VLBA imaging of NGC 5793: parsec-scale jets and water maser emission

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We have conducted VLBA observations to image water maser and radio continuum emission on parsec scales towards the type 2 Seyfert galaxy NGC 5793. We report here the first VLBI image of the blueshifted maser emission. Maser emission was detected earlier in single-dish observations and found to have both red- and blueshifted features relative to the systemic velocity. The blueshifted emission was found to originate in a single spot that was unresolved at a resolution of about 1.0 pc. No compact continuum emission was found coincident with the maser spot. A compact continuum source showing an inverted spectrum between 1.6 GHz and 5 GHz was found at a position about 6 pc from the maser spot. The spectral turnover might be due to synchrotron self-absorption caused by a shock in the jet owing to collision with the dense gas, or might be due to free-free absorption in an ionized screen foreground to the jet. The water maser could either be a part of a maser disk as believed to be the case in NGC 4258, or alternatively, could result from the amplification of a radio jet by circumnuclear molecular gas as has been proposed for the water maser in NGC 1052. Further VLBI observations are crucial to distinguish between the two possibilities.

1. Background

Observations of H_2O megamasers on (sub-)pc scales in Seyfert 2/LINER galaxies have proven to be a very powerful tool for the investigation of the central regions of active galactic nuclei (AGN). The most successful result from this kind of research was the discovery of a rotating disk around a super massive black hole in the center of NGC 4258 (Miyoshi *et al.* 1995, Greenhill *et al.* 1995). VLBI imaging of the H_2O masers in NGC 4945, the Circinus galaxy and NGC 1068 show the possible existence of super massive black holes inside their nuclei as well (e.g. Greenhill 2000, these proceedings). We need to investigate as many such H_2O megamasers as possible with VLBI to study how typical the (sub-)pc scale maser disk found in NGC 4258 is, to determine the physical parameters of the black hole and surrounding torus, and to check unified models involving an accretion disk, a black hole and a jet.

NGC 5793 is an edge-on disk galaxy with a bright compact nucleus seen in radio continuum emission (Gardner & Whiteoak 1986, Gardner *et al.* 1992). Baan et al. (1998) classified the optical emission of NGC 5793 as being Seyfert type 2. Hagiwara et al. (1997) first detected water maser emission in NGC 5793. Figure 1 shows the peak of the maser emission blueshifted by $\sim$ 245 km s^{-1} from the systemic velocity of the galaxy ($V_{\rm LSR}$ = 3442 km s^{-1}), and there may be a suggestion of features near the systemic velocity, which needs confirming. To investigate the spatial distribution of the water maser emission and the relationship between the water megamasers and the nuclear radio activity of NGC 5793, we have carried out VLBI observations using the NRAO† VLBA and VLA. We adopt a distance of 46 Mpc to NGC 5793, corresponding to a scale of 1 milliarcsec (mas) $\approx$ 0.23 pc.

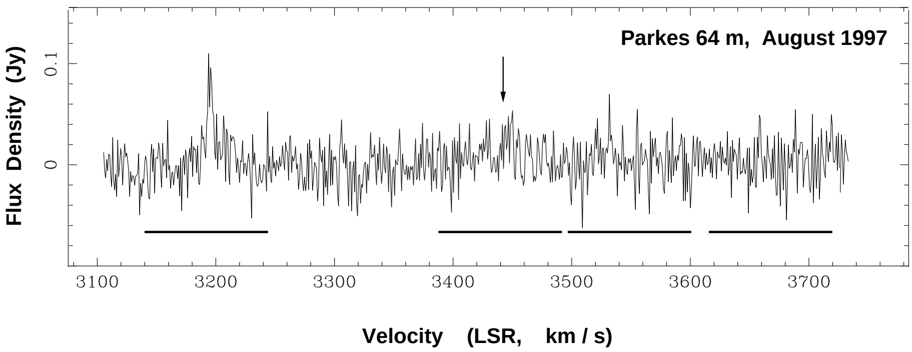

FIGURE 1. A spectrum of the water maser toward the center of NGC 5793, observed with the Parkes 64 m telescope. The spectrum is averaged over three days from August 18th to 20th, 1997. The accuracy of the flux-density scale is no better than 10 %. A downward arrow indicates the systemic velocity of the galaxy, V_{LSR}= 3442 km s^{-1}. Solid bars indicate the velocity ranges that we observed with the VLBA.

