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High-resolution X-ray imaging of the supernova remnant MSH 15-52

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ABSTRACT

We present high-resolution *ROSAT* observations of PSR 1509−58 and the supernova remnant MSH 15-52. The pulsar itself is resolved from the surrounding synchrotron nebula as a 75 per cent pulsed point source. The synchrotron emission forms a broad, elongated cross centred on the pulsar, and an extrapolation of the north-western arm of the cross to the supernova remnant rim coincides with the RCW 89 Hα nebula. More than half of the X-ray flux in RCW 89 is resolved into a partial ring of tight knots that closely follow the radio morphology of the region. We suggest that all of the X-ray emission in the field of PSR 1509−58 can be explained if the system is similar to the 'torus' and 'jets' of the Crab pulsar synchrotron nebula, but viewed at more than ~70° to the pulsar spin axis. For current theories, this inclination favours pulsar emission from the outer, rather than the inner, magnetosphere. The luminosity of RCW 89 is driven in our model by the pulsar wind, which suggests that the NW–SE axis of the synchrotron nebula marks a collimated outflow along the pulsar spin axis, making PSR 1509−58 the third example of an isolated pulsar with a polar outflow.

Key words: stars: neutron – pulsars: individual: PSR 1509−58 – supernova remnants – X-rays: stars.

1 INTRODUCTION

PSR 1509−58 is a 1550-yr-old pulsar sited within MSH 15-52, a supernova remnant (SNR) with an estimated age of 2100–10 000 yr (Seward et al. 1983). Despite controversy over the difference in their apparent ages, it is generally accepted that MSH 15-52 and the pulsar PSR 1509−58 are associated and that the SNR's age is probably exaggerated as a result of either expansion into a low-density region or an unusually powerful supernova explosion (Seward et al. 1983). It has also been suggested that the southern fragments of the nebula could be part of a separate SNR to the south-east (Milne, Caswell & Haynes 1993). On the north-west rim of MSH 15-52 is a filamentary optical nebula, RCW 89, that has been described both as a bright spot on the rim of MSH 15-52 and as a separate, whole supernova remnant (Caswell et al. 1975; van den Bergh, Marscher & Terzian 1973). Throughout this paper, it will be assumed that MSH 15-52 and PSR 1509−58 are associated, and a distance of 5 kpc will be adopted as a compromise between the pulsar dispersion measure distance of 5.9 kpc (Taylor & Cordes 1993) and the estimated distance of 4.2 kpc to RCW 89 (Caswell et al. 1975).

The pulsar is itself remarkable. With a dynamical age of 1550 yr, PSR 1509−58 is the second youngest in a population of almost 700 rotation-powered pulsars, but has a rotation period of 150 ms, much longer than the periods of other very young pulsars like the Crab ($\tau_d \sim 1260$ yr, $P \approx 33$ ms) and PSR 0540−69 ($\tau_d \sim 1650$ yr, $P \approx 50$ ms). Its period derivative $\dot{P} = 1.2 \times 10^{-12}$ s s^{-1} is, however, one of the largest measured for any pulsar. Recently detected at photon energies up to 2 MeV by the *Compton Gamma Ray Observatory* satellite (Carramiñana et al., in preparation), PSR 1509−58 has also joined the exclusive group of seven pulsars that are observed in gamma-rays; the gamma-ray pulse is a broad, asymmetric hump and lags the radio peak by 0.32 in phase (Ulmer et al. 1994).

Observations of MSH 15-52 have manifold interest: to study a rare, young pulsar and its immediate surroundings; to determine whether the SNR emission is driven by the impulse from the supernova or by the pulsar's continuing energy input; and to find whether RCW 89 is a feature on the SNR rim or is a separate physical object. The system has therefore been the subject of a number of X-ray observations. Data from the *Einstein* and *Ginga* satellites (Seward & Harnden 1982; Seward et al. 1983; Kawai et al. 1991) established two main areas of X-ray emission: the bright pulsar, PSR 1509−58, with its surrounding 10×6 arcmin^2 synchrotron nebula, and an extended source coincident with RCW 89.

