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VLBI OBSERVATIONS OF THE OH MEGAMASER IN IC 4553 (ARP 220)

P. J. DIAMOND
National Radio Astronomy Observatory[1]
R. P. NORRIS
Commonwealth Scientific and Industrial Research Organization
W. A. BAAN
Arecibo Observatory[2]
AND
R. S. BOOTH
Onsala Space Observatory
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ABSTRACT

IC 4553 (Arp 220) is an infrared-luminous galaxy at a redshift of 0.018 which shows characteristics of both Seyfert and starburst activity and is believed to be the result of a recent merger. It is also distinguished by its OH megamaser which is one of the most luminous OH masers discovered. The VLBI observations of the OH reported here reveal compact structure in the megamaser which is consistent with the suggested presence of two Seyfert nuclei in IC 4553.

Subject headings: galaxies: individual (IC 4553, Arp 220) — galaxies: nuclei — galaxies: structure — interferometry — masers

I. INTRODUCTION

The peculiar galaxy IC 4553 (Arp 220) has a total infrared luminosity (10^{12} $L_{\odot}$) which places it well within the domain of quasars, and yet a high nuclear extinction condemns it to appear in the visual waveband as two 14.4 mag nuclear regions surrounded by faint extended structure and bisected by a dust lane. There is evidence (e.g., Joseph, Wright, and Wade 1984) for starburst activity in the outer nuclear region, whereas infrared (Norris 1985; Becklin and Wynn-Williams 1987) and CO observations (e.g., Scoville *et al.* 1986) reveal a compact ($\leq 3''$) energetic source in the inner nuclear region.This Seyfert source announces its true nature in broad infrared lines (DePoy, Becklin, and Geballe 1987).

Shocked molecular hydrogen (Joseph, Wright, and Wade 1984) and optical plumes (Heckman, Armus, and Miley 1987) suggest an input of mechanical energy to the galaxy which may be readily explained only by a recent merger. This hypothesis is supported by continuum radio observations (Baan and Haschick 1987; Norris 1988) which are interpreted as showing two separate Seyfert nuclei.

Radio evidence for molecular gas in the nucleus of IC 4553 is provided by the detection of OH maser emission (Baan, Wood, and Haschick 1982) and CO emission (e.g., Sanders and Mirabel 1985). Recently Scoville *et al.* (1986) used the Caltech millimeter interferometer to observe the CO emission and have shown that nearly 10^{10} $M_{\odot}$ of molecular gas is concentrated in a radius of < 700 pc at the nucleus. The broad velocity width of the CO profile may indicate considerable turbulence in this region.

Baan and Haschick (1984) and Norris *et al.* (1985) have mapped the OH maser emission and have shown it to mimic the radio continuum emission. This implies that the OH gas in the disk of the galaxy is in a state of population inversion (pumped by far-infrared; Norris 1984; Henkel, Güsten, and Baan 1987) and acts as an amplifier of the radio-continuum image, producing an amplified image of the source in the OH line.

Here we report VLBI observations in which milliarcsec structure was detected. These observations not only confirm this model but also constrain the size of the nuclei yet further.

II. OBSERVATIONS

IC 4553 was observed at a frequency of 1636.48 MHz (corresponding to the redshifted 1667 MHz OH transition) for 11 hr on 1984 October 25 using four stations (Jodrell Bank 76 m, Effelsberg 100 m, Onsala 26 m, Westerbork 5 antennas) of the European VLBI network. Because of the low sensitivity of the Onsala baselines, no fringes on IC 4553 were detected to Onsala, and so these data were not used in the final data reduction. The minimum fringe spacing available was ~ 40 mas. At each station, data were recorded on standard Mk II terminals using a 2 MHz bandwidth. The data were correlated at the Max-Planck Institut für Radioastronomie, Bonn in spectral line mode, with 128 channel spectra being written to tape. The resultant frequency resolution of the data was 18.75 kHz, corresponding to a velocity resolution of 3.43 km s^{-1}. The total velocity range covered was only ~ 366 km s^{-1} and was centered at a velocity of 5465 km s^{-1}.