The earlier single-dish spectra, observed in January 1996, exhibited a symmetric velocity distribution of maser emission extending ± 245 km s^{-1} with respect to the systemic velocity. For this reason we proposed a simple maser disk model rotating around the nucleus by analogy with the case in NGC 4258 (Hagiwara *et al.* 1997).

2. Analysis of VLBA observations

Radio continuum observations towards the nuclear region of NGC 5793 with the VLBA were made during the period 1996-1999 over three epochs at the frequencies of 1.6 GHz (including OH absorptions at 1665 MHz and 1667 MHz), 4.9, 8.4, and 15.3 GHz. A VLBA spectral-line observation was conducted on May 10, 1998, including the phased-VLA, which was intended to reveal the spatial and kinematical structure of the maser emission. However, the observation detected only the blueshifted feature centered at 3190 km s^{-1}. The resultant synthesized beam size is 2.0 mas × 1.0 mas in P.A.= 4.8° and the rms noise in a continuum image with 8 MHz bandwidth is typically 1.5 mJy beam^{-1}. The maser features are seen to span at least five continuous spectral-line channels each of which has a velocity width of 4.2 km s^{-1}.

The blueshifted feature was found to be a single spatially unresolved maser spot, and preliminary analysis estimated the size to be $<$ 1.0 pc, yielding a lower limit to the brightness temperature of the maser spot of about 10^8 K. The maser spot is located 15.2 mas or 3.50 pc from the center of an unresolved radio continuum source at 22 GHz, which is coincident with a reference point (0,0) in Figure 2(a). The uncertainty of the relative maser position with respect to the reference point, which was obtained with Gaussian-model fitting, is less than 0.45 mas. The center positions of this source were determined at various frequencies by phase-referencing to a compact source, 1507−168, about two degrees away. This same calibrator was used for epochs. The location of the maser spot was also measured with respect to the same reference source. All the velocity features

† NRAO is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

within the range 3182 km s^{-1} to 3203 km s^{-1} were seen to lie within one unresolved region. The centroid position of the brightest maser feature centered at 3190 km s^{-1} is shown in Figure 2(a).

Continuum spectra of four major components seen in Figure 2(a) are shown in Figure 2(b). The component C2(E), located about 6 pc away from the detected maser spot, shows a low-frequency cutoff between 1.6 GHz and 4.9 GHz with the spectral index $\alpha >$ $+0.13$ ($S_\nu \propto \nu^\alpha$). At 1.6 GHz, C2(E) was not clearly detected in VLBA maps observed in 1996 and 1999 (Pihlström *et al.* 2000; Hagiwara *et al.* 2000). Other components show spectral indices of between -0.46 and -1.0.

