\tau \sim 100\ yr \cdot (n_o/1\ cm^{-3})^{-1/3} \cdot (E_{tot}/10^{51}\, erg)^{-1/2} \cdot (M_{ej}/10^{33}\, gm)^{5/6} ,$$

where $n_o$ is the ambient interstellar density, $E_{tot}$, the total explosion energy, and, $M_{ej}$, the ejected mass.

Just such a scenario is suggested by the failure of attempts to detect radio emission from the locations of many extragalactic supernovae that have occurred between a few years to almost a century ago. In Figure 2, we show the predicted evolution of the radio luminosity at the various search frequencies together with the observational limits. Note that these upper limits are grossly violated by both a backward extrapolation, of the observed luminosity-diameter relationship for older, galactic SNRs ($L \sim D^{-2}$; Milne, 1979) and a model that assumes the magnetic flux and total number of relativistic electrons in a young SNR such as, Cassiopeia-A to have been conserved at earlier epochs ($L \sim D^{-5}$, Shklovskii, 1968).

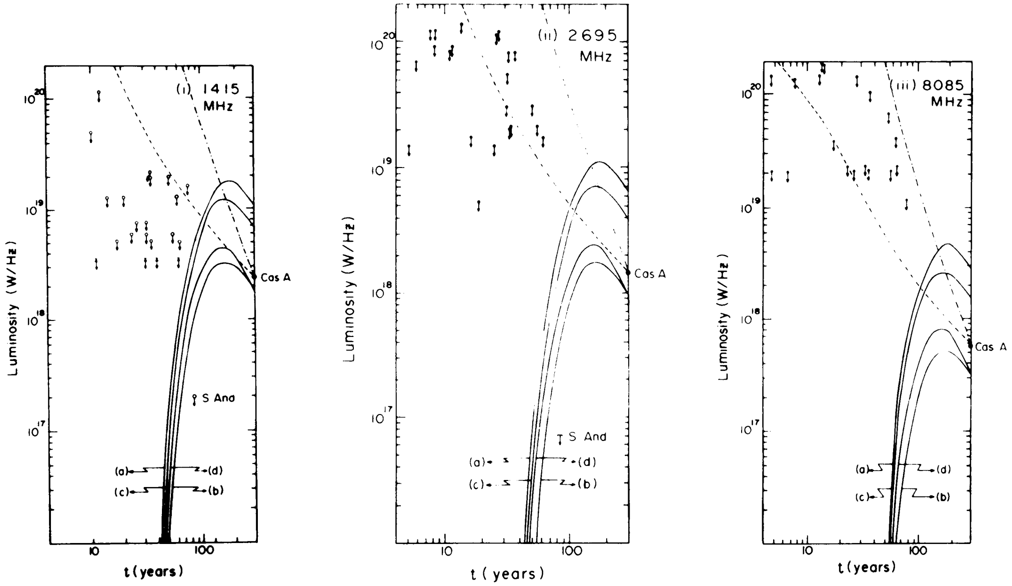

Fig.2. Evolution of the monochromatic synchrotron luminosity (solid lines) at different frequencies. Observational upper limits are derived from Spencer & Burke (1973, ⊤ ), de Bruyn (1973, ♀ ), Brown & Marscher (1978, ⫯ ) and Ulmer et al. (1980, ‡ ). The labels a-d refer to different choices of the initial conditions. The empirical evolution law of older galactic SNRs (broken lines) and a particle number-cum-magnetic flux conserving model for Cassiopeia-A (dot-dashed lines are shown for comparison.

## 2.3 The Supernova Remnant Cassiopeia-A

The many detailed observations that have been made of Cas A, the youngest galactic SNR, allow several tests of the theoretical model. The chaotic, cellular structure of its radio shell (Bell, Gull & Kenderdine, 1975), with its turbulent internal velocity field (Bell, 1977), as well as the strong anticorrelation between the polarized and unpolarized emission (Dickel and Greisen, 1979) do argue strongly in favour of small-scale turbulence as the origin of the radiating electrons and magnetic field. Independent observational evidence for the turbulent enhancement of the magnetic field has also been presented (Cowsik and Sarkar 1980). Moreover, the good spatial correlation between the radio emission and the soft X-ray emission from the ejecta (Fabian et al., 1980) demonstrates that the radio shell is well within the outer interstellar shock front.

