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H_2O megamaser emission from FR I radio galaxies

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Abstract. A systematic search for 22 GHz H_2O megamaser emission is reported for 50 nearby ($z \lesssim 0.15$) FR I galaxies. No detection was obtained, implying that ultraluminous H_2O masers ($L_{H_2O} > 10^3\,L_\odot$) must be rare in early-type galaxies with FR I radio morphology. Despite higher radio core luminosities the detection rate for our sample is lower than in similar surveys of late-type Seyfert galaxies. This puzzling difference between Seyferts and low-power radio galaxies could be explained in several ways: a) the maser emission is saturated and therefore independent of the radio core luminosity, b) the masers are unsaturated and originate in a thin circumnuclear gas disk, so the 'seed' radio continuum would come from the far jet which is relativistically dimmed or c) the amount, kinematics, or the distribution of the molecular gas in the nuclei of Seyferts and radio galaxies is different. Further studies of maser properties may provide clues to the differences between radio-loud and radio-quiet AGN.

Key words: Masers – ISM: molecules – galaxies: elliptical and lenticular – galaxies: ISM – galaxies: active – radio lines: galaxies

1. Introduction

Systematic radio searches for H_2O emission among $\sim$ 600 galaxies led to the detection of 17 'megamasers' and one 'gigamaser' in active galactic nuclei of the Seyfert 2 and LINER class (Braatz et al. 1994, 1996b, 1997; Koekemoer et al. 1995; Greenhill et al. 1997; Hagiwara et al. 1997). Typical isotropic luminosities are $L_{H_2O} \sim 100\,L_\odot$; for the strongest source $L_{H_2O} \sim 6100\,L_\odot$ is reached. Megamaser sources with sufficiently intense H_2O emission allow high resolution interferometric studies that provide interesting insights into active nuclear regions. This includes the discovery of a Keplerian disk in the LINER NGC 4258 (e.g. Greenhill et al. 1995a,b; Miyoshi et al. 1995): The rotational velocity ($V_{rot} \sim 1000\,km\,s^{-1}$) and galactocentric radius ($R_{GC} \sim 0.15$ pc) require a nuclear mass concentration of density $\gtrsim 10^9\,M_\odot\,pc^{-3}$ that is consistent with a supermassive black hole of a few times $10^7\,M_\odot$ (Maoz 1995).

Almost all extragalactic sources so far studied in H_2O are spirals. Few early-type galaxies have been observed. Here we present a survey of FR I (Fanaroff & Riley 1974) radio sources including 50 low redshift ($z < 0.15$) objects with $\delta > -30°$ from the Zirbel & Baum (1995; hereafter ZB 95) list of radio galaxies. Although the list is far from representing a complete sample, it provides a large number of candidate sources representative of this class of radio galaxy. The data were taken to make a statistical comparison between Seyfert (i.e. radio quiet spiral) and FR I (i.e. radio loud elliptical) galaxies w.r.t. H_2O detection rates, H_2O lineshapes, and nuclear cloud morphology. Strong differences would hint at different types of gas distributions (e.g. tori) in the very central parts of active galaxies (see Falcke et al. 1995).

2. Observations and results

Observations in the $6_{16} - 5_{23}$ transition of H_2O (rest frequency: 22.23508 GHz) were obtained with the 100-m telescope of the MPIfR at Effelsberg in December 1996 and March and April 1997. The beam width of the telescope was 40″. A K-band maser receiver was used in conjunction with a 1024 channel, three level autocorrelator. In most cases the bandwidth of the spectrometer was 50 MHz, corresponding to $\sim 680\,km\,s^{-1}$ at the rest frequency and providing a channel spacing of $0.66\,km\,s^{-1}$ and a velocity resolution of $0.79\,km\,s^{-1}$. Four sources were observed with a bandwidth of 25 MHz. All observations were made in a position switching mode. Due to superb weather in Dec. 1996, the system temperatures, including atmospheric contributions, were 110 - 160 K on a main beam temperature (T_{mb}) scale. During 1997, receiver temperatures were 150 – 500 K, depending on weather conditions and elevation of the source.