More recently, *ROSAT* PSPC images have revealed X-rays from the body of MSH 15-52 and from patches on the south-east rim (Trussoni et al. 1996). *ASCA* observations (Tamura et al. 1996) show that the non-thermal synchrotron nebula extends to connect spatially with thermal emission from RCW 89.

In this paper, we present results of the *ROSAT* HRI observations of PSR 1509−58, including detailed images of the RCW 89 region

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and the synchrotron nebula around the pulsar. The observations, split between a 19.6-ks observation in 1994 February and a 2.7-ks observation in 1994 September, together total an on-axis exposure of 22.3 ks. While a companion paper (Becker & Brazier, in preparation) will address the pulsed point source in detail, this present paper will concentrate more on the morphological features revealed by these high-resolution images.

2 THE SYNCHROTRON NEBULA AROUND PSR 1509−58

2.1 Observed morphology of the PSR 1509−58 nebula

Seward et al. (1983, 1984) inferred the existence of a synchrotron nebula from an elliptical halo around the pulsar on their *Einstein* IPC map and a power-law X-ray spectrum. They deduced that the nebula had an extent of 10×6 arcmin^2, but were unable to make a detailed spatial analysis of the emission from their IPC data and did not detect the nebula in higher resolution *Einstein* data. Greiveldinger et al. (1995) have more recently proposed, on the basis of *ROSAT* PSPC data, that the nebula contains a compact core of radius < 40 arcsec.

Fig. 1 shows the high-resolution soft X-ray image of MSH 15-52 from the sum of the *ROSAT* HRI observations. The bright source close to the centre is the pulsar; the diffuse synchrotron nebula and the clumpy emission around RCW 89 are also visible, and there is no detectable emission from other parts of the rim of MSH 15-52.

The large-scale features of the synchrotron nebula form into a rough, right-angled cross centred on the pulsar, with further substructure also visible. The longer of the two perpendicular 'axes' of the nebula stretches from the RCW 89 region in the north-west to the south-east, where it curves at large distances away to the east (cf. Trussoni et al. 1996). The shorter axis is confined to within ~3 arcmin of the pulsar and is approximately perpendicular to the long axis.

Finer elements are visible as faint filaments and small-scale features, including enhanced emission 1–2 arcmin from the pulsar to the south, south-west and north-west. These small features are also visible in the PSPC data in the wings of the point source, and are therefore not attributable to photon noise or aspect errors. Initial examination of the HRI data also suggested a 10-arcsec circular halo around the pulsar. Such a close halo around a bright point source is not easy to examine with the HRI, which is known to produce asymmetries in point sources, and the point spread function of which is known imperfectly (David et al. 1993). To avoid such uncertainties we used the pulsed source, which must be point-like (diameter < 150 light-ms), to construct an effective point spread function. Using this, we find that the total emission from the vicinity of the pulsar can be described adequately by the radial profile of the pulsed source plus a background corresponding to the average surface brightness of the synchrotron nebula between 10 and 40 arcsec from the pulsar. There is therefore no evidence for a sharp rise in X-ray emission close to the pulsar.