Due to the low signal-to-noise ratio of the total power spectra, the antenna gains could not be calibrated by the normal method used for spectral line VLBI data (e.g., Reid *et al.* 1980). Instead, the data were calibrated using the methods of Cohen *et al.* (1975) by utilizing the system temperatures measured at the time of the observations and known gain curves. The compact continuum source BL Lac was observed several times during the observing run for the purposes of

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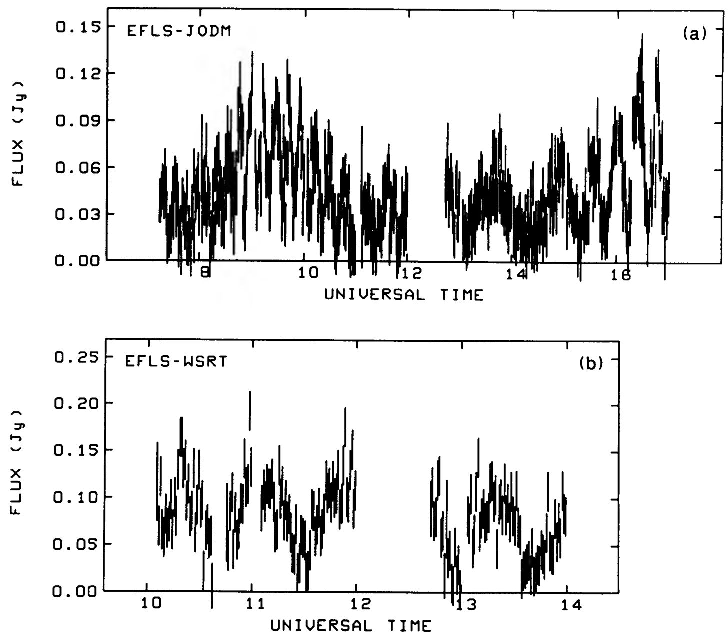

FIG. 1.—Typical plots of the fringe amplitude as a function of time of the OH emission from IC 4553 at 1637 MHz. Fig. 1*a* shows the fringe amplitude averaged over the velocity range 5336 km s^{-1} to 5450 km s^{-1} for the baseline Effelsberg to Jodrell Bank; note the 12 hr and 1 hr modulation periods. Fig. 1*b* shows the fringe amplitude averaged over the same velocity range for 4 hr of the data on the Effelsberg to Westerbork baseline; note the ~1 hr modulation of the amplitudes.

bandpass correction; these data were also used to establish the consistency of the calibration. An example of the resulting visibilities is shown in Figure 1. The delays were calibrated using BL Lac, and a large clock drift (~650 ns day^{-1}) observed at Jodrell Bank was corrected for.

The data were then phase-referenced to a group of averaged channels containing the strongest emission (the range defined by A in the total power spectrum shown in Fig. 2). Examination of the visibility function of this group of averaged channels demonstrated that any departures from a pointlike structure were minimal and would not affect the structure of the maps made from the phase-referenced data. The calibration just described and the resultant maps were made using the AIPS package at NRAO.

III. RESULTS

Because of the limited data available, we first consider the results that are immediately apparent from the calibrated data, an example of which is shown in Figure 1. Several significant results are apparent from this data with no further processing. First, fringes are detected with a visibility of about 0.4, indicating the presence of compact components with sizes less than about 30 mas. Second, the visibility data are modulated by beating on a 1 hr scale, indicating the presence of multiple components separated by about 1″. Third, the envelope of the visibility plots is modulated on a 12 hr time scale, indicating the existence of structure on a 0″.1 scale.

The data may be processed further to produce maps, but in view of the limited quality of the data, we are necessarily cautious about interpreting the details of these maps. The resulting maps of the OH emission integrated over four velocity ranges, together with the total power spectrum obtained on the Effelsberg antenna, are shown in Figure 2. The rms noise level in the maps is ~1.1 mJy beam^{-1}. No continuum emission was detected but clearly two principal regions of line emission (marked I and II) can be seen in the maps separated by approximately 1″ (1″.0 is equivalent to ~350 pc assuming $H_0 = 75$ km s^{-1} Mpc^{-1}). In addition maps 2*b* and 2*c* show that region II is clearly also a double (IIa and IIb), with the two components separated by 0″.14 (see Table 1). Components I and II are visible in the 18 cm map of Norris *et al.* (1985), in the 2 cm map of Baan *et al.* (1987), and in the 6, 2, and 1.3 cm maps of Norris (1988). The weaker westerly component of the Norris *et al.* map is now believed to be spurious (S. Unger, private communication).

VLBI observations normally do not preserve absolute phase and therefore we do not know the absolute positions of the VLBI maser components. However, due to the similarity of the overall structure we observed in IC 4553 compared to that observed by Norris *et al.* (1985) and Baan and Haschick (1984) we are confident that region I corresponds to the western component detected in the continuum observations, and region II to the eastern component. The position angles of components IIa and IIb relative to I are 109° and 116°, respectively. The 18

TABLE 1

COMPONENT RELATIVE POSITIONS

Feature	ΔR.A.	ΔDecl.	Peak Brightness (mJy beam^{-1})	Center Velocity (km s^{-1})	ΔV (km s^{-1})
I	0″.0	0″.0	48 ± 2	5346 ± 5	77 ± 5
IIa	0.992 ± 0.016	−0.344 ± 0.016	20 ± 2	5418 ± 5	66 ± 5
IIb	0.912 ± 0.016	−0.450 ± 0.016	15 ± 2	5386 ± 5	55 ± 5

