A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
01 (02.13.3; 11.01.2; 11.09.1 Mrk 348;11.10.1; 11.19.1; 13.19.1)

ASTRONOMY AND ASTROPHYSICS
April 26, 2000

Discovery of a very luminous megamaser during a radio flare in the Seyfert 2 galaxy Mrk 348

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Astronomy & Astrophysics Letters (2000), in press

Abstract. We report the detection of a new H_2O megamaser in the Seyfert 2 galaxy Mrk 348 with the MPIfR 100 m telescope in Effelsberg. With an apparent isotropic luminosity of $L_{\mathrm{H_2O}} \simeq 420 L_\odot$ the maser is the third most luminous maser discovered so far. The detected line is unusually broad ($\Delta v \simeq 130$ km s^{-1}), is redshifted by ~ 130 km s^{-1} from the systemic velocity, and is asymmetric with a pronounced blue wing. While evidence for obscuring material towards the nucleus of this galaxy was found earlier, this detection is the first direct observation of molecular material in the vicinity of the AGN. We also searched for absorption from ammonia (NH_3) and cyclopropenylidene (C_3H_2) against the bright radio nucleus. The H_2O line was only marginally detected in archival data indicating that the maser flared recently in conjunction with a huge radio continuum flare. Continuum and line flux density increased by a factor of three, suggesting an unsaturated maser. The radio continuum flare has made Mrk 348 the most radio luminous megamaser galaxy known. It is pointed out that megamaser galaxies contain a rather large fraction of galaxies with prominent radio cores and it is speculated that the flare in the maser emission in Mrk 348 is related to the flare in the nuclear jet.

Key words: masers – galaxies: active – galaxies: individual: Mrk 348 – galaxies: jets – galaxies: Seyfert – radio lines: galaxies

1. Introduction

Emission from H_2O masers has been found in a few galaxies, exhibiting apparent isotropic luminosities a million times higher than in typical stellar masers (Dos Santos & Lepine 1979; Gardner & Whiteoak 1982; Claussen, Heiligman, & Lo 1984; Henkel et al. 1984; Haschick & Baan 1985; Braatz, Wilson, & Henkel 1994). The detection rate of these megamasers is very low, i.e. about 5% among Seyfert galaxies (Braatz, Wilson, & Henkel 1997) and almost zero among radio galaxies (e.g., Henkel et al. 1998). The maser is associated with dense and warm material, possibly a molecular torus or disk, around an active galactic nucleus (AGN). The AGN apparently produces the seed radio photons and the X-ray photons needed to pump the masing material (Neufeld, Maloney, & Conger 1994).

With the help of Very Long Baseline Interferometry (VLBI) megamasers can be used to investigate the small-scale structure of an AGN in great detail. In the case of NGC 4258 this has helped to establish the presence of a thin, warped disk around the nucleus, to determine the black hole mass, and even to measure the precise distance to this galaxy (Miyoshi et al. 1995; Herrnstein et al. 1999).

Finding new megamaser galaxies is therefore of prime interest. The only clear trend that has emerged in recent years is that megamasers are exclusively found in type 2 AGN, i.e. those Seyferts and LINERs which are expected to be obscured by a molecular torus according to the unified scheme (Antonucci 1993). Many have high absorbing column depths inferred from X-ray spectroscopy. There is also an indication of an excess of megamasers in highly inclined galaxies (Braatz, Wilson, & Henkel 1997; Falcke et al. 2000). Here we report the discovery of a hitherto undetected and very luminous megamaser in the Seyfert galaxy Mrk 348 during a radio flare of the AGN.

Mrk 348 (NGC 262, $z = 0.01503$ Huchra, Vogeley, & Geller 1999, luminosity distance $D = 62.5$ Mpc for z converted into the Galactic Standard of Rest and $H_0 = 75$ km s^{-1} Mpc^{-1}), is a well-studied Seyfert 2 galaxy with broad emission-lines in polarized light (Miller & Goodrich 1990). The galaxy is classified as an S0 with a rather low inclination ($i = 16°$, see Braatz, Wilson, & Henkel 1997). Ground-based (Simpson et al. 1996) and Hubble Space Telescope imaging (Falcke, Wilson, & Simpson 1998) have revealed a dust lane crossing the nucleus and an excitation cone in emission-lines. Ginga observations found hard X-ray emission and a high absorbing column depth of $N_\mathrm{H} = 10^{23.1}\,\mathrm{cm}^{-2}$ towards the nucleus (Warwick et al. 1989). All this suggests the presence of an obscuring torus

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Line	ν [GHz]	Δv [km s^{-1}]	S_ν [mJy]
NH_3(1,1)	23.694496	1	< 17
NH_3(2,2)	23.722631	1	< 15
NH_3(3,3)	23.870130	1	< 11
NH_3(4,4)	24.139417	1	< 12
C_3H_2 1_{10}–1_{01}	18.343146	5	< 6

Table 1. Upper limits for absorption lines measured towards the nucleus of Mrk 348. Col. (1) – molecule and transition observed; Col. (2) – rest frequency of transition in GHz; Col. (3) – channel width in km s^{-1}; Col. (4) – upper limits (1σ) for flux per channel in mJy.

in Mrk 348. Attempts to detect the obscuring material through radio spectroscopy have failed so far (e.g. H I, Gallimore et al. 1999).

