Letter to the Editor

The Radio Structure of 3 C 358, the Remnant of Kepler’s Supernova

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Received May 16, 1975

Summary. 21 cm synthesis observations of 3 C 358 show the remnant to be a slightly elliptical object, roughly 3.2 × 4.2 in size with the major axis north-south. The eastern, western and southern edges are sharp while to the north the emission dies away more gradually. There is no clear indication of shell structure. The source is linearly polarized, typically by 3%. 3 C 358 is compared briefly with the remnant of Tycho’s supernova and it is shown that despite their dissimilar structures, in terms of energy content and other physical parameters the two objects are nearly alike.

Key words: Kepler’s supernova — young supernova remnants

Introduction

Only a limited number of high resolution radio studies have been made of 3 C 358, the remnant of Kepler’s supernova of 1604. They include lunar occultations analyzed by Talen (1965) and Hazard and Sutton (1971); and interferometric observations made by Milne (1969), Fomalont (1971) and Hermann and Dickel (1973). In these measurements structural information was not obtained in all position angles. Thus an east-west extent of about 3′ appears to be fairly well determined, while the north-south size, which may be larger, remains somewhat uncertain.

It is important to determine the radio structure of 3 C 358 for it is one of the few galactic remnants which can be confidently classified as young (less than 1000 years old), indeed whose age is extremely well known. Recently, Van den Bergh et al. (1973) have noted that the most prominent nebulsity associated with Kepler’s remnant is very different from filaments found in Tycho’s, the remnant of SN 1572. One would especially like to know whether, like Tycho’s remnant, 3 C 358 has a shell type radio structure.

Observations

3 C 358 was observed with the Westerbork Synthesis Radio Telescope at 21 cm in 1971. Högblom and Brouw (1974) have discussed the Westerbork instrument in some detail, Weiler (1973) described the technique of polarization measurement, while Van Someren Grèvé (1974) has outlined the data reduction procedure. Table 1 summarizes parameters relevant to the present observations.

Because of its low declination, 3 C 358 can be observed for no more than about seven hours from Westerbork. Moreover, since the telescopes on the shortest baselines partially shadow one another at extreme hour angles and there are uncertainties in the refraction correction we have limited the observations to an even shorter time. Thus the resolution plane coverage (see Fig. 1) is incomplete, producing a distorted synthesized beam with deep (∼30%) negative sidelobes to the east and west, and a low level plateau extending several minutes of arc north and south. For this reason we have used the so-called CLEAN technique (Högblom, 1974) to deconvolve the raw maps from the synthesized antenna pattern. An extensive package of CLEAN and related programs has been developed in Leiden by Harten; they will be discussed in some detail in a forthcoming publication (Harten, 1976). The technique, like most model fitting procedures,
obtains solutions which are not necessarily unique. The extent to which source structure can be correctly recovered depends on such factors as the complexity of the true brightness distribution, its intensity, the completeness of the resolution plane coverage and the degree to which the data have been properly calibrated. A necessary though by no means sufficient condition which must be satisfied is that with the removal of the source brightness, all sidelobes, grating responses and large scale ripple must also disappear from the entire map plane.

The observations of 3C 358 passed this test particularly well, for the remainder after CLEAN amounted to no more than a few percent of the peak source intensity. The brightness components recovered have been convolved with an artificial beam to “restore” the source intensity distribution. The restoring function was an elliptical gaussian with half power dimensions of 25″ × 68″. Each map has been restored on the noise background left over after the CLEAN operation; in this way imperfections are not artificially suppressed.

**Results**

The data can be best summarized as restored maps of the total intensity (Stokes parameter I) and linearly polarized (Q and U) brightness distributions. There is no significant circular polarization (V). A contour plot of the I map (Fig. 2) shows most of the emission to come from a slightly elongated central region, with weak extensions to the north and south. The existence of the latter is uncertain in view of the absence of observations along north-south baselines. Observations with the Molonglo radio telescope at 408 MHz with a resolution of about 2.9″ show no evidence of these weak extensions; however the measurements are not quite precise enough to completely discount their existence. Since they could be artefacts of the synthesized beam, imperfectly removed in the CLEAN procedure, we consider their existence tentative pending confirmation with more complete data.
The bulk of the emission is restricted to the region inside the 0.2 f.u. per beam contour. The contour spacings to the east, west and south are consistent with steep outer edges, but there is a more gradual boundary to the north. Peaks to the east and west produce a saddle point near the remnant's geometrical center. The widths of the eastern and western boundaries must certainly be less than 0.5. If it is assumed that they are unresolved, the east-west diameter is 3.2. The north-south extent, as arbitrarily defined by an assumed sharp edge to the south and the 0.2 f.u. per beam contour to the north, is 4.2. Although clearly not a shell remnant in the mold of 3 C 10 (Strom and Duin, 1973), the presence of a weak or partial shell structure cannot be ruled out.

The linearly polarized intensity [i.e., $(Q^2 + U^2)^{1/2}$] appears as a contour plot in Fig. 3, while the position angle and degree of polarization are displayed as vectors in Fig. 4.