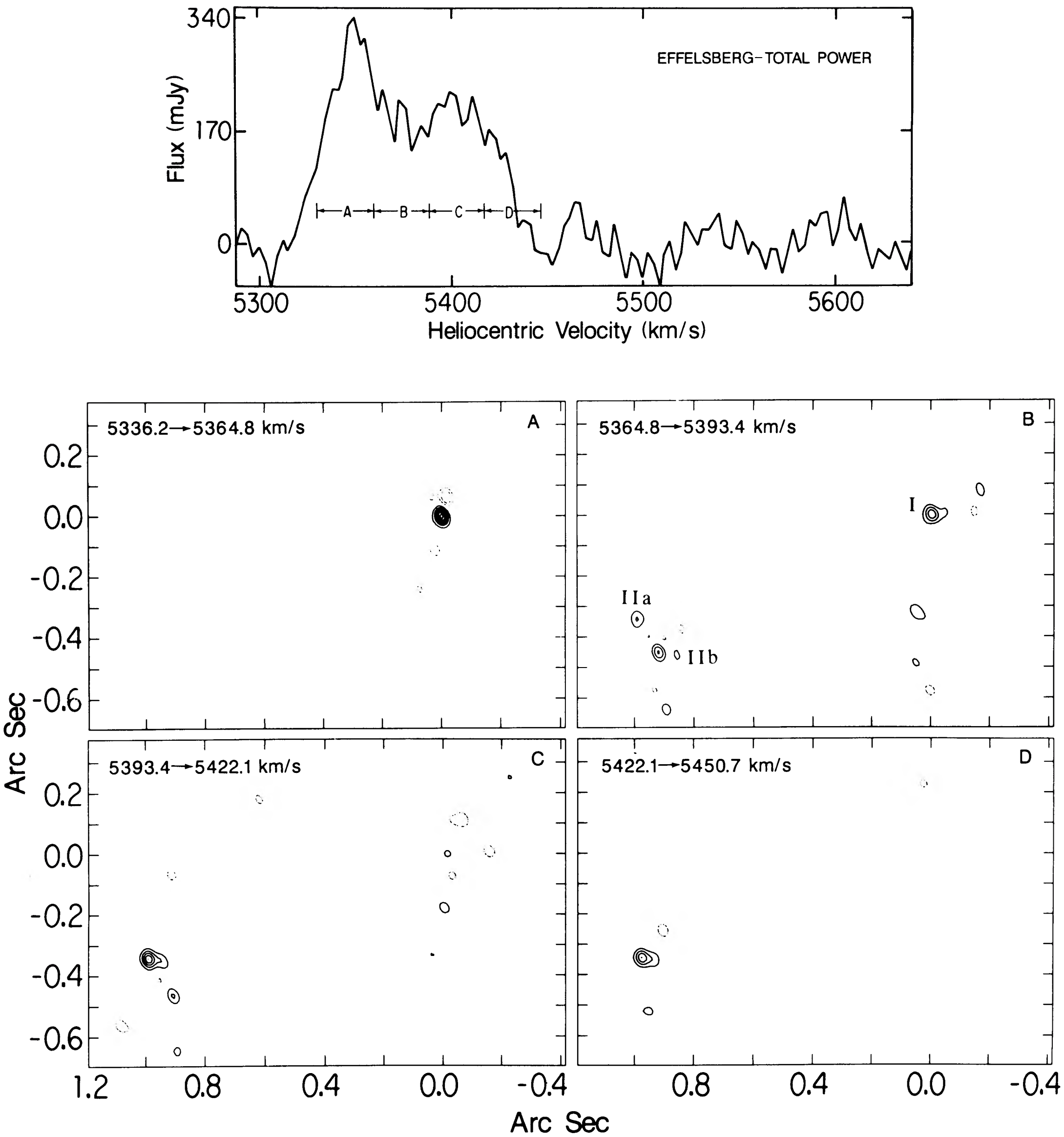

FIG. 2.—The total power spectrum of the 1667 MHz OH emission from IC 4553 and maps of the OH emission integrated over four velocity ranges. The velocity ranges are indicated on the maps and correspond to the letters shown on the spectra. The contour levels are 4, 8, 12, 16, 20, 24, 28, 32, 36, 40 mJy beam^{-1} area except for map A in which they are 6, 12, 18, 24, 30, 36, 42, 48, 54, 60 mJy beam^{-1} area. Negative contours are shown dashed. The maps were restored with a CLEAN beam of 47 × 34 mas. The regions marked I, IIa, and IIb are referred to in the text.

cm eastern component observed by Norris *et al.* (1985) covers a position angle range of 100°–112° with respect to the central component; this is significantly different from our VLBI result. However, components IIa and IIb do lie within the area covered by the lowest contour of the 18, 6, and 2 cm maps. The masers detected with VLBI need not necessarily correspond with the continuum emission peaks, but probably amplify the most compact continuum spots. Since the position of the most compact spots within the continuum emission regions is unknown the apparent difference between our maps and the continuum maps is not totally unexpected.