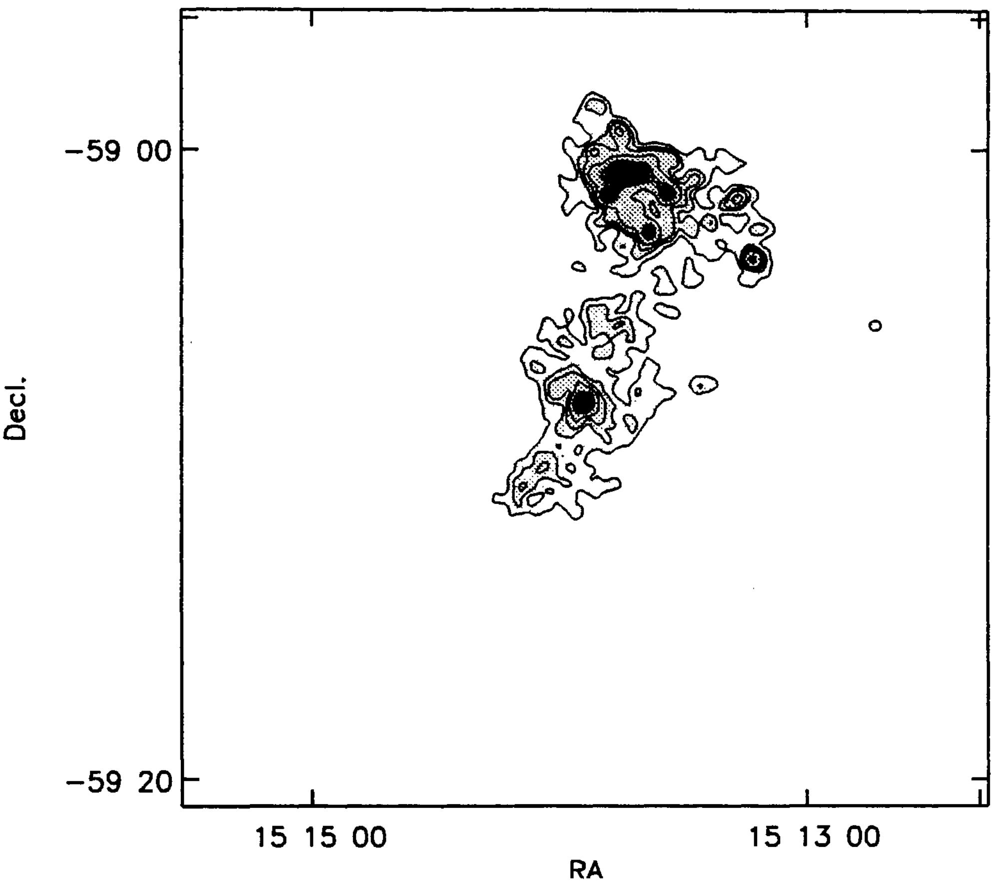

Figure 1. High-resolution soft X-ray image of MSH 15-52. The pulsar is the bright point source at the centre of the image, and RCW 89 is resolved as a clump towards the top. The diffuse synchrotron nebula around the pulsar is also visible. The image has been smoothed on a scale of 10 arcsec and contours are at 1.5, 2.0, 2.5, 3.0, 3.5 and 7.0 smoothed count pixel^{-1}.

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In the wider, anisotropic synchrotron nebula, a radial profile is less useful, and we have estimated the flux in this nebula from the number of excess photons in a 10×10 arcmin^2 box about the pulsar position. The box dimensions were chosen to encompass all of the nebula whilst excluding the emission around RCW 89. The pulsar point source was estimated from our effective point spread function to have a flux of ~0.04 count s^{-1} and to be approximately 75 per cent pulsed; the (vignetting-corrected) background was estimated from an area centred 10 arcmin west, 5 arcmin south of the pulsar to be 0.41 ± 0.005 count s^{-1} in a 10×10 arcmin^2 box. From this procedure the synchrotron nebula flux is estimated to be 0.32 ± 0.01 count s^{-1} in the area stated. Our estimate that the pulsed flux is ~75 per cent of the point source is higher than the fraction measured by Greiveldinger et al. (56 ± 10 per cent) probably because the HRI data permit better resolution of the pulsar from the extended emission.

2.2 Synchrotron nebula morphologies compared

The synchrotron nebula around PSR 1509−58 is the most luminous soft X-ray source in MSH 15-52. The flux from the 10×6 arcmin^2 nebula amounts to 10 times the pulsed flux from the pulsar, similar to the ratio in the Crab. Also like the Crab, the nebula has a striking degree of symmetry that, with hindsight, is also visible in the PSPC data (cf. Greiveldinger et al. 1995). There is substructure within the nebula, but we find no evidence for a separate, compact nebula, and suggest that the < 40-arcsec nebula found by Greiveldinger et al. (1995) is not a distinct region.