Flux calibration was obtained by frequent measurements of NGC 7027 and 3C 286, which were assumed to have 22 GHz flux densities of 5.86 and 2.55 Jy, respectively (Baars et al. 1977; Ott et al. 1994). Variations of these fluxes and of the receiver's calibration signal as a function of frequency were taken into

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account; the data were also corrected for gain variations of the telescope as a function of elevation. First to third order polynomials were used to fit the baseline. Observational results are displayed in Table 1. None of the observed 50 sources was detected. Single channel 1σ noise limits, of order 100 mJy in most cases, are given in column 7.

3. Early-type radio galaxies versus spirals

3.1. FR I, FR II, and spiral samples

The FR I sources displayed in Table 1 include 75% of all the ZB 95 FR I galaxies and 89% of the ZB 95 FR I sources with declination $\delta >$ –30° and redshift $z <$ 0.15. Hubble types from the NASA/IPAC Extragalactic Database (NED) are consistent with an early-type nature. Data from previous surveys include non-detections of H_2O emission from the ZB 95 FR I sources 3C 84, B2 0915+32, B2 1122+39, 3C 274.0, B2 1254+27, B2 1525+29, B2 1553+24, and B2 2116+26 (Braatz et al. 1996b, hereafter BWH 96). All these galaxies are also observed by us. 22 GHz H_2O upper limits for FR II galaxies of the ZB 95 sample were reported from 3C 390.3 and Cyg A (3C 405) (BWH 96). The sample of ZB 95 FR II upper limits is therefore too small for a statistical evaluation.

The Braatz et al. (1997; hereafter BWH 97) spiral sample contains 193 observed galaxies ($0 \leq T \leq 9$ according to the de Vaucouleurs et al. (1991) notation) and 10 H_2O detections; including the four spirals that would have been part of the sample if they had not been detected before (see Braatz et al. 1994), the detection rate is 7.1$\pm$1.6% (the error being the standard deviation from the Bernoulli theorem). For the distance limited sample (c$z \lesssim$ 7000 $\mathrm{km\,s^{-1}}$), the corresponding values are 176, 14, and 8.0$\pm$1.8%. Our sample of nearby (c$z \lesssim$ 7000 $\mathrm{km\,s^{-1}}$) FR I objects only comprises 15 sources. All of these were measured with high sensitivity ($1\sigma \lesssim 5\,\mathrm{L_\odot}$ for an individual channel), so that any megamaser would have easily been seen. Assuming the same detection rate as for the distance limited BWH 97 sample leads to 1.2$\pm$0.3 expected detections that do not deviate significantly from our null result.

To estimate detection probabilities for our entire sample of galaxies, we note that the spiral BWH 97 and the early-type FR I sample differ by the power and distance of their radio cores. For the distance limited BWH 97 sample, few nuclear λ = 1.3 cm radio fluxes are known; at λ = 6 cm, however, VLA A or B array data are available for 45 (26%) sources. For the corresponding distance limited FR I sample, 13 (87%), and for the more distant (c$z \gtrsim$ 7000 $\mathrm{km\,s^{-1}}$) FR I galaxies, 24 (69%) sources have known λ = 6 cm core fluxes. The FR I core fluxes are larger than those of the spiral sample. *Assuming unsaturated maser amplification of the radio core*, the observational sensitivity for H_2O 22 GHz radiation depends almost linearly on nuclear radio fluxes (e.g. Reid & Moran 1981). Assuming similar radio source covering factors, *the overall sensitivity of our maser search is*, for both the nearby and the distant FR I sources, *higher than that for the BWH 97 spiral sample*. The sensitivity ratio is of order 10.

