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Discovery of a luminous water megamaser in the FR II radiogalaxy 3C 403

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Abstract. We report the first detection of a water megamaser in a radio-loud galaxy, 3C 403. This object has been observed as part of a small sample of FR IIs with evidence of nuclear obscuration. The isotropic luminosity of the maser is $\sim$1200 $L_\odot$. With a recessional velocity of cz $\sim$ 17 680 km s^{-1} it is the most distant H_2O maser so far reported. The line arises from the densest interstellar gas component ever observed in a radio-loud galaxy. Two spectral features are observed, likely bracketing the systemic velocity of the galaxy. These may either arise from the tangentially seen parts of a nuclear accretion disk or from dense warm gas interacting with the radio jets.

Key words. galaxies: individual: 3C 403 – galaxies: active – galaxies: ISM – masers – radio lines: ISM – radio lines: galaxies

1. Introduction

So far, water megamasers have been detected in radio-quiet active galactic nuclei (AGN; for a definition of radio-quiet AGN, see e.g. Kellerman et al. 1989), mostly in Seyfert 2 and LINER galaxies. Only one H_2O megamaser may have been found in a Seyfert 1 type AGN (Nagar et al. 2002) and another one is known to be associated with a radio-quiet elliptical galaxy, NGC 1052. Assuming that all megamasers are associated with molecular material orbiting around the central engine (e.g. Miyoshi et al. 1995) or interacting with the nuclear jet(s) of the host galaxy (see Claussen et al. 1998) and that their amplification is unsaturated (i.e. the maser intensity grows linearly with the background radio continuum), one should expect a much higher detection rate in radio-loud AGN than is actually observed.

The first systematic search for H_2O maser emission from radio-loud galaxies was performed by Henkel et al. (1998) in $\sim$50 FR I[1] galaxies with redshift $z < 0.15$ but no masers were detected. The most plausible and simple explanation is that FR I galaxies (or at least the majority of them) lack a geometrically and optically thick molecular torus. This scenario is now supported by an increasing number of studies (e.g. Chiaberge et al. 1999; Perlman et al. 2001; Whysong & Antonucci 2001; Verdoes Kleijn et al. 2002).

Within the framework of the AGN unification scheme (e.g. Urry and Padovani 1995), narrow-lined (NL) FR IIs are believed to represent the "parent population" of radio-loud quasars and broad-lined (BL) radio galaxies. In order to account for unification between these objects, the presence of a geometrically and optically thick obscuring structure has been proposed, in analogy to the radio-quiet unifying picture (Barthel 1989). Samples of radio galaxies belonging to the BL and NL FR II class have been recently observed with the Effelsberg telescope (Tarchi et al.; Lara et al., priv. comm.). As in the case of FR Is, no maser detections have been obtained.

In this Letter we report the first detection of water maser emission in a powerful radio galaxy. The H_2O megamaser has been detected in the FR II galaxy 3C 403, observed as part of a small sample of sources described in Sect. 2.

2. Sample selection

We have considered nearby ($z < 0.1$) FR IIs from the 3CR catalog (Spinrad 1985), for which information on the radio and optical nuclear emission, and the flux of the [OIII] emission line are available.

Our sample (Table 1) comprises all 3 FR IIs spectrally classified as High Excitation Galaxies (HEGs, Jackson & Rawlings 1997) with nuclear equivalent widths of the [OIII]λ5007

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[1] Radio galaxies are classified according to their radio morphology: FR Is are edge-darkened sources, while FR IIs are edge-brightened (Fanaroff & Riley 1974).

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Table 1. Target galaxies: Source name, coordinates, redshift, 178 MHz total flux, 5 GHz core flux, [OIII] line Equivalent Width, maser luminosity and observed velocity range are given. The data were taken from the NASA/IPAC extragalactic database (NED), from Table 1 of Chiaberge et al. (2002) and references therein, and from the observations presented here.