There are few well-studied pulsar X-ray synchrotron nebulae, and, although the basic production of the X-rays has been readily explained as synchrotron radiation from a fast pulsar wind, the diversity of spatial forms is not understood. Of all the X-ray synchrotron nebulae, the Crab is the best-studied example. The entire nebula exhibits a cylindrical symmetry that can be traced back to the central pulsar and Pelling et al. (1987) summarize the arguments that the axis of symmetry marks the pulsar rotation axis. The symmetry is clear in X-ray and optical images of the vicinity of the pulsar, and at *ROSAT* energies is seen in two short 'jets' along the postulated direction of the pulsar spin axis and a perpendicular 'torus' in the pulsar's equatorial plane (Brinkmann, Aschenbach & Langmeier 1985; Hester et al. 1995). The observations are interpreted as tracers of an equatorial particle wind and an additional polar outflow (Brinkmann et al. 1985; Michel 1991; Arons & Tavani 1994). (Although the polar outflows are referred to as 'jets', this is a description of their appearance and does not necessarily imply that they are physically jet-like.)

The Vela pulsar has also been found to possess two long X-ray 'jets' in addition to the compact X-ray nebula immediately surrounding the pulsar (Smith & Zimmermann 1985; Markwardt & Ögelman 1995). The jets lie approximately along the projected direction of the neutron star spin axis, and the strong suggestion they give of a collimated pulsar outflow has attracted some attention (e.g. de Jager, Harding & Strickman 1996). Offset nebulae around several other pulsars could be explicable as Vela-like systems with outflows that are inclined to the line of sight. Biconical pulsar outflows have also been suggested by Manchester (1987) as an explanation for bipolar radio SNRs.

As in the Crab and Vela pulsars, it is difficult to construct the remarkable symmetry seen in the X-ray synchrotron nebula around PSR 1509−58 unless the structure is linked to the pulsar rotation axis. We suggest that a plausible explanation for the morphology is that the system is geometrically similar to the Crab synchrotron nebula, with axial and equatorial emission regions. While neither axis of the observed cross can be resolved into the torus seen in the Crab, if one axis of the nebula is a torus viewed at high inclination ζ, then even the shorter axis constrains the inclination of the spin axis to the line of sight to be $\zeta \gtrsim 70°$. A high inclination is also suggested by the position of the pulsar under both arms of the cross, since relativistic beaming would enhance one side of the torus section of an inclined nebula. This geometry accounts well for the symmetry and large-scale features of the nebula, even though it is clearly a simplification of the total structure.

3 RCW 89

3.1 The X-ray structure of RCW 89

RCW 89 is an optical nebula on the north-western edge of MSH 15-52, and consists of a dense tangle of Hα filaments. Its compact appearance suggests that it is a complete physical object, but enhanced optical images show some filaments well beyond the main structure, and support suggestions that the nebula is part of MSH 15-52 (Seward et al. 1983). The radio object (Caswell, Milne & Wellington 1981) is dominated by an extended source that covers the site of the optical filaments; radio polarization measurements show that the bright parts have an aligned magnetic field, which is difficult to explain in terms of a separate SNR (Milne et al. 1993). Despite extensive observations, there is no consensus on the nature of RCW 89.

Fig. 2 is an expanded view of the RCW 89 region in soft X-rays. The emission is clumpy, with at least half of the flux coming from a number of tight knots. Table 1 lists the positions and count rates of the most prominent knots, which we have numbered N0–N10 in an extension of the notation used by Trussoni et al. (1996). Note that both tabular quantities are calculated on the premise that the sources are point-like; all of the labelled knots bar N0 can be represented reasonably well by the radial profile of the pulsar emission. N0–N9 lie within the central 'horse-shoe' of the radio emission, and echo its orientation and morphology closely. The knots appear not to be discrete sources, but to be the peaks in a complex emission structure. They are not closely connected with the many optical filaments, nor can any of them convincingly be identified with a star in the field. Diffuse emission is visible around the knots, and follows the outline of the broader radio source.

