PKS 1209 – 51/52: a supernova remnant with a well-defined magnetic field

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ABSTRACT
The supernova remnant PKS 1209 – 51/52 displays remarkable structural symmetry and a well-defined tangential magnetic field. Total intensity and polarization maps are presented at 2.4, 4.8 and 8.4 GHz. The distribution of Faraday rotation, projected magnetic field and depolarization, deduced from these maps, are presented. The Faraday rotation is low, with a mean value of $-39$ rad m$^{-2}$, and there is little depolarization, consistent with a uniform magnetic field.

Key words: magnetic fields – polarization – ISM: individual: PKS 1209 – 51/52 – supernova remnants – radio continuum: ISM.

1 INTRODUCTION
The radio sources PKS 1209 – 51/52 (G 296.5 + 10.0) are seen as two well-separated opposing crescents – the opposite sides of the supernova remnant (SNR) shell G 296.5 + 10.0. This remnant is well away from the Galactic plane, and its symmetrical form suggests that it is expanding in a region free of small-scale irregularities in the interstellar medium (ISM). Whiteoak & Gardner (1968) identified it as an SNR after detecting typically 15–25 per cent linear polarization at 2650 MHz at selected points around the shell. Comparison with the direction of the polarization at other frequencies yielded a near-zero Faraday rotation, and suggested a tangential magnetic field direction (i.e. one running parallel to the SNR edge). A more extensive polarization survey was made at 5 GHz by Milne & Dickel (1975) and, later, these authors quoted Faraday rotations of between $+16$ and $+38$ rad m$^{-2}$ in the eastern arm, and between $-18$ and $-5$ rad m$^{-2}$ in the western arm of G 296.5 + 10.0 (Dickel & Milne 1976).

In a detailed analysis of the structure of G 296.5 + 10.0, Roger et al. (1988) concluded that the symmetry, so obvious in this object, was the result of the SNR expanding into an orderly aligned magnetic field with a substantial component normal to the line of sight, and that the tangential field direction was the result of compression of this ambient magnetic field – a model first proposed for old SNRs by van der Laan (1962). In this paper, we present maps of the total intensity and polarization at 2.4, 4.8 and 8.4 GHz; the last is at a somewhat higher frequency and resolution than used previously.

2 OBSERVATIONS
Observations were made with the Parkes 64-m radio telescope at 2.4, 4.8 and 8.4 GHz. At each frequency the dual-channel FET receivers accept right- and left-hand circular polarization from the feed horn. These are then converted to linear Stokes parameters $Q$ and $U$ in the correlation polarimeter. A linearly polarized radio signal transmitted from the telescope vertex, together with the sources 3C 138, 3C 348 and Hydra A, was used for calibration. Flux densities and polarization parameters for the calibration sources were taken from the Parkes Catalogue (Wright & Otrupcek 1990) and the compilation of Tabara & Inoue (1980), and are given, together with the telescope and receiver parameters, in Table 1.

The observations were made at 2.4 GHz in 1987 October, at 4.8 GHz in 1992 August, and at 8.4 GHz in 1988 November and 1989 February. The field was scanned at each fre-

| Table 1. Observing parameters for G 296.5 + 10.0. |
|-----------------|-----|-----|-----|
| Frequency (GHz) | 2.4 | 4.8 | 8.4 |
| Bandwidth (MHz) | 300 | 500 | 500 |
| $T_{\text{sys}}$ (K) | 48  | 65  | 70  |
| Beamwidth (arcmin) | 8.3 | 4.5 | 3.0 |
| $S_{\text{Hydra}}$ (Jy) | 27.1 | 13.8 | 8.1 |
| $S_{3C348}$ (Jy) | 26.5 | 12.7 | 7.2 |
| $S_{3C138}$ (Jy) | 6.6  | 4.2  | 2.4  |
| Pol $3C348$ ($^\circ$/per cent) | 37/4.8 | 25/8.9 | 21/10.8 |
| Pol $3C138$ ($^\circ$/per cent) | 166/9.0 | 170/10.1 | 173/10.7 |