The polarized emission is strongest near the central saddle point where it is about 4% of the total intensity. In several places where the degree of polarization reaches about 10% the emission is weak, and the errors are consequently rather high. The position angles are, for the most part, about 90°, though along the eastern flank they are nearer 135°.

**Discussion**

Our results appear generally consistent with previous studies of 3 C 358. Talen's (1965) description of an object 4' × 7' in size with the major axis approximately north-south is a fair assessment of Fig. 2, but only if the low brightness regions are included. The strip distribution in position angle 58° produced from a lunar occultation (Hazard and Sutton, 1971) shows steep outer edges and a diameter of 2.8. The more gradual slope on its northeastern side could be due to the manner in which the curved limb of the moon passed across the weak emission to the north. The occultation strip distribution also contains a significant central dip which is in excellent positional agreement with the saddle point mentioned above. However, the Westerbork map contains no evidence of the additional source (4) mentioned by Hazard and Sutton, and we conclude that it arose from a fault on the occultation record.

Milne (1969) has presented interferometer fringe amplitudes for baselines out to 1900 wavelengths. We have not attempted to incorporate these results in our analysis. Milne's curves are for position angles 3°, 68° and 93° and show that the source is essentially circularly symmetric on a scale of about 1'. They are in good agreement with our corresponding curves which were restricted to position angles 73° to 107°. In the north-south direction Milne's results are consistent with our description of the main region of emission. The effect of the weak emission to the north and south would not be obvious on Milne's curves. Fomalont (1971) has also measured fringe amplitudes in the north-south direction, and they are similar to Milne's.

We have also constructed several one-dimensional strip scans of the remnant, with a resolution of about 30°. The distribution in position angle 82° agrees very well with that obtained at a wavelength of 11 cm by Hermann and Dickel (1973), when one takes account of the difference in resolution. Hermann and Dickel also present an 11 cm map whose gross features—peaks east and west of center, weak extensions north and south as well as several lesser details—are identifiable in our 21 cm map. The authors suggest that their map shows "...that
Table 2. Properties of 3 C 358 and 3 C 10

<table>
<thead>
<tr>
<th></th>
<th>3 C 358</th>
<th>3 C 10</th>
</tr>
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<tbody>
<tr>
<td>Angular diameter, arc'</td>
<td>$3.2 \times 4.2'_{\pm}$</td>
<td>7.8</td>
</tr>
<tr>
<td>Distance (assumed), kpc</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Linear diameter, pc</td>
<td>$9.3 \times 12.2'_{\pm}$</td>
<td>13.6</td>
</tr>
<tr>
<td>Distance from Galactic plane, pc</td>
<td>1200</td>
<td>140</td>
</tr>
<tr>
<td>Average expansion rate, km s$^{-1}$</td>
<td>$12400 \times 16300'_{\pm}$</td>
<td>16700</td>
</tr>
<tr>
<td>Radio power (1400 MHz), W Hz$^{-1}$ sterad$^{-1}$</td>
<td>$1.4 \times 10^{16}$</td>
<td>$1.4 \times 10^{16}$</td>
</tr>
<tr>
<td>Total radio energy$^{a}$, erg</td>
<td>$2.9 \times 10^{49}$</td>
<td>$7.7 \times 10^{49}$</td>
</tr>
<tr>
<td>Equipartition magnetic field strength$^{b}$, G</td>
<td>$2.1 \times 10^{-4}$</td>
<td>$2.2 \times 10^{-4}$</td>
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$^{a}$) East-west by north-south, the northern boundary arbitrarily taken as 20% of the peak brightness.

$^{b}$) Assuming that the total energy in protons exceeds that in electrons by a factor of 100, that the radio spectrum extends from 10 MHz to 10 GHz, and that 3 C 358 is a prolate spheroid.

Conclusion

Thus 3 C 358 has a radio morphology unlike that of most other young remnants, and most significantly unlike that of 3 C 10. It is interesting that Van den Bergh et al. (1973) also find the optical nebulosity associated with 3 C 358 to be very different from that in 3 C 10. These authors point out that in Kepler's remnant the radio and optical expansion rates appear to be inconsistent, and they suggest that the material in the nebulosity may already have been external before the supernova occurred in 1604. Whether this could also account for the curious radio structure, or indeed whether there is any relationship between the optical and radio peculiarities, are matters best left until more detailed observational studies have been carried out.

Acknowledgements. This project was initiated while J. Sutton was associated with the Laboratorio di Radioastronomia CNR, University of Bologna. J. Sutton wishes to thank Prof. H. van der Laan for the opportunity to use the Westerbork facilities. The Westerbork Synthesis Radio Telescope is operated by the Netherlands Foundation for Radio Astronomy with the financial support of the Netherlands Organization for the Advancement of Pure Research (Z.W.O.).

Note Added on 19 June, 1975: Since this manuscript was prepared, a 5 GHz synthesis map of 3 C 358 has been published by Gull [Monthly Notices Roy. Astron. Soc. 171, 237 (1975)]. These measurements, which include information from north-south interferometer spacings and have a resolution more than twice as good as ours, show an irregular shell structure. Its outer boundary closely follows the 0.3 J. u. per synthesized beam contour in Fig. 2. The indentation in the steep southern edge of our map corresponds to a large gap in the shell.

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