3.2 What is RCW 89?

With its optical filaments and strong, complex radio and X-ray emission, RCW 89 is difficult to classify. It has some extensions tangential to the shell of MSH 15-52, but otherwise appears not to link well with the SNR, and a number of authors have therefore considered the possibility that RCW 89 is a separate object, particularly that it is a supernova remnant. The concept of a separate remnant suffers several difficulties, however, including the unidirectional radio polarization across RCW 89 and the presence of optical filaments and radio and X-ray emission well beyond the central compact object. Alternative explanations make RCW 89 part of MSH 15-52: either the expanding shell of MSH 15-52 may have encountered a dense clump of interstellar material at this point, or the nebula could be the working surface terminating the stream of particles responsible for the north-western arm of the synchrotron nebula. This last explanation is analogous to the interpretation of the Vela X region as the termination of the softer X-ray jet emanating from the Vela pulsar (Markwardt & Ögelman 1995;

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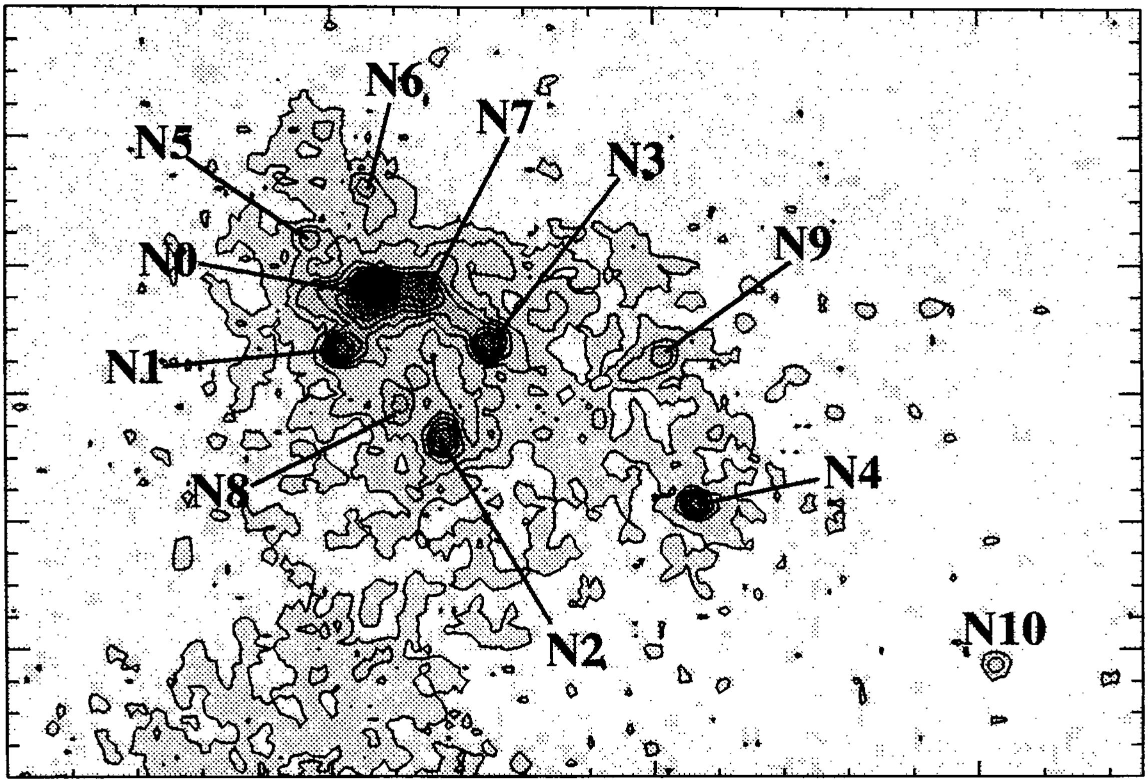

Figure 2. An expanded view of RCW 89 in soft X-rays. The image has been slightly smoothed as in Fig. 1 to suppress noise, and is compressed on a logarithmic scale. Individual knots are labelled, and the more diffuse structure is also visible.

cf. Greiveldinger et al. 1995) and it is also the explanation favoured by Tamura et al. (1996) on the basis of spatially resolved X-ray spectra.