The flux densities are taken from the Parkes Catalogue (Wright & Otrupcek 1990), and the polarization parameters are from Tabara & Inoue (1980). The probable errors on these polarization data are $\pm 2^\circ$ in angle and $\pm 3$ per cent of the polarization values given here.
frequency in both declination and right ascension; the data were logged on a 2.0-arcmin grid at 2.4 and 4.8 GHz, and on a 1.2-arcmin grid at 8.4 GHz. The correlation receiver has a much higher sensitivity against gain instabilities in polarization than in total intensity and is less sensitive to poor weather conditions. G 296.5 + 10.0 has a fairly low surface brightness; four separate maps were added to produce the 8.4-GHz data (Fig. 1), and two maps were added at 4.8 and 2.4 GHz to produce Figs 2 and 3, respectively. All of the total-intensity maps, however, show the presence of noise on this low-brightness source. The rms noise on each map is quoted in the figure caption. The total-intensity maps were digitally integrated to obtain the flux densities quoted in Table 2. Uncertainties in these flux densities have been estimated, allowing for errors in observations of the calibration sources, and establishment of the base level over which the integration was performed; the latter is by far the largest uncertainty.

3 RESULTS

In the 8.4-GHz total intensity map (Fig. 1a) we see contours of a source with fairly low surface brightness. The contour unit is 30 mJy beam$^{-1}$, the peak brightness is only 240 mJy beam$^{-1}$, and the integrated flux density of the source is 18.8 ± 3 Jy. In Fig. 4, we have convolved the 843-MHz Molonglo Observatory Synthesis Telescope (MOST) map (Roger et al. 1988) to the resolution of the 8.4-GHz data. Allowing for the lack of short spacings on the MOST array and the consequent loss of broad structure in Fig. 4, the general appearance is similar to the 8.4-GHz map (Fig. 1a), indicating that the spectral index is fairly constant over the entire remnant. The discrete field sources in the 843-MHz map are not prominent at 8.4 GHz, suggesting that they have steep, non-thermal spectra.

The intensity of the 8.4-GHz polarized radiation of G 296.5 + 10.0 (Fig. 1b) is relatively low. In many directions it was comparable with the background noise, and Milne’s (1992) method was used to suppress the noise, i.e. the polarization intensity is weighted by the uniformity in direction at that point. (In Fig. 1b we accepted < 20° as the criterion of uniformity.) The degree of polarization in Fig. 1(b) is typically 5 to 15 per cent and somewhat higher over the eastern arm than over the western. The only area where it is substantially greater than 20 per cent is along the outer edge of the eastern arm, near the total-intensity peak, where it exceeds 35 per cent.

The 4.8-GHz total-intensity and polarization maps (Figs 2a and b, respectively) are similar to the partial map of Milne & Dickel (1975). The total integrated flux density is 23 ± 3 Jy, and the percentage polarization is similar in its distribution and magnitude to that at 8.4 GHz (Fig. 1a), indicating, as we shall see in a later section, that the 8.4/4.8-GHz depolarization is low.

The 2.4-GHz total-intensity and polarization maps (Figs 3a and b, respectively) are of poor resolution compared with the other data, and the total-intensity map suffers from a low signal-to-noise ratio. They were, however, included to correct any ambiguities that might occur in the Faraday rotation computation to follow. The integrated flux density is 33 ± 3 Jy, and the polarization exceeds 25 per cent in some areas.

4 DISCUSSION

4.1 Radio spectrum

The flux densities derived in this paper, together with the published values, are listed in Table 2, and the spectrum derived from those is displayed in Fig. 5. The best-fitting, power-law spectrum, $\alpha = -0.48$, is indicated. The 4.9-GHz point (from Milne & Dickel 1975) spoils an otherwise excellent fit to a spectral index of $-0.5$. Since their flux density was from an incomplete map, and since they do not quote an error, it is probably best to omit this value, in which case we would accept a spectral index of $-0.5$.