Source	RA (J2000)	Dec (J2000)	z	$S^{\rm tot}_{\rm 178\,MHz}$ (Jy)	$\log(S^{\rm core}_{\rm 5\,GHz})$ (erg cm^{-2} s^{-1} Hz^{-1})	$\log(EW_{\rm [OIII]})$ (Å)	$L^a_{\rm maser}$ ($L_\odot$)	$V^b_{\rm min}$ (km s^{-1})	$V^b_{\rm max}$ (km s^{-1})
3C 98	03 58 54.4	+10 26 02	0.0304	35.5	−24.99	4.463	<2.8	8700	9800
3C 285	13 21 17.8	+42 35 15	0.0794	6.0	−25.11	4.385	<6.3	23 300	24 400
3C 403	19 52 15.8	+02 30 24	0.0590	17.8	−24.94	4.181	∼1200	17 000	18 700

[a] Maser luminosities assuming isotropic emission and using $[L_{\rm H_2O}/L_\odot] = 0.023 \times \left[\int S \,{\rm d}V/{\rm Jy\,km\,s^{-1}}\right] \times [D/{\rm Mpc}]^2$. 3σ upper limits for for the non-detected sources are calculated assuming emission in a single 1.1 km s^{-1} wide channel.

[b] Observed velocity range (optical convention). V is related to the observed frequency by $\nu_{\rm obs} = \nu_{\rm rest}\left(1+\frac{V}{c}\right)^{-1}$.

emission line[2] EW([OIII]) > 10^4 Å. A high value for the nuclear EW([OIII]) in HEGs has been interpreted as a hint for the obscuration of the central ionizing continuum source (Chiaberge et al. 2002). In these sources the nuclear ionizing continuum would be obscured to our line-of-sight and only a small fraction of the emission is seen through scattered light. The same indicator has been used to identify absorbed sources among Seyfert galaxies (e.g. Kinney et al. 1991). Therefore, our selection criteria provide us with a sample of galaxies with both high radio flux densities and nuclear obscuration of the central ionizing source.

3. Observations and data reduction

Observations of the 6_{16}–5_{23} transition of H_2O (rest frequency: 22.23508 GHz) were carried out with the 100-m telescope of the MPIfR at Effelsberg[3] in January and March 2003. The beam width was 40″. The observations were made in a dual beam switching mode with a beam throw of 2′ and a switching frequency of ∼1 Hz. The system temperature, including atmospheric contributions, was ∼20–40 K on an antenna temperature scale ($T^*_{\rm A}$). The beam efficiency was $\eta_{\rm b}$ ∼ 0.3. Flux calibration was obtained by measuring W3(OH) (see Mauersberger et al. 1988). Gain variations of the telescope as a function of elevation were taken into account (Eq. (1) of Gallimore et al. 2001). The pointing accuracy was better than 10″. All data were reduced using standard procedures in the GILDAS software package (`http://www.iram.fr/IRAMFR/GS/gildas.htm`).

4. Results

Table 1 summarizes characteristic properties of the three observed sources. Coordinates, redshifts and total 178 MHz fluxes (Cols. 2–5) were taken from the NASA/IPAC Extragalactic Database (NED), while the values for the 5 GHz core luminosity and [OIII] equivalent width (Cols. 6–7) are taken from Chiaberge et al. (2002) and references therein. Upper limits for the non-detected sources as well as the isotropic luminosity of the maser detected in 3C 403 are given in Cols. 8–10 show the velocity ranges of our spectra.

The maser spectra of 3C 403, taken in January, are shown in Fig. 1. The profile is composed of two main components (asymmetrically) bracketing the nominal systemic velocity of the galaxy (17 688 km s^{-1}, see Sect. 5.2): the stronger one has a velocity of 17 827 ± 1 km s^{-1}, a width of 31 ± 2 km s^{-1}, and a flux density peak of 23 ± 3 mJy; the weaker one has a velocity of 17 644 ± 5 km s^{-1}, a width of 53 ± 8 km s^{-1}, and a peak flux density of 4.0 ± 0.5 mJy. Subcomponents, like the blueshifted shoulder of the main component (∼17 790 km s^{-1}) and the feature near 17 610 km s^{-1} are also apparent. Using a distance of 235 Mpc (H_0 = 75 km s^{-1} Mpc^{-1}), the total isotropic

