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Determining the evolutionary status of supernova remnants

The determination of the evolutionary stage for a supernova remnant is a demanding task. This guide for radio observers presents a relatively straightforward way to establish the evolutionary phase of newly observed supernova remnants.

Dejan Urošević

Among other properties, those derived from radio continuum observations of supernova remnants (SNRs) include the radio surface brightness (Σ) and diameter (D). The evolution of an SNR can be described by changes in the surface brightness with increasing diameter, that is, the so-called Σ–D relation[1,2]. We propose that the precise evolutionary stage of an SNR can be determined by performing three assessments: a method based on the radio surface brightness evolution of an SNR with the increase of its diameter is the first ingredient in the concept introduced here. The second method is based on the different forms of SNR radio continuum spectra[3]. For the different stages of evolution of an SNR, the forms of their radio spectra are different, and these forms can be defined by the values of the flux densities at different frequencies. Finally, the third method is based on the magnetic field strengths in SNRs. The equipartition (eqp) calculation model[4] is used for the determination of the magnetic field strength. Younger SNRs provide conditions for stronger magnetic fields, while older SNRs have weaker ones. All three methods mentioned here are based on the diffusive shock acceleration (DSA) model — the DSA theory of particle acceleration describes the production of high-energy particles, so-called cosmic rays, on the strong shock waves of SNRs.

The new determination of evolutionary status

We can start with the Σ–D analysis for determination of the evolutionary status of an observed SNR in the radio regime. The theoretically derived evolutionary paths from ref. [5] are shown in Fig. 1.

For a given combination of the supernova (SN) explosion energy and ambient density, a line in Fig. 1 represents an evolutionary path. The evolution of a very young SNR in the early free-expansion phase is represented by the rising part of an evolutionary path. The late free-expansion phase corresponds to the part of a line when it starts to decline. After that an SNR enters the early Sedov phase of evolution, with the steepest constant slope of an evolutionary path corresponding to the full Sedov phase of evolution. The lines terminate at the end of the late Sedov phase. The Σ–D tracks obtained by these supercomputer simulations do not cover the radiative phases of evolution. Radio observers can use the observationally derived quantities in Fig. 1 to locate newly detected SNRs somewhere in the Σ–D plane. Moreover, they can estimate the SN explosion energies and the ambient densities into which SNRs expand. An interesting aspect obtained from these simulations is that the evolutionary paths in Fig. 1 are very close together and intercept one another. Due to this we can expect that a unique Σ–D track does not exist for each analysed SNR. Therefore we must use the next method to refine the determination: the form of the spectrum of a newly observed SNR should be checked. The spectral index value (α), or whether or not a spectrum is curved, can be analysed. By using Table 1 and the analysis in ref. [3], more information on the evolutionary status of an SNR can be obtained. Generally, from the form of the SNR spectrum we can estimate the age of an analysed SNR — is it young or evolved?

By inspection of Table 1, we can see that the concave-up spectra can represent both young and evolved SNRs. Also, at the start of SNR evolution the spectral index slopes are steeper than 0.5. This is a consequence of strong non-linear DSA effects. On the other hand, for evolved SNRs the steeper spectral slopes are consequences of low-efficiency particle acceleration. We can combine the Σ–D and spectral form methods. If we again do not obtain a unique conclusion, we should use one further method: the eqp calculation for determination of the magnetic field strengths. Determination of the magnetic field strengths by the eqp method is a very straightforward process.

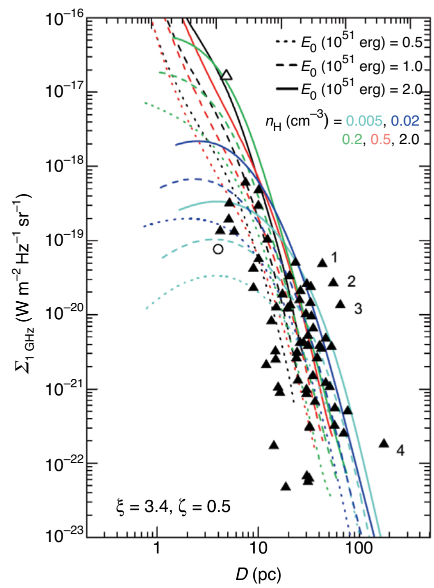

Fig. 1 | Radio surface brightness-to-diameter diagram for SNRs at 1 GHz. Different line colours correspond to the different ambient densities of the circumstellar environment, n_H, and different line styles correspond to the different explosion energies, E_0. Experimental data represent 65 Galactic SNRs with known distances (triangles) taken from ref. [16]. Cas A is shown with an open triangle, while an open circle represents the youngest Galactic SNR, G1.9+0.3 (see ref. [7] for detailed modelling). Numbers 1–4 represent specific SNRs: (1) CTB 37A, (2) Kes 97, (3) CTB 37B and (4) G65.1+0.6. The figure shows evolutionary tracks for representative cases with an injection parameter $\xi = 3.4$ and nonlinear magnetic field damping parameter $\zeta = 0.5$. For more details see ref. [5]. Figure adapted with permission from ref. [5], AAS.