What makes this galaxy stand out among Seyfert galaxies is its bright and variable radio nucleus. Neff & de Bruyn (1983) found a compact radio core on VLBI scales with a flux density of several hundred milli-Jansky and a flat to inverted spectrum. Ulvestad et al. (1999) presented more recent VLBI observations for two epochs, showing a two-component structure expanding with sub-relativistic speeds. They also noted a flare of the radio continuum emission at 15 GHz with the flux rising from 120 mJy to 570 mJy between 1997.10 and 1998.75. In the following we will present and discuss results of K-band radio spectroscopy of this galaxy.

2. Observations and Results

Data were taken in March and April 2000, using the Effelsberg 100 m telescope of the MPIfR equipped with a dual channel K-band HEMT receiver. The system temperature was of order 70 K on a T_A^* temperature scale; the beam size was 40″. The data were recorded using an autocorrelator with 8 × 256 channels and bandwidths of 80 MHz each. The eight backends were configured in two groups of four, sampling the two orthogonal linear polarizations. Frequency shifts between the four backends representing a given linear polarization were adjusted in such a way that a total velocity range of 3000 km s^{-1} could be covered.

The measurements were carried out in a dual beam switching mode (switching frequency 1 Hz) with a beam throw of 121″ in azimuth. Only linear baselines were subtracted. Calibration was obtained by measurements of W3OH (3.2 Jy according to Mauersberger, Wilson, & Henkel 1988). Pointing could be checked on Mrk 348 itself and was found to be stable to within 5–7″.

The galaxy was initially observed to look for ammonia (NH_3) and cyclopropenylidene (C_3H_2) absorption against the bright radio nucleus. No absorption features were found. The transitions, rest frequencies, and upper limits of these observations are listed in Table 1.

Since the H_2O ($6_{16} - 5_{23}$) transition is very close we also observed the redshifted 22.23508 GHz line and detected an emission feature on March 17. We repeated the observations on five subsequent days and detected the line each time. The six spectra are shown in Fig. 1. We also produced a combined spectrum of all days (Fig. 2, top) and fitted the H_2O line with a Gaussian profile. A one component fit yields a central velocity of $v = 4641.6 \pm 1.2$ km s^{-1} for the line, which is redshifted by 133 km s^{-1} from the systemic velocity. The peak flux is $S_\nu = 34$ mJy with a full width at half maximum of $\Delta v = 130 \pm 3$ km s^{-1}. The integrated flux is 4.71±0.1 Jy km s^{-1}, yielding an apparent isotropic luminosity of 420 $L_\odot$. A two component fit yields a narrow line at $v = 4677.7 \pm 0.8$ km s^{-1} with $\Delta v = 58.6 \pm 3.2$ km s^{-1} and $S_\nu = 27$ mJy plus a broad line with $v = 4609.5 \pm 1.9$ km s^{-1}, $\Delta v = 101.8 \pm 1.9$ km s^{-1}, and $S_\nu = 26$ mJy. The latter fit indicates that the line is asymmetric and has a pronounced blue wing. If we compare our two best spectra from 17 March and 5 April we tentatively find some variability in the shape of this blue wing. We searched for additional high velocity features and did not detect anything down to a limit of 6 mJy (1σ, 4 km s^{-1}) in the range 3250 to 6200 km s^{-1} and down to a limit of 10-15 mJy in the range −1470 to 10480 km s^{-1}. The continuum flux density we find at 22 GHz is 0.8 ± 0.1 Jy, corresponding to $4 \cdot 10^{23}$ Watt Hz^{-1}.

We also reduced some archival data of earlier observations of Mrk 348 taken between October 1997 and February 1998 and combined them into one data set (Fig. 2, bottom). In this spectrum the broad line is marginally detected with a flux density approximately three times lower than in the current observations. The smaller and variable baseline in these earlier observations made a reliable identification of this line impossible without *a priori* information.

3. Discussion and Summary

We have clearly discovered a new megamaser in Mrk 348. Its luminosity is comparable to the emission from NGC 3079 which contains the second most luminous H_2O maser after TXS 2226-184 (Koekemoer et al. 1995). The line width is among the broadest found for a megamaser, similar to the masers in TXS 2226-184 and NGC 1052. Assuming the emission is associated with material close to the center this is the first spectroscopic evidence for molecular gas possibly obscuring the nucleus.