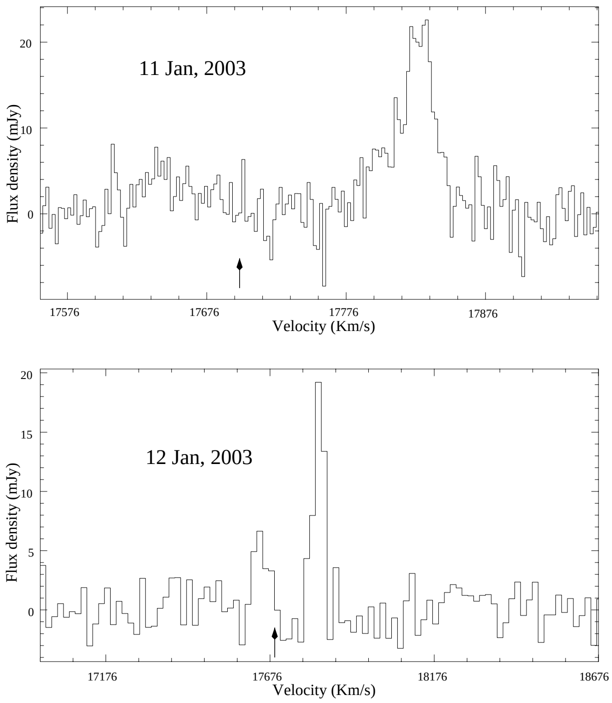

Fig. 1. Maser lines in 3C 403 with a channel spacing of 78 kHz or 1.15 km s^{-1} (*upper panel*) and 1.25 MHz or 17.8 km s^{-1} (*lower panel*). The arrow marks the systemic velocity of the galaxy, $V_{\rm sys}$ = cz = 17 688 km s^{-1}.

[2] The nuclear EW of the [OIII]λ5007 emission line is measured with respect to the nuclear unresolved continuum source observed in HST images (Chiaberge et al. 2002).

[3] The 100-m telescope at Effelsberg is operated by the Max-Planck-Institut für Radioastronomie (MPIfR) on behalf of the Max-Planck-Gesellschaft (MPG).

luminosities are 950 ± 140 and 280 ± 55 $L_\odot$ for the main components, respectively.

A further observation was performed on March 25. No significant change in the line profile was found.

5. Discussion

The standard unified scheme of AGN requires an obscuring region, possibly containing molecular gas that surrounds the central engine and that effectively shields the inner few parsecs from view, if the radio axis lies close to the plane of the sky (Antonucci 1993). In the innermost part, at radii up to some tenths of a parsec, this material is likely to form a rapidly rotating accretion disk around a central supermassive black hole. At larger distances (up to about 50–100 pc) the atomic and molecular gas is possibly distributed in a toroidal structure providing obscuration of the central regions to particular lines-of-sight.

As mentioned in Sect. 1, interferometric studies of H_2O megamasers have shown that the emission is either associated with a nuclear accretion disk (for NGC 4258, see e.g. Miyoshi et al. 1995) or with the radio-jets interacting with dense molecular material near the center (for Mrk 348, see Peck et al. 2003). According to this picture, we expect to detect water megamaser activity in FR II radio galaxies, where accretion disks are likely present and powerful radio jets have been extensively mapped.

The absence of water maser detections among early-type radio galaxies has been discussed by Henkel et al. 1998. Although this work was focused on FR I galaxies, the lack of similar studies on FR IIs and the presumed geometrical similarity between FR Is and FR IIs make their conclusions also relevant for our study. Among the different scenarios, Henkel et al. proposed that radio galaxies may be lacking molecular gas in the nuclear region. Indeed, very few direct detections of molecular gas in radio-loud galaxies have been reported so far (H_2 in Cygnus A: Evans et al. 1999; CO in 3C 293: Wilman et al. 2000). The detection discussed here strongly favors the presence of molecular material near the central engines of at least some FR IIs. Past negative results in molecular line surveys may also be a consequence of observational sensitivity limits (such a possibility was also mentioned by Henkel et al. 1998). Furthermore, because of the high gas densities required for H_2O masers to operate ($>10^7$ cm^{-3}; e.g. Elitzur et al. 1989), our detection represents the densest interstellar gas component ever observed in a radio-loud galaxy (typical values for molecular gas densities range between $\sim10^3$ and $\sim10^5$ cm^{-3}; e.g. Wilman et al. 2000).