Approximately 60% of the line flux seen in the single-dish measurements does not appear in the VLBI maps and may therefore be attributed to emission from a region larger than ~0".15.

IV. DISCUSSION

a) The Nature of the Maser Components

The unresolved components seen in Figure 2 each have a size less than 0".01, or 3.5 pc. Such a small size could be caused by either the emission being from high-gain masers similar to those in our own Galaxy (e.g., W3OH), or from low-gain amplification of a compact background object. Our observations show the unresolved emission to have a velocity width of ~60 km s^{-1}, and a flux density of ~0.1 Jy. Following the arguments of Baan and Haschick (1984) and by comparison with the properties of a typical high-gain Galactic maser, we estimate that ~10^7 OB stars in a 3.5 pc diameter volume would be required to maintain the observed emission; we regard this as an implausibly high stellar density.

The larger scale properties of megamasers are well explained in terms of low-gain amplification of radio continuum emission by clouds of OH pumped by far-infrared (Baan and Haschick 1984; Henkel, Güsten, and Baan 1987); this hypothesis also naturally explains the small-scale emission. Norris (1988) and Baan *et al.* (1987) have demonstrated the presence of radio continuum cores of size ≤ 50 pc at the same positions as those of the compact components discussed here. Furthermore, region II in Figure 2 is slightly resolved in the 2 cm and 1.3 cm maps of Norris (1988), to an extent (85 pc) consistent with the break-up of components we observe. Since the masers mimic the continuum structure, we are satisfied that the low-gain maser hypothesis simply and naturally explains the VLBI results.

b) The Kinematics of the Masers

The central velocities and the FWZP of the three maser components are listed in Table 1. As can be seen the velocity changes in a systematic way across the source, with a total change of ~ 70 km s^{-1} between components I and II. This is similar to the values obtained by Baan and Haschick (1984) and Norris *et al.* (1985). However, our higher resolution observations reveal that there is also velocity structure within component II. The velocity difference between components IIa and IIb is ~ 30 km s^{-1} implying a local velocity gradient of ~ 200 km s^{-1} $arcsec^{-1}$ in the vicinity of region II. Similar gradients may have been detected in the optical domain (Norris 1985).

c) The Nature of the Continuum Source

Norris *et al.* (1985) have suggested that the masers are amplifying images of Seyfert nuclei. This appears more likely than the alternative possibility, that the background source is a starburst nucleus, since (1) Helou, Soifer, and Rowan-Robinson (1985) have shown that the radio emission from starburst nuclei is dominated by cosmic rays and so is unlikely to contain significant compact structure; and (2) the assumption of a low maser gain would imply the brightness temperature of the background sources must be in excess of 10^8 K, which is well above that seen in normal starburst galaxies but is consistent with observations of Seyfert nuclei.

Norris (1988) and Baan and Haschick (1987) have suggested that IC 4553 is a merger of two galaxies. We believe our data support this supposition since (1) the pumping conditions for regions I and II are known to be totally different (Baan and Haschick 1987; Henkel, Güsten, and Baan 1987); (2) region II is dynamically different from region I in that is has a high-velocity region (Baan *et al.* 1987) and has a velocity gradient perpendicular to the I–II axis and the previously observed gradient. The latter may possibly be due to the systemic velocities of the two nuclei being different rather than any gross rotation of the system; and (3) components I, IIa, and IIb are not collinear which argues against a single core-jet system being responsible for all three components.

V. CONCLUSION

The results presented here suggest that at the core of the OH megamaser galaxy IC 4553 lie two compact (~ 3.5 pc) emission regions. They are seen as a result of the imaging properties of the low-gain masing OH gas lying along the line of sight. The regions have been shown to have very different dynamical and physical properties, and this is consistent with the suggestion that the compact regions are in fact two Seyfert nuclei in the process of merging.

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W. A. BAAN: Arecibo Observatory, P.O. Box 995, Arecibo, PR 00613

R. S. BOOTH: Onsala Space Observatory, S-43900, Onsala, Sweden

P. J. DIAMOND: National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22901

R. P. NORRIS: Division of Radiophysics, CSIRO, P.O. Box 76, Epping, NSW 2121, Australia