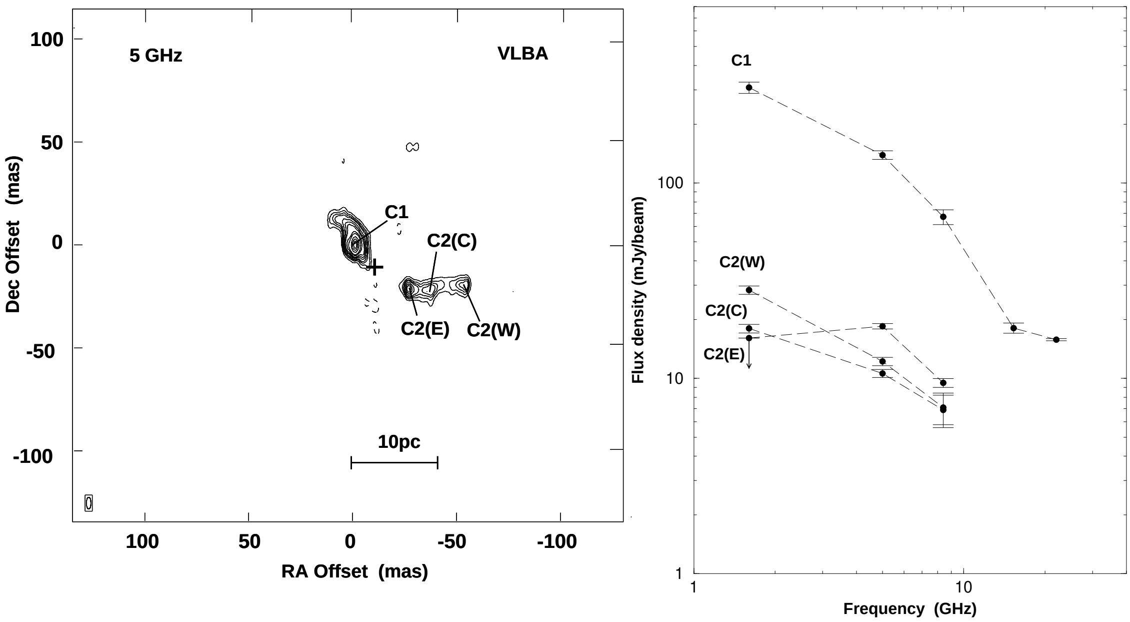

FIGURE 2. (a) Left: A 5 GHz continuum image of the nuclear region (Hagiwara *et al.* 2000). The contour levels are $-1, 1, 2, 3, 4, 6, 8, 10, 15, 20, 40, 60, 80,$ and 100 % of the peak surface brightness of 91.1 mJy beam^{-1}. The synthesized beam of (3.7 × 1.4) mas in P.A. = − 4.7° is shown in the left-hand corner. The cross marks the center position of the unresolved maser spot. The center position (0,0) in the map coincides with that of the 22 GHz continuum peak. (b) Right: Continuum spectra of the four main compact components in Figure 2(a). The flux density of C2(E) at 1.6 GHz is an upper limit.

3. What is the H_2O maser in NGC 5793 ?

We discuss two possibilities for the origin of H_2O masers in NGC 5793, based on our observations:

(*a*) The water maser in NGC 5793 does NOT lie in a molecular disk around a super massive object, like that in NGC 4258. The maser could result instead from the amplification of a radio jet by the circumnuclear molecular gas foreground to the jet. The brightness of such a radio jet component is not sufficient to be detected by VLBI in this case. The parsec-scale distribution of molecular gas was observed around C1 also in OH absorption using the VLBA (Hagiwara *et al.* 2000). Off-nuclear masers have been seen in NGC 1052 (Claussen *et al.* 1998) and NGC 1068 (Gallimore *et al.* 1996), and comparison to these cases may help us understand NGC 5793.

(*b*) The maser lies in a rotating molecular disk around the nucleus of the galaxy as proposed by Hagiwara et al. (1997). Unfortunately, the systemic and red-shifted features became weaker during our observation, and we could not detect the velocity structure and brightness distribution of the water masers at all.
One might ask 'Where is the nucleus of NGC 5793?'. It is likely that a 'true' nucleus is in the gap between the two continuum structures, and it is highly obscured by dense ionized gas. The measured surface brightness of C2(E) is at least 3.2×10^8 K and could in principle be as high as $\sim 10^{10}$ K required for synchrotron self-absorption. It is conceivable that the component C2(E) was produced by a strong shock with the circumnuclear gas. The jet bent and deflected near C2(E) extends further out to the component C2(W). Alternatively, the component C2(E) could be free-free absorbed by dense ionized foreground gas. The spectral index value of $+0.13$ is not steep enough for free-free absorption, but as it is a lower limit, it is not inconsistent with free-free absorption. If C2(E) is a free-free absorbed component, it could be an inner part of the disk/torus. However, at this stage we *conservatively* consider that the spectral turnover at C2(E) is due to synchrotron self-absorption which was caused by the collision of a jet from the central engine with a dense gas in the circumnuclear region.

Further observations of the water masers are crucial to distinguish between the two possible cases (a) and (b). We found that the systemic velocity features flared during early 2000 and additional VLBA observations, following up our present result, are already underway.

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