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EVN Observations of the OH megamaser galaxies Mrk 231 and IC 694

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Abstract. We present EVN observations of hydroxyl (OH) main–line emission in two megamaser sources Mrk 231 and IC 694. The observations indicate that the broad maser emission lines originate within the nuclear regions. A single 1667 MHz main–line feature is seen at the nucleus of IC 694. In Mrk 231 both main–lines were observed in an extended "half-circular" region of 150 pc by 50 pc surrounding the radio nucleus.

1. Introduction

Extragalactic hydroxyl in broad main–line emission has been discovered in (ultra–) luminous infrared galaxies (LIG & ULIG) with an unexpectedly high isotropic luminosity (e.g. Arp 220; Baan et al. 1982). These OH megamaser (OH MM) galaxies are characterized by morphological peculiarities, interactions with neighbours, highly ionized species and Active–Galactic–Nuclear (AGN) phenomena. So far, about 90 extragalactic sources have been discovered with isotropic luminosities ranging from 10^3 to 10^6 times that of the brightest galactic source W3(OH) ($10^{-3}L_{\odot}$). The OH MM emission provides a unique view of the kinematic, dynamic, and physical state in the nuclear region of galaxies.

At high resolution using very–long baseline interferometry, only a few megamasers, Arp 220, III Zw 35, and IRAS 17208–0014, have been observed so far (Lonsdale et al. 1998; Diamond et al. 1999; Pihlström 2001; Londsdale 2001 this issue for a review). For these sources both main–lines or only the 1667 MHz line appear in several bright or/and diffuse components, which indicate that the OH maser emission may result from two different types of emission mechanism. The first mechanism results in diffuse and unsaturated emission superposed on weak radio continuum structures as explained by the classical megamaser model (Baan 1989), and the second shows compact and saturated emission that may not be associated with any observable compact underlying continuum emission. In certain sources, single emission line features with line widths of several 100 $\mathrm{km\,s^{-1}}$ could relate to the structure of a rotating compact (molecular) disk or torus in the inner kiloparsec region of the nucleus.

Here we present hydroxyl observations obtained in September 1999 with the European VLBI Network (EVN) and correlated at the Joint Institute for VLBI in Europe (JIVE) in Dwingeloo. The 12 hr observations per source have been done in phase referencing mode, in two polarizations, with a total bandwidth of 8 MHz, and with 256 spectral channels. This setup leads to a rest–frame

velocity resolution of 5.6 and 5.5 km s^{-1} respectively. The good uv–coverage for each of the sources provides an angular resolution of 13 mas, which corresponds to a spatial resolution of 10 pc and 3 pc respectively[1]. Calibration, editing, and analysis where performed by using the AIPS package.

2. The outstanding galaxy Mrk 231

Mrk 231 is the most ultra–lumimous infrared galaxy in the local universe ($\sim$ 300 Mpc) showing all major properties of an OH megamaser galaxy. There is the evidence for massive star formation in the nuclear region co–existing with a powerful monster, which is quite exceptional for megamaser galaxies, and which provides a unique environment for the OH emission within the nucleus.

Observations at galactic scales show optical tidal tails as evidence of a ongoing merging event. The large–scale radio emission displays a bright and unresolved nucleus embedded in an emission structure of an arcminute in size extended towards the south–west, which is somewhat larger than the optical galaxy (Canalizo & Stockton 2000; Carilli et al. 1998). The nuclear power source has been classified by various authors as an optical Seyfert 1 and a radio AGN nucleus. The possibility of a second nucleus has been ruled out by optical observations with HST, which detected only one bright compact nucleus surrounded by a dense arc of star–forming knots. Radio observations at parsec scales show evidence for jet–like radio outflow, while at the highest resolution the nuclear source has a compact double structure of less than 2 pc with a minimum brightness temperature of 10^9 K and spectral turnover between 2 and 10 GHz. At larger scale–sizes the emission structures turn into a north–south elongated triple source with 40 pc in extent and inclined at a position angle relative to the 2 pc central source of about 65 degrees. In addition, at sub–kiloparsec (350 pc) scales there is a diffuse radio continuum "nuclear halo" with a spectral index of –0.41 indicating star–formation (Ulvestad et al. 1999). Line observations of CO and HI at similar resolution confirm the existence of a sub–kiloparsec gas disk (Carrili et al. 1999; Downes & Solomon 1998). The HI absorption seen toward the nuclear region occurs predominantly against this diffuse nuclear halo.

Our EVN observations show for the first time OH emission within the central region of a Seyfert 1 nucleus (Klöckner & Baan 2001). Figure 1a shows the spatial distribution of the OH emission, which has a half–circular shape and straddles the nuclear source on the north side. The OH emission spectrum in Figure 1b shows both the 1667 MHz (left) and 1665 MHz (right) lines with peak flux density of 26 mJy. Compared with previous single–dish observation we detect 50% of the flux density (Baan 1885), which is consistent with MERLIN observations of Mrk 231 (Richards 2000). This missing flux could be related to an even more diffuse emission component on kiloparsec scales. Comparing the FWHM emission strengths of main–lines, we find a ratio of 1.8, which is the LTE ratio for optical thin OH emission.