A departure from spherical symmetry is evident in both the radio and X-ray structures suggesting that the expansion has been decelerated more on the eastern side, presumably due to a higher local interstellar density (Dickel and Greisen, 1979). Our model then predicts that the radio spectrum should have evolved further and become flatter on this side, in accordance with tentative observational evidence for such a variation of the spectral index across the remnant (Rosenberg, 1970). A similar assymetry is perhaps also evident in the distribution of flux variations across the remnant, with most of the brightening features being located on the western side (Dickel and Greisen, 1979), consistent with the above suggestion that it is 'dynamically' younger.

A fit to the the spectum of the total radio emission that takes into account such a distribution of 'ages', or equivalently acceleration rates, in the remnant is shown in Figure 3. We have assumed that the compact features in the radio shell are the primary sites of low energy electron injection and that the electrons leak out of them in an energy independent manner into the surrounding extended regions. The average spectral index of the compact features would then be the same as that of the total emission as is, in fact, observed (Rosenberg 1970). The spectral shape of the total emission can then be fitted by summing together the compact feature spectra. The average rates of decay of the compact and extended features would however be different, as shown in Figure 4. A weighted average of the two in accordance with their respective contribution (1 : 2) to the total flux is in reasonable accord with observations.

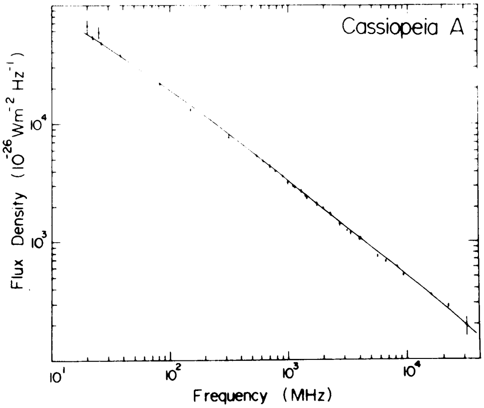

Fig.3 Fit to the radio spectrum of Cas A, with data from Baars et al. (1977).

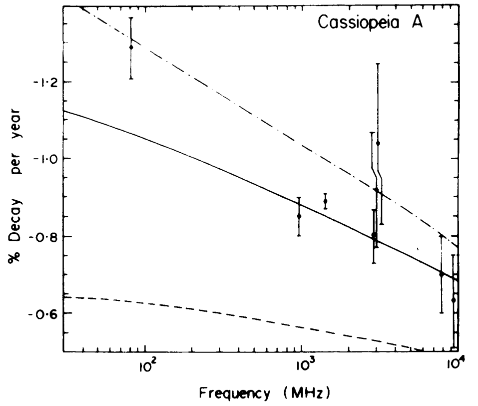

Fig. 4 The expected decay rate of compact (broken line) and extended (dot-dashed line) features in the radio shell, and of the total flux (solid line) of Cas A. Data are from Baars et al. (1977).

Finally we note that any turbulence initiated at the present epoch in Cas A would generate radio emission with a steep spectrum which would contribute to the total flux primarily at low frequencies. This contribution would decrease rapidly with time as the spectrum flattens. The recently observed 'flare' at 38 MHz (Read 1977) could be due to such an event.