Manchester (1987) included MSH 15-52 as an example of a radio SNR driven possibly by biconical pulsar beams, with one beam directed towards RCW 89. The X-ray data support this concept. The NW–SE axis of the synchrotron nebula has the appearance of a double cone of half-angle 10°–20°, both in the HRI image and in the PSPC data, and extrapolation of this cone to RCW 89 matches the angular extent and position of the latter well. The location of RCW 89 on the limb of the SNR is consistent with the high inclination of the pulsar spin axis postulated above, and bombardment by a hollow, conical beam also explains the 'horse-shoe' morphology as part of a ring of emission: the projected dimensions are again consistent with an inclination of ~70°.

Table 1. Details of compact X-ray sources in the RCW 89 vicinity, assuming that all of the sources are point-like. The X-ray position and flux of the pulsar are also shown.

Label	RA(2000)	Dec(2000)	*ROSAT* name	cts/s	error
PSR	15 13 55.3	−59 08 12	RX J1513.9-5908	0.036	0.001
N0	15 13 46.7	−59 00 55	RX J1513.7-5900	0.046	0.002
N1	15 13 49.2	−59 01 36	RX J1513.8-5901	0.012	0.001
N2	15 13 39.3	−59 02 46	RX J1513.6-5902	0.014	0.001
N3	15 13 34.8	−59 01 31	RX J1513.5-5901	0.019	0.001
N4	15 13 14.0	−59 03 37	RX J1513.2-5903	0.008	0.001
N5	15 13 52.4	−59 00 16	RX J1513.8-5900	0.007	0.001
N6	15 13 46.6	−58 59 36	RX J1513.7-5859	0.008	0.001
N7	15 13 40.6	−59 00 53	RX J1513.6-5900	0.020	0.001
N8	15 13 43.9	−59 02 20	RX J1513.7-5902	0.008	0.001
N9	15 13 17.6	−59 01 42	RX J1513.2-5901	0.006	0.001
N10	15 12 44.0	−59 05 42	RX J1512.7-5905	0.002	0.0003

4 CONCLUSIONS

High-resolution X-ray images of PSR 1509−58 have shown that this unusual pulsar lives in a complex environment. The direct emission from the region of the pulsar magnetosphere is approximately 75 per cent pulsed and is resolved from the structure of the surrounding synchrotron nebula. Fine structure seen close to the pulsar is confirmed by lower resolution PSPC images. The coarser, dominant features of the synchrotron nebula form a right-angled cross, which we interpret as a system similar to the synchrotron nebula around the Crab pulsar, with emission confined to equatorial and polar regions. The position of the pulsar is found to be very close to the intersection of the axes of the synchrotron cross, and neither axis can be resolved into a equatorial 'torus', implying that our line of sight is at $\gtrsim 70°$ to the pulsar spin axis.

The estimate of a highly inclined line of sight is in contrast to previous estimates of 34°–52° (Beskin, Gurevich & Istomin 1993), made on the assumption that the X-rays were from a hot polar cap. That assumption now seems unlikely, since the soft X-ray pulse matches the profile and phase of the one seen in hard X-rays and low-energy γ-rays, and probably originates in the magnetosphere. We conclude that our new measurement should be used in preference to the earlier estimate.

Knowledge of the pulsar viewing angle is critical to an understanding of the pulse emission mechanism. A high inclination is favourable to generic models in which the outer magnetosphere is the source of X- and γ-radiation (e.g. Romani & Yadigaroglu 1995)