The OH emission with a total extent of about 122 pc is placed within the northern boundary of the diffuse nuclear halo. In analogy with the HI absorption, no OH emission has been seen against the central and southern part of the nuclear triple. Together with an east–west velocity gradient similar

[1] Assuming q_0=0.5 km s^{-1} and H_0=75 km s^{-1} Mpc^{-1}

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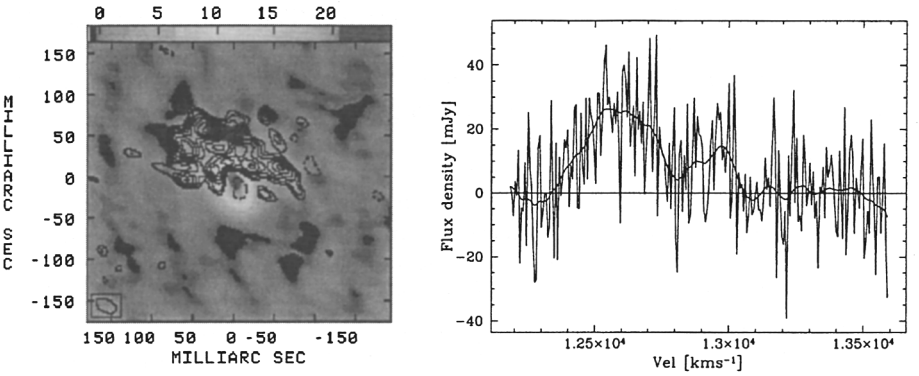

Figure 1. The OH emission in Mrk 231. a) The contours of the integrated line emission superposed on the nuclear continuum emission (greyscale) and b) the OH emission spectrum showing the 1667 and 1665 MHz lines.

to the HI and CO observation, there is support for the notion that the OH emission is also embedded in the nuclear disk/torus rotating perpendicular to the jet direction. Due to the missing single–dish flux of 50% for the MERLIN and these observations, the spatial distribution of the OH cannot be clearly determined. Assuming similar disk properties as for the CO and HI (i ~45°), the observed OH line emission can take place from 20 pc up to 90 parsec from the nucleus.

3. The starburst galaxy IC 694

IC 694 is part of a strongly merging system Arp 299, which consists of IC 694 and NGC 3690. At a distance of 42 Mpc, Arp 229 is one of the nearest examples of an interacting system with an infrared luminosity of $5\times10^{11}L_{\odot}$. As for other (U)LIGs, the molecular gas in IC 694 is highly concentrated towards the nuclear region with a molecular mass based on the CO(1–0) emission of $\sim 10^{9}M_{\odot}$. IC 694 shows also strong nuclear HI absorption, while its companion NGC 3690 only shows extended HI absorption (Baan & Haschick 1990). Observations with the HST–NICMOS do not show any point–like AGN source within the nuclear region of IC 694, but rather it shows identifiable sources within a region of ~ 175 pc possibly relating young stellar clusters (Alonso–Herrero et al. 2000). Observations of HI and OH with the MERLIN array show that the atomic and molecular gas is located in a flattened rotating structure, and that the OH occupies a region closer to the dynamical center (Polatidis 2000).

Our EVN observation show the central OH emission within the region of the starburst nucleus (Figure 2a). We could detect only one of the main–line features of the single–dish observations (Baan 1985). Figure 2b shows the integrated OH emission spectrum with a peak flux density of 3 mJy. The weak emission at 3050 $\mathrm{km\,s^{-1}}$ corresponds to the 1667 MHz emission, with a FWHM of about 100 $\mathrm{km\,s^{-1}}$. The continuum emission as well as the line emission at 1665 MHz have been resolved out. We are able to detect 50% of the MERLIN line emission in a single feature, which might be associated with the inner 100 pc of a disk–like structure. Furthermore, our observation indicate that the maser emission is

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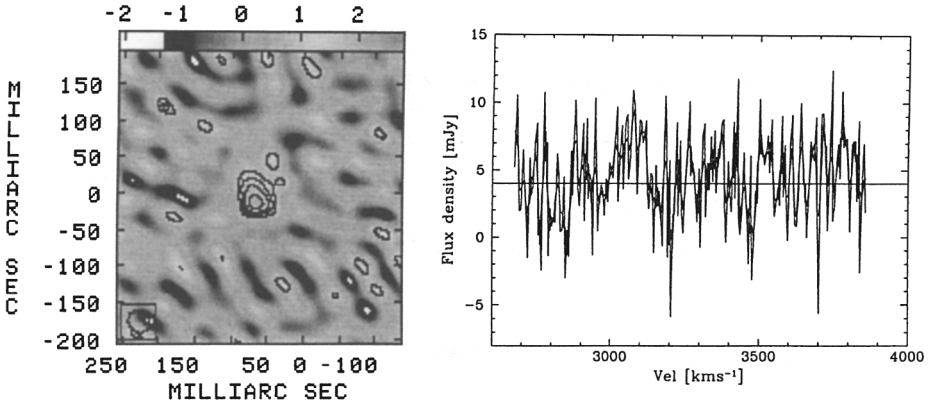

Figure 2. The OH emission in IC 694. a) The integrated OH emission at the nucleus of IC 694 and b) the line emission spectrum. No compact continuum was detected in this nucleus.

diffuse and could amplify a more diffuse continuum with a low gain.

4. Conclusion

The OH emission observed in the two megamaser galaxies Mrk 231 and IC 694 suggest that the masering region are embedded in an gravitational bounded system within the nuclear regions. There is evidence for optically thin OH emission, which suggests low–gain amplification of a diffuse underlying background continuum structure supporting the classical amplification scheme.

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