To estimate detection probabilities, some qualitative knowledge of the H_2O luminosity function is also needed. In their Table 1, BWH 96 list eight masers with 10–100 $\mathrm{L_\odot}$, seven with 100–1000 $\mathrm{L_\odot}$, and one with 6100 $\mathrm{L_\odot}$. We note that the BWH 96 detection rate decreases with increasing redshift (their Figs. 2–4) which implies that some of the less luminous ($L_{\mathrm{H2O}} <$ 100 $\mathrm{L_\odot}$) masers are not detected because of sensitivity limits. We also note that the location of the gigamaser (Koekemoer et al. 1995) is slightly outside the systematically studied cz $\lesssim$ 7000 $\mathrm{km\,s^{-1}}$ redshift range. Since sources in the gigamaser range are definitely rare, the spatial density of H_2O masers of a given luminosity is consistent with $n_{\mathrm{H2O}} \propto L_{\mathrm{H2O}}^{-\alpha}$, $\alpha > 0$. With a 'reasonable' luminosity function ($\alpha \gtrsim$ 0.5) and accounting for the net sensitivity gain of our FR I versus the BWH 97 spiral survey in the case of unsaturated amplification of the radio core, the detection rate for FR I galaxies becomes at least five times higher than that for spirals with AGN. The expected FR I detection rate then is $\gtrsim$40%.

3.2. Interpretation

In view of our unsuccessful search for H_2O masers in FR I galaxies, *expected detection rates inferring unsaturated maser emission of the radio core are far too large*. What is causing the discrepancy between expected and measured values?

– Rotating disk scenario: If unsaturated maser amplification occurs in a slightly inclined (i.e. not perfectly edge-on) circumnuclear thin disk, the core radio flux is not amplified. Instead, the background arises from the receding counter jet that, relativistically dimmed, may be too weak a source of 'seed' photons.
– Saturated maser emission: *If* masers are saturated (see Greenhill et al. 1995a; Braatz et al. 1996a; Kaufman & Neufeld 1996; Trotter et al. 1996; Herrnstein et al. 1997; Claussen et al. 1998), we can relax the assumed correlation between radio core and maser luminosity and obtain with the detection rate for the distance limited spiral BWH 97 sample and $\alpha \gtrsim 1$ (see Sect. 3.1) a total of 1.4$\pm$0.4 expected FR I galaxy detections. This is consistent with our observational result.
– Very broad line emission: The limited velocity coverage of our spectra, $\Delta V \sim 600\,\mathrm{km\,s^{-1}}$, leaves chances for further improvement. The superposition of thousands of individual maser components, covering a velocity range $>$1000 $\mathrm{km\,s^{-1}}$, or rapidly rotating tori with only the tangential parts showing strong (highly red- and blue-shifted) maser emission are possible scenarios consistent with an absence of detections.
– Lack of molecular gas: Towards a number of prominent radio galaxies, HI absorption was detected that may be associated with the nuclear region (e.g. van Gorkom et al. 1989; Conway & Blanco 1995; Henkel & Wiklind 1997). With the notable exception of Cen A, however, nuclear CO has not been seen with certainty. It remains open whether this is caused by amount and composition of the nuclear gas or