Despite the bright radio continuum and the molecular maser line we have found no absorption lines from either NH_3 or C_3H_2. This is in line with the earlier non-detection of H I absorption (Gallimore et al. 1999). C_3H_2 is an organic ring molecule which is widespread in the Galaxy and is associated with diffuse gas in the ISM (Matthews & Irvine 1985). It was also found in absorption against the nucleus of the radio galaxy Centaurus A (Seaquist & Bell 1986). From our non-detection we find a 1σ upper

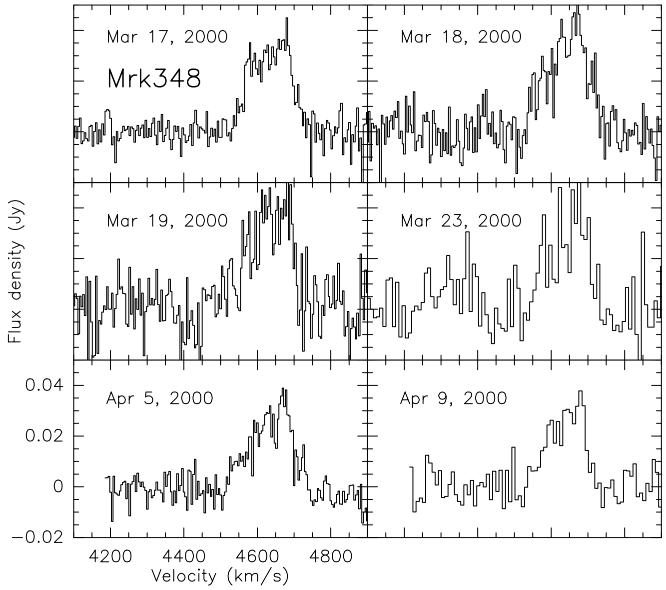

Fig. 1. Spectra of Mrk 348 (α=00$^{\rm h}$ 48$^{\rm m}$ 47.1$^{\rm s}$, δ=31° 57′ 25″, J2000) taken with the 100 m telescope at Effelsberg. The x-axis displays Local Standard of Rest (LSR) velocities ($v_{\rm LSR}-V_{\rm Hel}$ = 1.7 km s^{-1}, $v_{\rm sys}$=4509 km s^{-1}). Velocities and channel widths follow the optical convention. The broad H_2O maser line is clearly detected on all six days at v=4640 km s^{-1}.

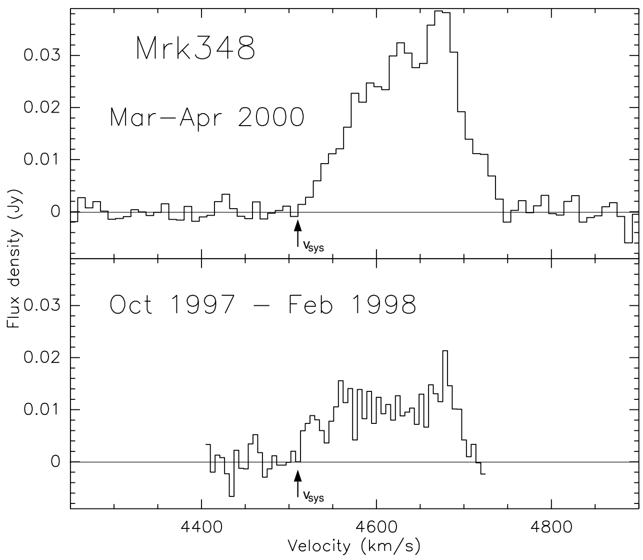

Fig. 2. Combined spectra of Mrk 348 for spectra taken in March – April 2000 (top) and October 1997 – February 1998 (bottom) indicating that the maser has flared significantly between the two epochs. The arrow marks the systemic velocity.

limit for the optical depth τ times the covering factor f of $\tau \cdot f < 0.0075$. This is seven times smaller than the value found for Centaurus A and might be related to the fact that we see Mrk 348 almost face on.

On the other hand, with its type 2 AGN, polarized broad emission-lines, and a nuclear dust lane seen, Mrk 348 falls right into the roster of typical megamaser galaxies, where it is suggested that the masing material is part of the obscuring 'torus' in the unified scheme of AGN. The face-on orientation of Mrk 348 then would suggest that the axis of this torus and the galaxy disk axis are severely misaligned.