Observational sensitivity limits could also explain the result reported by Morganti et al. (2001) on 3C 403. They searched for neutral hydrogen absorption in a small sample of FR I and FR II galaxies using the VLA. H I absorption was mostly found in NL FR IIs, while none was detected in broad-lined (BL) FR IIs and only one detection was obtained in an FR I. This result is, to first order, consistent with the unified schemes. Interestingly, among the NL FR IIs the only H I non-detection was 3C 403 (with a 3σ H I column density upper limit of $\sim5\times10^{20}$ cm^{-2}, using $T_{\rm spin}$ = 100 K and a linewidth of 30 km s^{-1}, that is smaller than the linewidths of the associated gaseous nebulae as e.g. observed by Baum et al. 1990). This non-detection may either be due to the rather high upper column density limit or to an intrinsic lack of dense gas in the galaxy's nuclear region. Our maser detection favors the former possibility.

5.1. Is 3C 403 a peculiar FR II?

While optical photometric and morphological profiles of the galaxy 3C 403 indicate a normal elliptical structure (Govoni et al. 2000), its radio morphology is quite peculiar. An 8.4 GHz VLA map of 3C 403 (Black et al. 1992 (BBL); their Fig. 13) shows that the radio galaxy has a remarkable X-shape, with "wings" of ~100 kpc extending in NW and SE directions. A weak jet feature (labeled as F7&8 by BBL) is present between the core and the exceptionally bright knot F6. The lobes and their hot-spots (F1&2 and P1&2 in BBL), well displaced from the wings, are also prominent and confirm the FR II classification. Can 3C 403 be considered to be a typical FR II? Or does it belong to a peculiar class of objects where water masers are more likely found. We also note that 3C 403 has a larger total radio luminosity (by factors of almost 2) than the other sources in our sample (see Table 1). To discriminate between effects related to radio power or morphological peculiarities, more extended H_2O maser surveys are needed.

5.2. Accretion disk or jet interaction?

For the following discussion it is worth to emphasize the uncertainty of the systemic velocity of 3C 403. $V_{\rm sys}$ derived from optical emission lines may be uncertain or biased by motions of the emitting gas (e.g. Morganti et al. 2001). In view of the rotation curve measured by Baum et al. (1990), however, uncertainties may be <100 km s^{-1} in the case of 3C 403, so that we assume in the following that the systemic velocity is placed (as indicated by Fig. 1) in between the two main H_2O maser components. Only interferometric observations will allow us to pinpoint the location of the H_2O emitting region(s), to determine (or to provide an upper limit to) the extent of the emission, and to associate the maser with an accretion disk or the radio jets. Nevertheless, a qualitative discussion is possible on the basis of the single-dish spectra of Fig. 1.

The handful of bright knots visible in the radio image shown in BBL (their Fig. 13) hints at the presence of jets interacting in several regions with the interstellar medium. Interactions between jets and dense molecular clouds produce strong shocks which have been shown to be possible causes of megamaser emission (e.g. Gallimore et al. 2001; Peck et al. 2003). Also the profile of the spectrum does not contradict a "jet-origin" of the detected maser emission in 3C 403. If we assume a symmetric molecular distribution, the two observed features could be interpreted as the red-shifted and blue-shifted counterparts of the maser line, arising from opposite jets close to the core.

Interestingly, the accretion disk scenario is a viable alternative, making use of the expected nuclear obscuring layer that should be oriented almost edge-on (see Chiaberge et al. 2002). As in the case of the Seyfert galaxy NGC 4258 (e.g.