Table 1. Observed sources$^{a)}$

Source		α_{1950}	δ_{1950}	$P^{b)}_{core}$	$T^{c)}_{int}$ (min.)	1 σ luminosity$^{d)}$ (mJy)	(L$_\odot$)	$V^{e)}_{min}$ km s^{-1}	$V^{e)}_{max}$ km s^{-1}	Epoch$^{f)}$
3C 29		00 55 01.6	–01 39 44	23.58	31	47	22.9	13200	13700	3
3C 31		01 04 39.2	+32 08 44	22.04	12	34	2.4	4800	5400	1
PKS0115–261		01 15 52.8	–26 07 35	23.35	25	123	83.9	15600	16200	3
3C 66B		02 20 01.7	+42 45 55	23.56	25	23	2.7	6300	6900	1
PKS 0247–207		02 47 17.4	–20 42 57	23.45	18	246	452.2	25800	26400	3
3C 75		02 55 03.2	+05 50 59	22.96	18	41	5.3	6620	7220	3
3C 76.1		03 00 27.3	+16 14 33	22.66	25	33	8.5	9550	9950	1
3C 78		03 05 49.1	+03 55 13	24.48	50	27	5.5	8450	8950	1
3C 83.1B		03 14 56.8	+41 40 33		37	19	3.1	7650	7950	1
3C 84	NGC 1275	03 16 29.6	+41 19 52		12	46	3.5	5100	5450	1
3C 89		03 31 42.4	–01 22 21	24.53	25	85	396.5	41350	41800	3
3C 120		04 30 31.6	+05 15 00	25.19	25	40	10.8	9600	10300	2
					56	31	8.2	9600	10200	3
PKS 0449–175		04 49 07.0	–17 35 12	21.58	12	121	28.2	9000	9600	2
PKS 0545–199		05 45 45.1	–19 59 03	23.23	12	189	128.9	15600	16200	2
PKS 0634–205		06 34 22.3	–20 32 14	22.74	12	161	118.3	16200	16800	2
					12	182	133.7	16200	16800	3
B2 0722+30		07 22 27.6	+30 03 13	22.90	25	22	1.9	5550	5850	1
B2 0800+24		08 00 16.3	+24 49 02	22.38	12	24	11.6	13250	13550	1
3C 218		09 15 40.8	–11 53 10	24.51	12	159	163.2	19200	19800	2
B2 0915+32		09 15 57.4	+32 04 20	23.12	12	30	27.9	18250	18900	1
B2 1108+27		11 08 44.1	+27 13 48		6	83	22.0	9600	10200	1
B2 1122+39	NGC 3665	11 22 01.3	+39 02 17	21.06	12	44	0.5	1700	2300	1
3C 264		11 42 29.1	+19 53 05	23.58	12	40	4.3	6000	6600	2
B2 1144+35		11 44 12.6	+35 45 09	24.62	12	50	48.2	18550	19250	1
3C 270	NGC 4261	12 16 49.9	+06 06 09	22.68	56	16	0.2	1950	2500	1
3C 272.1		12 22 31.5	+13 09 50	21.92	18	27	0.1	600	1200	2
3C 274.0	NGC 4486	12 28 17.8	+12 39 58	23.37	18	36	0.1	900	1500	2
3C 278		12 51 59.6	–12 17 08	22.87	18	40	2.0	3900	4800	2
B2 1254+27		12 54 02.4	+27 15 27		25	21	2.4	6150	6750	1
					12	42	6.2	7100	7700	2
B2 1317+33		13 17 58.7	+33 24 24		37	16	5.6	11050	11700	1
B2 1322+36		13 22 35.3	+36 38 18	23.29	31	26	2.0	5050	5650	2
B2 1346+26		13 46 34.2	+26 50 25	23.95	12	46	44.2	18650	19100	1
3C 296.0		14 14 26.4	+11 02 19	23.27	12	45	6.3	6900	7500	2
B2 1422+26		14 22 26.5	+26 51 02	23.16	12	33	11.0	10800	11400	1
3C 315		15 11 30.8	+26 18 40		6	23	65.6	32150	32850	1
3C 317		15 14 17.1	+07 12 15	24.50	12	34	9.6	9950	10550	1
B2 1525+29		15 25 39.6	+29 05 28	22.66	12	59	61.2	19250	19950	1
B2 1553+24		15 53 56.2	+24 35 33		12	26	11.5	12450	13100	1
NGC 6047	NGC 6047	16 02 54.0	+17 51 51		12	31	7.4	9150	9650	1
					18	77	18.6	9150	9750	2
B2 1610+29		16 10 35.6	+29 36 41		12	56	13.2	9100	9600	1
B2 1621+38		16 21 16.9	+38 02 16	23.31	12	36	8.4	9000	9600	1
3C 338		16 26 55.7	+39 39 40	23.61	18	72	15.7	8700	9300	2
3C 386		18 36 12.0	+17 09 09		12	35	2.5	4800	5400	1
B2 1855+37		18 55 54.3	+37 56 26		12	20	14.6	16200	16700	1
3C 424		20 45 44.4	+06 50 12		6	456	1988.7	39900	40500	2
					18	512	2005.7	37800	38400	3
PKS 2104–25		21 04 30.0	–25 37 54	23.25	37	213	69.2	10770	11170	3

