ABSTRACT.

G320.4–01.2 is a complex radio and X-ray source, coinciding on the sky with the young energetic pulsar B1509–58. A young pulsar embedded in a SNR would seem to accord with expectations, but previous observations suggest that all may not be what it seems. Controversy persists over whether the pulsar and the SNR are associated, and as to what causes the remnant’s unusual appearance. To answer these questions, we have undertaken a set of high-resolution radio observations of the system. We present the results of this study, which provide new evidence that PSR B1509–58 is associated with and is interacting with G320.4–01.2.

1. Introduction

G320.4–01.2 (MSH 15–52) and the young pulsar PSR B1509–58 are one of the best-studied but least-understood pulsar / supernova remnant (SNR) pairings. We here summarise the results of a new radio study of this system; this work is discussed in more detail by Gaensler et al (1998).

Existing radio and X-ray images of G320.4–01.2 are shown in Figure 1. The radio image shows two distinct components: a bright centrally-condensed source to the north (coincident with the optical nebula RCW 89), and a fainter filamentary arc to the south. In X-rays three bright sources are apparent: the pulsar itself, a surrounding non-thermal pulsar-powered nebula (a “plerion”), and thermal emission from the RCW 89 region.

1.1. Are G320.4–01.2 and PSR B1509–58 associated?

The distance of 4.2 kpc determined for RCW 89 through $\text{H}_1$ absorption (Caswell et al 1975) is roughly consistent with the pulsar’s dispersion-measure distance of ~6 kpc. However the ages of the pulsar and SNR are hard to reconcile: assuming standard supernova and ISM parameters results in an age for the SNR in the range $(6–21) \times 10^3$ yr.
G320.4–01.2 is not a typical, roughly circular, shell SNR. Some of the possible explanations for its unusual morphology are that it is actually multiple remnants, that its appearance is the result of expansion into a complicated environment, or that an outflow from the pulsar (see §1.1) has distorted its shape.

2. New Observations and Results

We have carried out extensive observations of the region with the Australia Telescope Compact Array (ATCA). The main results are as follows:
Fig. 2. Radio / X-ray comparison of the region near PSR B1509–58. The grey-scale corresponds to 20 cm ATCA data, while the contours represent ROSAT PSPC data (Greiveldinger et al 1995). The pulsar’s position is marked by a “+”; corrugations seen in the radio emission are low-level artifacts resulting from deconvolution.

- $\text{H}_\text{i}$ absorption is consistent with all radio components of G320.4–01.2 being at a distance $5.2 \pm 1.4$ kpc (PSR B1509–58 is too weak to obtain $\text{H}_\text{i}$ absorption against).

- In the region surrounding PSR B1509–58, radio emission from G320.4–01.2 is highly linearly polarised ($\sim 60\%$) and has the same rotation measure as the pulsar. As shown in Figure 2, within this plateau of emission is a channel of reduced radio emission which closely follows a collimated X-ray feature (part of the plerion powered by PSR B1509–58).

- At high resolution, the radio peak of RCW 89 forms a ring of linearly polarised knots of spectral index $\alpha \approx -0.5$ ($S_\nu \propto \nu^\alpha$). The radio and X-ray morphologies of the region are compared in Figure 3, where it can be seen that there is a marked
3. Discussion

The radio emission seen near the pulsar in Figure 2 has a distinctly high fractional polarisation, has the same rotation measure as the pulsar, and shows an anti-correspondence with X-ray emission associated with the plerion. Thus it seems certain that this radio emission is in some way connected with the pulsar. We would argue that this region is not radio emission from the plerion itself, since the radio emission is not centred on the pulsar, nor are the X-ray bright regions bright in the radio. Indeed any radio plerion is expected to be too faint to be detectable (e.g. Seward et al 1984). Figure 2 demonstrates that radio emission is enhanced along the sides of the collimated X-ray feature but not within it. This anti-correspondence can be explained if the X-ray feature is a focussed relativistic jet or outflow, as has been argued by Brazier & Becker (1997). Radio emission is then produced by shocks generated in a cylindrical sheath around the jet, as seen for SS 433 (Hjellming & Johnston 1986, 1988) and possibly for the jet in Vela X (Frail et al 1997).

The polarisation and spectral index of the knots in Figure 3 indicate that at least in the radio, their emission mechanism is synchrotron. The X-ray / radio correspondence suggests that the X-ray emission from these knots might also be synchrotron, and indeed a single power law can be extrapolated from their radio flux densities through to those measured by ROSAT HRI. Although in X-rays the RCW 89 region as a whole is thermal, a power-law spectrum from the knots could easily be hidden within.

The problems raised in §1.1 involving an outflow from the pulsar can be resolved if
these compact synchrotron knots are interpreted as the point of interaction between the pulsar outflow and the SNR. The energy in these knots can be easily accommodated by the pulsar spin-down, and it is easier to see how these features, rather than the whole extended RCW 89 nebula, might be the termination of the energetic outflow. The rest of the RCW 89 region may be part of the SNR blast wave.

Correspondences between the discrete radio components of G320.4–01.2 and the overall X-ray remnant, together with the results of H\textsubscript{i} absorption, argue that G320.4–01.2 is a single SNR. Its agreement in rotation measure with PSR B1509–58, and the evidence seen in Figures 2 and 3 for outflow and interaction respectively, make a strong case that SNR G320.4–01.2 and PSR B1509–58 are associated.

If the SNR and pulsar are indeed associated, then the age discrepancy between them must somehow be resolved. We find that a consistent picture of a system of age 1700 yr can be constructed if a supernova of high energy or low mass ($E_{51}/M_{ej} \sim 2$) occurred near the edge of an elongated cavity. As well as the SNR’s large apparent age, this model can also explain the two well-separated components of the remnant’s radio morphology, the significant offset of the pulsar from the SNR’s centre and the faintness of any plerion at radio wavelengths (see Gaensler et al 1998 for a detailed discussion of this model).

4. Conclusions

Observations with the ATCA have resulted in the following main conclusions:
1. The radio components of G320.4–01.2 are all part of a single SNR at a distance $5.2 \pm 1.4$ kpc and with an age $\lesssim 1700$ yr.
2. PSR B1509–58 is physically associated with G320.4–01.2. The pulsar emits twin jets or collimated outflows of relativistic particles. One of these jets is seen as a collimated X-ray feature surrounded by a polarised radio sheath, while the other interacts with the SNR in the form of radio/X-ray knots within RCW 89.
3. SNR G320.4–01.2 was formed in a supernova of high kinetic energy or low ejected mass ($E_{51}/M_{ej} \sim 2$) which occurred near the edge of a low-density cavity.

A variety of further observations can support or refute these claims. For example, the cavity we propose may be visible in H\textsubscript{i} emission, while forthcoming AXAF observations will allow a detailed study of the physical conditions within the knots. While we have side-stepped the details of how pulsar jets might be generated and how they interact with the SNR, it seems that PSR B1509–58 can now join the Crab, Vela and possibly PSR B1951+32 in showing evidence for collimated outflows; evidence is mounting that spherically symmetric pulsar winds are a gross over-simplification.

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