4.2 Faraday rotation

The 8.4-GHz polarization map was convolved to 4.5 arcmin for comparison with the 4.8-GHz polarization map and, from these, we derived the distribution of Faraday rotation measure shown in Fig. 6. Here we have limited the display to those points where the polarization intensity exceeds 5 per cent of the peak polarization at each frequency, thus removing most of the more uncertain rotation measure (RM) estimates. Furthermore, from the 2.4-GHz polarization data (Fig. 3b) we are able to say that there are no additional rotations between these two frequencies. The RM is negative over most of G 296.5 + 10.0, but with a region of positive RM in the upper eastern arm and in two smaller regions in the central area; these three regions of positive RM are indicated in Fig. 5. In general, the values of RM tend to be more negative in the western than in the eastern arm. Mean values of RM are $-73 \, \text{rad m}^{-2}$ in the south-west, $-92 \, \text{rad m}^{-2}$ in the north-west, $-41 \, \text{rad m}^{-2}$ in the south-east, $+44 \, \text{rad m}^{-2}$ in the area outlined in the north-east, and $-57 \, \text{rad m}^{-2}$ to the north of this latter area. The overall mean RM is $-39 \, \text{rad m}^{-2}$. The effects of lower brightness in the western arm are obvious in the higher noise levels on that side of the figure. It is worth remarking that, whilst the extreme values of RM lie along the edges of the arms (which is to be expected, since the polarization intensities there are more uncertain), they have the same sign as the more moderate, adjacent values. This puzzled us, and so we examined the full RM map for an explanation. It appears that the noisiest pixels have RM of the same sign but, moving a little further off the arms, the RM becomes random. It would seem, then, that the RM increases around the two arms, and that the longitudinal component of magnetic field retains the same direction as in the adjacent arm.

4.3 The direction of the magnetic field

Fig. 7 shows the direction of the magnetic field deduced from the 8.4- and 4.8-GHz polarization maps. This assumes synchrotron emission (i.e. with the magnetic field perpendicular to the intrinsic E vector). In this figure, the ‘vector’ magnitude is the geometrical mean of the 8.4- and 4.8-GHz polarization intensities at each point and indicates the reliability of the direction at that point. A ‘tangential’ projected magnetic field can be seen, well defined in the brighter eastern arm but with a peculiar ‘stepped’ pattern in the western arm.
Figure 1. (a) Total intensity contours and (b) polarization $E$ vectors of the SNR G296.5+10.0 at 8.4 GHz. The contour interval is 30 mJy beam$^{-1}$, and the rms noise in this map is 8 mJy beam$^{-1}$. The polarization scale is indicated by a 100-mJy beam$^{-1}$, $E$ vector in the inset (the maximum polarization intensity is 80 mJy beam$^{-1}$), and the rms noise is 2.5 mJy beam$^{-1}$. The half-power beamwidth is 3.0 arcmin.
Figure 2. (a) Total-intensity contours and (b) polarization $E$ vectors of G196.5 + 10.0 at 4.8 GHz. The contour interval is 66 mJy beam$^{-1}$. The polarization scale is indicated by a 100-mJy beam$^{-1}$ $E$ vector in the noise (a) and in the synthesized beam (b). The half-power beamwidth is 4.5 arcmin.
Figure 3. (a) Total-intensity contours and (b) polarization $E$ vectors of G 296.5 + 10.0 at 2.4 GHz. The contour interval is 278 mJy beam$^{-1}$. The polarization scale is indicated by a 400-mJy beam$^{-1} E$ vector in the inset (the maximum polarization intensity is 423 mJy beam$^{-1}$). The rms noise is (a) 60 mJy beam$^{-1}$ and (b) 10 mJy beam$^{-1}$. The half-power beamwidth is 8.3 arcmin.
4.4 The 8.4/4.8-GHz depolarization ratio

Fig. 8 shows the 8.4/4.8-GHz depolarization ratio $R$ (= percentage polarization at 8.4 GHz/percentage polarization at 4.8 GHz); the data have been limited to those regions of G296.5 + 10.0 where the total intensity is greater than 10 per cent of the peak value. The figure also shows higher depolarization in the eastern arm of G296.5 + 10.0 than in the western. In fact, in the western arm there are many values of $R$ less than unity, making $R$ physically unacceptable; they probably reflect the poor signal-to-noise ratio in total intensity, coupled with the low brightness in the western arm. As an additional indication of the low depolarization, we estimated the integrated percentage polarization at each frequency with the 4.8- and 8.4-GHz data, convolved to