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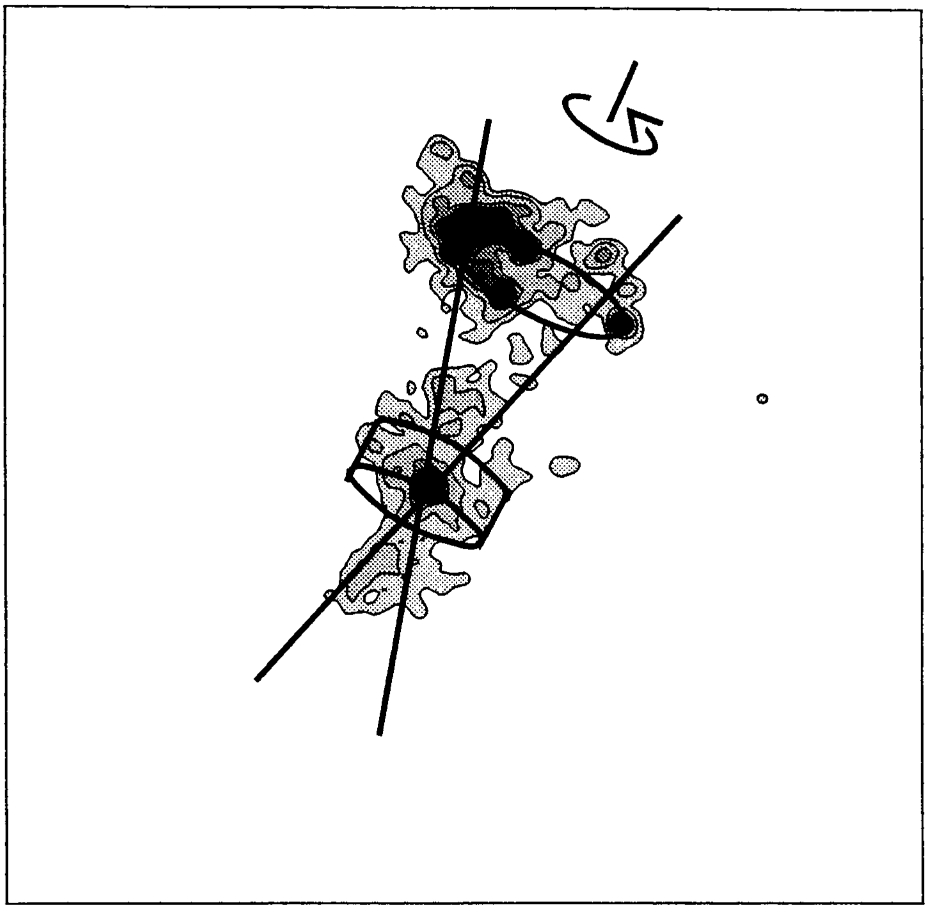

Figure 3. Sketch of suggested geometry for PSR 1509−58 and the nebulous emission driven by its outflowing wind, for a viewing inclination of 70°.

and, with the broad pulse, is unfavourable to models that invoke particle acceleration close to the magnetic poles of the neutron star.

The NW–SE axis of the synchrotron nebula has a bi-conical appearance and is directed in the north-west to the RCW 89 region on the SNR rim. RCW 89 has proved to be a highly complex site of X-ray emission, with bright knots that map the radio emission very closely and form a 'horse-shoe' or partial ellipse within an area of diffuse X-radiation. Of several suggestions that have been proposed in the past to explain RCW 89, we find that this peculiar region is most probably a portion of the rim of the SNR and that its luminosity is driven by the pulsar. This is supported by the alignment with one of the two axes of the pulsar synchrotron nebula, by the match in angular extent between RCW 89 and the extrapolated north-western arm of the synchrotron nebula, by the apparently thermal spectrum and by the presence of the fainter X-ray and radio sources on the opposite side of the supernova remnant. Furthermore, the location of RCW 89 on the limb of the SNR is consistent with a high pulsar inclination. If our interpretation of RCW 89 is correct, then the NW–SE axis of the synchrotron nebula appears to follow the spin axis of the neutron star rather than the equator, with the suggested geometry sketched in Fig. 3. PSR 1509−58 is then the third pulsar to show an outflow along the spin axis, joining the Crab and Vela pulsars. The emission and transport of a considerable flux of fast particles in a polar, collimated outflow have not yet been much studied in the context of isolated pulsars, but clearly have much to offer in our understanding of the emissions of these objects and of their effects on the visible structure of their supernova remnants. The ubiquity of the phenomenon must now be tested by deep observations of other young pulsars.

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