Miyoshi et al. 1995), the spectrum should then show three distinct groups of features: one centered at the systemic velocity of the galaxy (originating along the line of sight to the nucleus) and two groups symmetrically offset from the systemic velocity, arising from those parts of the disk that are viewed tangentially. If the latter are the two lines we are observing, the rotational velocity of the disk is ~100 km s^{-1}. In NGC 4258 the systemic features are dominant, likely because the disk is slightly inclined, thus amplifying the southern radio jet. In 3C 403 the systemic lines seem instead to be missing. To explain this fact by following the hypothesis proposed in Henkel et al. (1998), we could argue that the circumnuclear disk is thin and not perfectly edge-on, thus not amplifying the radio flux of the core. In this case the background source would arise from the receding counter jet that may be too weak, because of relativistic dimming, to provide enough "seed" photons for a detection. So far, the orientation of the jets in 3C 403 w.r.t. the plane of the sky has not been studied in detail. Higher resolution maps are needed to determine which of the two scenarios, accretion "disk-maser" or "jet-maser" emission, is most favorable to explain the observational data.

6. Conclusions

Our discovery of water maser emission in the FR II galaxy 3C 403 is:

- the first detection of a water megamaser in a radio-loud galaxy,
- one of the very few direct detections of molecular gas, and the first indicating very high density (>10^7 cm^{-3}), in radio-loud galaxies,
- another argument in support of the presence of molecular gas near the nuclear engine of FR II galaxies,
- a starting point to investigate, through follow-up high-resolution observations, the optically obscured inner parsecs of FR IIs. Such observations will allow us to discriminate between nuclear "disk-" and "jet-maser" emission, the latter inferring an interaction between the nuclear jet(s) and the ambient gas.

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References

Antonucci, R. 1993, ARA&A, 31, 473
Barthel, P. D. 1989, ApJ, 336, 606
Baum, S. A., Heckman, T., & van Breugel, W. 1990, ApJS, 74, 389
Black, A. R. S., Baum, S. A., Leahy, J. P., et al. 1992, MNRAS, 256, 186 (BBL)
Chiaberge, M., Capetti, A., & Celotti, A. 1999, A&A, 349, 77
Chiaberge, M., Capetti, A., & Celotti, A. 2002, A&A, 394, 791
Claussen, M. J., Diamond, P. J., Braatz, J. A., Wilson, A. S., & Henkel, C. 1998, ApJ, 500, L129
Elitzur, M., Hollenbach, D. J., & McKee, C. F. 1989, ApJ, 346, 983
Evans, A. S., Sanders, D. B., Surace, J. A., & Mazzarella, J. M. 1999, ApJ, 511, 730
Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31
Gallimore, J. F., Henkel, C., Baum, S. A., et al. 2001, ApJ, 556, 694
Govoni, F., Falomo, R., Fasano, G., & Scarpa, R. 2000, A&AS, 143, 369
Henkel, C., Wang, Y. P., Falcke, H., Wilson, A. S., & Braatz, J. A. 1998, A&A, 335, 463
Jackson, N., & Rawlings, S. 1997, MNRAS, 286, 241
Kellermann, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, AJ, 98, 1195
Kinney, A. L., Antonucci, R. R. J., Ward, M. J., Wilson, A. S., & Whittle, M. 1991, ApJ, 377, 100
Mauersberger, R., Wilson, T. L., & Henkel, C. 1988, A&A, 201, 123
Miyoshi, M., Moran, J., Herrnstein, J., et al. 1995, Nature, 373, 127
Morganti, R., Oosterloo, T. A., Tadhunter, C. N., et al. 2001, MNRAS, 323, 331
Nagar, N. M., Oliva, E., Marconi, A., & Maiolino, R. 2002, A&A, 391, L21
Peck, A. B., Henkel, C., Ulvestad, J. S., et al. 2003, ApJ, accepted [astro-ph/0303423]
Perlman, E. S., Sparks, W. B., Radomsky, J., et al. 2001, ApJ, 561, L51
Spinrad, H., Marr, J., Aguilar, L., & Djorgovski, S. 1985, PASP, 97, 932
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Verdoes Kleijn, G. A., Baum, S. A., de Zeeuw, P. T., & O'Dea, C. P. 2002, AJ, 123, 1334
Whysong D., & Antonucci, R. 2001, ApJ, submitted [astro-ph/0106381]
Wilman, R. J., Edge, A. C., Johnstone, R. M., Crawford, C. S., & Fabian, A. C. 2000, MNRAS, 318, 1232