Observers should obtain from their observations the radio flux density at a particular frequency for an SNR, the spectral index, distance, and volume-filling factor (the volume of the synchrotron-emitting shell). These quantities can be combined

Table 1 | Different forms of SNR radio spectra

	Linear radio spectra			Curved radio spectra	
	$\alpha = 0.5$	Steep ($\alpha > 0.5$)	Flat ($\alpha < 0.5$)	Concave-up	Concave-down
Theoretical predictions					
Young SNRs	Test particle DSA ($\alpha = 0.5$)	Amplified magnetic field + quasi-perpendicular shocks	DSA (Fermi 1) + Stochastic acceleration (Fermi 2)	Non-linear DSA	Observational effects + DSA effects
Evolved SNRs	DSA	Test particle DSA	DSA + stochastic acceleration	Synchrotron + bremsstrahlung or spinning dust	Observational effects + DSA effects
Observational examples					
Young SNRs	–	For example, Cas A, G1.9+0.3	–	For example, Cas A, Tycho, Kepler, SN 1006	–
Evolved SNRs	For example, Monoceros and Lupus loops	For example, HB 3, HB 9	For example, W 28, Kes 67, 3C434.1	For example, IC 443, 3C391, 3C396	For example, S 147, HB 21, J0455-6838

Theoretically predicted spectral forms and some examples of observationally obtained radio spectra of shell-like, composite and mixed-morphology SNRs from ref. [3].

according to the theory developed in refs. [6–8] or, for simplicity, the eqp calculator can be used. After a split second the eqp magnetic field strength (and minimal total energy) will be calculated according to the final formulae from the abovementioned papers. The higher the calculated magnetic field, the younger the newly observed SNR.

The evolutionary status of an SNR can be preliminarily determined with optimal reliability by combining all three of the previously described methods. This concept for determining the evolutionary status of (Galactic and several extra-Galactic) SNRs was successfully applied to newly observed SNRs in, for example, refs. [9–11].

As an example, we present the analysis for the one of the youngest Galactic SNRs, Cassiopeia A (Cas A, approximately 330 years old). This SNR is the most radio-luminous SNR in our Galaxy. It has been studied many times and we know the phase of evolution that it is in. Cas A is shown by an open triangle in Fig. 1. The interesting fact that should be emphasized here is that SNRs do not exhibit the rising part of surface brightness evolution for expansion in higher-than-average environmental densities[5]. The estimated evolutionary status of Cas A using Fig. 1 is as follows: it is a young SNR, expanding in a dense environment, between average and high density, and the SN explosion energy is higher than average. The spectral index of Cas A is very steep ($\alpha = 0.77$) and the spectrum is slightly concave-up[12]. These findings support that Cas A is a very young SNR in which non-linear effects provide the curved spectral form[3,12]. The electron eqp magnetic field strength is 760 μG (ref. [8]), in agreement with an observed average magnetic field strength of >500 μG (ref. [13]). By using the concept presented here, Cas A is a young SNR in the late free-expansion phase. This conclusion is in very good agreement with the known facts for Cas A. It is a so-called oxygen-rich SNR, which evolves in a high-density medium (~3 cm^{-3}; see ref. [14] and references therein). The Σ–D tracks from Fig. 1 indicate that Cas A is expanding in a slightly lower density environment, and due to this they give a slightly older evolutionary status. Here we should emphasize that, given its place on the radio Σ–D diagram, Cas A is not a standard SNR. It is an extremely bright Galactic SNR (see Fig. 1). We obtain a reliable evolutionary phase for Cas A even though it is an object of extreme characteristics.

The youngest Galactic SNR is G1.9+0.3 (120 years old[15], signified by an open circle in Fig. 1). It is a low-brightness remnant for its diameter, in contrast to Cas A. Our estimate is that it is in the free-expansion phase around maximum brightness. Observations from the last forty years demonstrate that the radio brightness of this SNR is increasing (for details, see ref. [15]). Again, we obtain a reliable evolutionary phase for G1.9+0.3, but we miss its sub-phase.

Finally, by using the concept presented here, we can freely conclude that the preliminary estimate of the evolutionary status for a newly observed SNR can be achieved in a very simple and fast way.

Summary

Here we have suggested a new concept for the preliminary determination of the evolutionary status of SNRs. This is based on a combination of three different methods that use data obtained by radio observations in continuum. The first is based on the Σ–D tracks, where we try to find the location of an observationally obtained radio surface brightness and corresponding diameter of an SNR in the Σ–D plane. The second is based on the form of the radio spectra. Finally, the third is based on the magnetic field strengths estimated by the equipartition calculation. Each of these methods have been continuously developed over the last two decades by the Belgrade SNR Research Group. ❐

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Competing interests

The author declares no competing interests.