In October 1997 – February 1998 the flux density of the line was three times lower than it was in March 2000. In the earlier survey by Braatz, Wilson, & Henkel (1996) the maser line was not detected and given its line width and low flux density it would have resulted only in a broad feature at the 3σ level. Linear interpolation with time of the continuum flux density given in Ulvestad et al. (1999) suggests a continuum flux density for Mrk 348 around 310 mJy in October 1997 at 15 GHz. The level we measure is roughly a factor of three higher – assuming a flat spectrum – and this increase in flux density is similar to the increase in flux density of the line. This could indicate a correlation between continuum and maser flux density, implying an unsaturated maser. With its current radio luminosity the galaxy is now the most radio luminous megamaser galaxy ever discovered. The response of the line to the continuum flare within about 2 years sets an upper limit to the distance of the masers from the nucleus of $\lesssim$0.6 pc, which is of similar order as the size scale of the molecular disk found in NGC 4258.

Indeed, Braatz, Wilson, & Henkel (1996) noted a certain excess of detected megamaser galaxies with large radio powers. Mrk 348 certainly adds to this trend. The distribution of radio powers at 6 cm of the parent samples of AGN selected by Braatz, Wilson, & Henkel (1996) has a peak around $10^{21.75}$ Watt/Hz. If we add Mrk 348 and more recently discovered megamasers (Greenhill et al. 1997; Hagiwara et al. 1997) and also complement the radio data in Braatz, Wilson, & Henkel (1996) with more recent data from the NASA Extragalactic Database, we find that 12 out of 19 detected megamaser galaxies are at or above the peak in the distribution of radio power for galaxies without megamaser detections.

Because of the possibly biased selection of the detected megamasers this is not highly significant. However, it highlights an apparently necessary prerequisite for megamaser emission, namely an AGN with a compact radio core to provide seed photons. So far all detected megamasers have compact ($< 1''$), mostly flat-spectrum, radio emission at a level of a few milli-Jansky. In some cases, like Mrk 348 (Neff & de Bruyn 1983), NGC 1052 (Shaffer & Marscher 1979), Mrk 1210 (Heisler et al. 1998), NGC 2639 (Wilson et al. 1998), NGC 3079 (Trotter et al. 1998), NGC 5793 (Whiteoak & Gardner 1987; Gardner et al. 1992), NGC 5506 (Sadler et al. 1995), and possibly NGC 4945 (Elmouttie et al. 1997) the radio cores can even reach several tens to hundreds of milli-Jansky.

While compact radio cores in Seyfert and LINER galaxies are not uncommon, only very few are so prominent as those in some of the radio-bright megamaser sources. We find that all megamasers mentioned above, i.e. more than a third of known megamasers, have compact radio cores above a fiducial limit of 25 mJy at 5 GHz. On the other hand, in a survey of spiral galaxies Sadler et al. (1995) find only 3 out of 54 galaxies (22 of which are Seyfert galaxies) with compact cores above 25 mJy at 5 GHz. Similarly, in a survey of nearby AGN Nagar et al. (2000) find roughly 40% of Seyfert and LINER galaxies to contain compact flat-spectrum radio cores. However, only three out of 48 galaxies have flux densities >25 mJy. Known megamasers therefore seem to prefer galaxies with relatively bright compact radio emission.

Mrk 348 currently has the brightest and most prominent radio core among megamaser galaxies. Morphology, spectrum, and variability of the core are very similar to the radio core in III Zw 2 which was the first Seyfert galaxy discovered to contain a superluminal jet. This galaxy has a millimeter-peaked spectrum and a jet which shows a stop-and-go behavior indicative of a strong interaction with dense material on the sub-parsec scale (Falcke et al. 1999; Brunthaler et al. 2000). Ulvestad et al. (1999) therefore speculate whether the bright inverted radio core in Mrk 348 could be interpreted similarly to those in Compact Symmetric Objects (CSOs) with a Gigahertz-Peaked-Spectrum (GPS, see O'Dea 1998). In these galaxies bright hotspots are formed in a jet that terminates already on the parsec scale. In III Zw 2 and Mrk 348 this seems to happen on even smaller scales, leading to higher peak frequencies and could be due to frustration of the jet by a molecular cloud or even a warped or misaligned torus.

Since the masers in NGC 1052, which have similar broad line widths as in Mrk 348, are found along the radio jet (Claussen et al. 1998) it should be checked whether in Mrk 348 one has an analogous situation. One can speculate that in such a case the evolution of the radio flare and the evolution of the maser flare and its blue wing could be related, possibly providing a unique diagnostic tool to study jet-ISM interactions.

In any case, with its bright radio core Mrk 348 provides an ideal opportunity to observe the maser lines in this galaxy at high resolution with VLBI during this flare even though the lines still have a rather low flux. Since radio and maser emission seem to be highly variable both should be monitored frequently. Given that Mrk 348 was not discovered in an earlier survey this finding also suggests that existing samples should be revisited to search for more flaring megamasers.

Acknowledgements. We thank Alan Roy for helpful discussions. We are grateful to Jim Ulvestad for a prompt referee report and useful suggestions. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by JPL, Caltech, under contract with NASA.

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