Table 2. Integrated flux densities for G296.5 + 10.0.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Flux density (Jy)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>182</td>
<td>Mills, Slee &amp; Hill (1961)</td>
</tr>
<tr>
<td>629</td>
<td>62±4</td>
<td>Whiteoak &amp; Gardner (1968)</td>
</tr>
<tr>
<td>1410</td>
<td>40±4</td>
<td>Whiteoak &amp; Gardner (1968)</td>
</tr>
<tr>
<td>2400</td>
<td>33±3</td>
<td>This paper</td>
</tr>
<tr>
<td>2650</td>
<td>30±3</td>
<td>Whiteoak &amp; Gardner (1968)</td>
</tr>
<tr>
<td>4800</td>
<td>23.3±3</td>
<td>This paper</td>
</tr>
<tr>
<td>5000</td>
<td>30</td>
<td>Milne &amp; Dickel (1975)</td>
</tr>
<tr>
<td>8400</td>
<td>18.8±3</td>
<td>This paper</td>
</tr>
</tbody>
</table>

Figure 5. The radio spectrum of G296.5 + 10.0, using data given in Table 2. The three values obtained in this present paper are indicated by filled circles. The best-fitting spectral index of $-0.48$ is shown. A spectral index a little steeper than this ($\alpha = -0.5$) is suggested in the text.

Figure 4. The 843-MHz MOST map of G296.5 + 10.0 at 843 MHz (Roger et al. 1988) convolved to 3-arcmin resolution for comparison with Fig. 1(a). Contours are shown at 20, 50, 100, 200 and 400 mJy beam$^{-1}$.
8.3-arcmin resolution and accepting data only where the total intensity exceeded 10 per cent of its peak value at each frequency. These integrated values are 12.6, 11.7 and 10.1 per cent at 8.4, 4.8 and 2.4 GHz, respectively — an overall value of depolarization (corresponding to $R = 1.08$ between 8.4 and 4.8 GHz) which is low.

5 CONCLUSIONS

This paper describes G 296.5 + 10.0 as two moderately symmetrical arcs which are usually interpreted as two sides of a spheroidal shell SNR. The radio spectral index of $-0.5$ is typical of an SNR. G 296.5 + 10.0 is strongly polarized, in excess of 30 per cent at both 8.4 and 4.8 GHz, and exhibits very low depolarization between these two frequencies.

The distributions of magnetic field and rotation measure contribute little that was not previously known for this source, except in the details resulting from complete coverage at higher frequency and resolution. The startling point about the magnetic field is that it is so clearly tangential, an alignment not so well defined in any other SNR. It is hard to imagine that the interstellar field and density are so uniform over the size of this object that van der Laan's (1962) model of interstellar compression can be solely responsible for shaping the remnant and its magnetic field. Should the usually accepted spheroidal model for G 296.5 + 10.0 be questioned? Does it really have circular symmetry, or does it consist of two arms formed by the ejection of relativistic particles along pre-existing magnetic fields, with the magnetic field somehow drawn out along these arms?

The rotation measure is negative (i.e. the magnetic field is directed away from the observer) over the western arm, but is closer to zero (and indeed positive in the north-east) over the eastern arm. This suggests a twist in the magnetic field along the arms (or around the shell if preferred) such that the field is twisting away as it moves north in the western arm and vice versa in the eastern. The generally low rotation measure suggests, however, that there is not a strong component of magnetic field along the line of sight in either the remnant or in the ISM in this direction.

The low depolarization in this source (integrated 8.4/4.8-GHz depolarization ratio = 1.08) reflects the uniformity in the direction of polarization. Also, there is a correlation between the more negative rotation measure and a lower depolarization in the western arm, while the reverse is true in the eastern, but this may simply reflect the poorer signal-to-noise ratio in the western arm. We have remarked on the lack of randomness in the sign of the rotation measure along the edges of the arms, and cannot explain this phenomenon further.
Figure 7. Direction of the magnetic field over G 296.5 + 10.0. The magnitude of these 'vectors' is proportional to the mean value of the polarization at 4.8 and 8.4 GHz, and provides an indication of the reliability of the field direction at that point.

Figure 8. Depolarization ratio (8.4/4.8 GHz) over G 296.5 + 10.0. Depolarization ratios of 1, 2, 4, 7 and 11 are indicated in the inset. Values are shown only where the total intensity at both frequencies is > 10 per cent of the peak intensity.
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REFERENCES