## 2.4 The collective properties of galactic radio SNRs

In old SNRs such as IC 443 and the Cygnus Loop, the radio emission is from the compressed interstellar field in the associated radiative shock waves (Duin and van der Laan, 1975). Most galactic SNRs however appear to be the adiabatic phase of evolution (Clark and Caswell 1976), so that their radio emission is presumably still of internal origin. Their surface brightnesses are however much higher than would be expected if the radio emission simply decayed with the adiabatic expansion of the convection zone, following the Rayleigh-Taylor instability phase. Moreover, the spectral index appears to continue flattening with increasing diameter, while the total (minimum) energy in particles and field does not show any appreciable decrease. Taken, together these observations imply a mild, ongoing stochastic acceleration of particles throughout the adiabatic phase, counteracting the energy losses due to expansion.

We have examined two possible sources of such energy inputs; sporadic regeneration of turbulence by interactions with interstellar 'clouds', and absorption of magnetic dipole radiation from a central, spinning neutron star that has failed to become a pulsar (Radhakrishnan and Srinivasan, 1980). A semi-quantitative study suggests that the general trends in the collective properties (e.g. $\Sigma - D$) relationship) can be reproduced, and the large scatter ascribed to differences in the local environments of SNRs in the inhomogeneous interstellar medium. Further since the total energy in electrons (of up to a few GeV) does not decrease appreciably in the expansion, SNRs might, after all, contribute significantly to the galactic cosmic rays.

## 3. CONCLUSIONS

(a) The sudden emergence of SNRs as radio sources several decades after the explosion is explained. (b) Their subsequent evolution with the complex spectral and temporal changes as well as several structural details exemplified by the remnant Cas A follows naturally. (c) Their collective properties such as the $\Sigma$-D relationship are reproduced and these provide evidence for a mild ongoing acceleration throughout the adiabatic phase. (d) When the SNRs finally merge into the interstellar medium they contain enough relativistic electrons to contribute significantly to galactic cosmic rays.

## REFERENCES

Baars, J.W.M., Genzel, R., Paulini-Toth, I.I.K. and Witzel, A.: 1977, Astron.Astrophys., 61, p.99.
Bell, A.R. : 1977, Monthly Notices Roy.Astron.Soc., 179, p.573.
Bell, A.R., Gull, S.F. and Kenderdine, S.: 1975, Nature, 257, p.463.
Brown, R.L. and Marscher, A.P. : 1979, Astrophys.J., 220, p.467.
Clark, D.H. and Caswell, J.L.: 1976, Monthly Notices Roy.Astron.Soc., 174, p.267.
Cowsik, R and Sarkar S.: 1980, Monthly Notices Roy.Astron.Soc., 191, p.855.
Cowsik, R. and Sarkar, S.: 1982, Monthly Notices Roy.Astron.Soc., to be published.
de Bruyn, A.G.: 1973, Astron.Astrophys., 26, p.105.
Dickel, J.R. and Greisen, E.W.: 1979, Astron.Astrophys., 75, p.44.
Duin, R.M. and van der Laan, H.: 1975, Astron.Astrophys., 39, p.33.
Fabian, A.C., Willingale, R., Pye, J.P., Murray, S.S. and Fabbiano, G.: 1980, Monthly Notices Roy.Astron.Soc., 193, p.175.
Gull, S.F.: 1973, Monthly Notices Roy.Astron.Soc., 161, p.47.
Gull, S.F.: 1975, Monthly Notices Roy.Astron.Soc., 171, p.263.
Kulsrud, R.: 1979, in 'Particle Acceleration Mechanisms in Astrophysics', A.I.P. No.56, p.13.
Milne, D.K.: 1979, Aust.J.Phys., 32, p.83.
Radhakrishnan, V. and Srinivasan, S. : 1980, J. Astrophys.Astron., 1, p.25.
Read, P.L. : 1977 : Monthly Notices Roy.Astron.Soc., 181, p.63.
Rosenberg, I. : 1970 : Monthly Notices Roy.Astron.Soc., 151, p.109.
Shklovskii, I.S. : 1968, 'Supernovae', Wiley-Interscience, London.
Spencer, J.H. and Burke, B.F. : 1973, Astrophys.J., 185, L83.
Ulmer, M.P., Crane, P.C., Brown, R.L. and van der Hulst, J.M. : 1980, Nature, 285, p.151.