Table 1. (continued)

Source		α_{1950}	δ_{1950}	$P_{core}^{b)}$	$T_{int}^{c)}$ (min.)	1 σ luminosity[d)] (mJy)	($L_\odot$)	$V_{min}^{e)}$ $km\,s^{-1}$	$V_{max}^{e)}$ $km\,s^{-1}$	Epoch[f)]
B2 2116+26	NGC 7052	21 16 20.8	+26 14 08	22.73	12	33	2.1	4600	5200	1
3C 449		22 29 07.6	+39 06 03	22.72	12	43	3.2	4950	5550	1
4C+11.71		22 47 25.1	+11 20 36		12	34	5.6	7500	8100	1
PKS 2322–123		23 22 43.7	–12 23 57	23.31	37	144	236.1	24530	24770	3
3C 465		23 35 59.0	+26 45 16	24.02	12	33	6.7	8400	9000	1

a) For radio properties and optical emission line parameters, see ZB 95.
b) Logarithm of the 5 GHz radio core power in units of W/Hz (see ZB 95)
c) T_{int} (column 6) includes Effelsberg 22 GHz (H_2O) on- and off-source integration time.
d) Root mean square (rms) flux density in one spectral channel (nominal width: 0.66 $km\,s^{-1}$; velocity resolution: 0.79 $km\,s^{-1}$). Quoted (isotropic) H_2O luminosities are [$L/L_\odot$] = 0.023 [rms/Jy] [$\Delta v_{1/2}$/$km\,s^{-1}$] [D/Mpc]^2 for a 0.66 $km\,s^{-1}$ wide channel; H_o = 75 $km\,s^{-1}$ Mpc^{-1}. Luminosities of detected sources are 20 $\leq L_{H_2O}/L_\odot \leq$ 6100 (BWH 96).
e) Approximate optical velocity range searched. V is related to the observed frequency by $\nu_{observed}$ = ν_{rest} (1 + V_{opt}/c)$^{-1}$.
f) 1: Dec. 22 – 24, 1996; 2: Mar 24 – 25, 1997; 3: Apr. 7 – 9, 1997

whether it is merely a consequence of observational sensitivity limits (see Henkel & Wiklind 1997 for a review).

4. Conclusions

Having searched in 50 nearby ($z < 0.15$) FR I galaxies for 22 GHz H_2O emission, our main conclusions are as follows:

(1) No new megamaser has been detected.

(2) Our detection rate is much smaller than that for spiral galaxies with AGN if unsaturated maser emission, amplifying the observed nuclear continuum, is assumed.

(3) Our negative result can be explained in terms of maser saturation (i.e. a large optical depth in the maser line), in terms of unfavorable geometries minimizing the number of available 22 GHz seed photons (e.g. a thin, circumnuclear gas disk which projects in front of the more distant, relativistically dimmed jet), by different kinematics of the molecular material (e.g. leading to very broad lines), or by a general lack of warm dense molecular gas in the nuclear regions of FR I galaxies.

At present we cannot decide which of the possibilities given here is more likely to explain our low detection rate. However, if further searches in larger samples of low-power radio galaxies continue to yield negative detection rates, an explanation in terms of saturated maser emission alone may no longer be viable and could point to an intrinsic difference in the nuclear properties of Seyferts and low-power radio galaxies. Such a result could then be corroborated by further and more sensitive observations of molecular lines and VLBI observations of the continuum sources in Seyferts and low-power radio galaxies.

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