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Detection of 183 GHz H_2O Megamaser Emission towards NGC 4945

E. M. L. Humphreys[1], W. H. T. Vlemmings[2], C. M. V. Impellizzeri[3,4], M. Galametz[1], M. Olberg[2], J. E. Conway[2], V. Belitsky[2], and C. De Breuck[1]

[1] European Southern Observatory (ESO), Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany
e-mail: ehumphre@eso.org
[2] Department of Earth and Space Sciences, Chalmers University of Technology, Onsala Space Observatory, 439 92 Onsala, Sweden
[3] Joint Alma Office, Alsonso de Cordova 3107, Vitacura, Santiago, Chile
[4] National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA

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ABSTRACT

Aims. The aim of this work is to search Seyfert 2 galaxy NGC 4945, a well-known 22 GHz water megamaser galaxy, for H_2O (mega)maser emission at 183 GHz.
Methods. We used APEX SEPIA Band 5 (an ALMA Band 5 receiver on the APEX telescope) to perform the observations.
Results. We detected 183 GHz H_2O maser emission towards NGC 4945 with a peak flux density of ~3 Jy near to the galactic systemic velocity. The emission spans a velocity range of several hundred kms^{-1}. **We estimate an isotropic luminosity of** > 1000 $L_\odot$, classifying the emission as a megamaser. A comparison of the 183 GHz spectrum with that observed at 22 GHz suggests that 183 GHz emission also arises from the AGN central engine. If the 183 GHz emission originates from the circumnuclear disk, then we estimate that a redshifted feature at 1084 kms^{-1} in the spectrum should arise from a distance of 0.022 pc from the supermassive black hole (1.6×10^5 Schwarzschild radii), i.e. closer than the water maser emission previously detected at 22 GHz. This is only the second time 183 GHz maser emission has been detected towards an AGN central engine (the other galaxy being NGC 3079). It is also the strongest extragalactic millimetre/submillimetre water maser detected to date.
Conclusions. Strong millimetre 183 GHz H_2O maser emission has now been shown to occur in an external galaxy. For NGC 4945, we believe that the maser emission arises, or is dominated by, emission from the AGN central engine. Emission at higher velocity, i.e. for a Keplerian disk closer to the black hole, has been detected at 183 GHz compared with that for the 22 GHz megamaser. This indicates that millimetre/submillimetre H_2O masers can indeed be useful probes for tracing out more of AGN central engine structures and dynamics than previously probed. Future observations using ALMA Band 5 should determine unequivocally the origin of the emission in this and other galaxies.

Key words. Galaxies: Seyfert – Masers – Submillimeter: general

1. Introduction

Water megamaser galaxies have become the object of extensive study at 22 GHz, since the discovery that the emission traces a sub-parsec scale portion of the circumnuclear disk in NGC 4258, within 1 pc of the supermassive black hole (SMBH) (Miyoshi et al. 1995). Very Long Baseline Interferometry (VLBI) observations of the masers have provided detailed information on the kinematics and structure of Active Galactic Nuclei (AGN) circumnuclear disks (e.g. Moran et al. 1995; Greenhill et al. 1997; Trotter et al. 1998; Kondratko et al. 2005; Argon et al. 2007; Humphreys et al. 2008; Braatz et al. 2010; Impellizzeri et al. 2012; Reid et al. 2013; Kuo et al. 2015; Gao et al. 2016). Geometric modelling of VLBI disk maser data, provided acceleration or proper motion measurements are also possible, can be used to perform maser cosmology, and has yielded high-accuracy Hubble constant estimates (e.g., Humphreys et al. 2013; Braatz et al. 2015). Additionally, water megamasers can originate from the interaction of AGN radio jets with the interstellar medium, yielding masers in shocked gas within radii of 1 – 10 pc of the central regions (e.g., Claussen et al. 1998).

Radiative transfer models for galactic water masers have long predicted, and observations have found that, the 22 GHz maser does not occur in isolation - very similar conditions to those required to produce this maser yields additional H_2O maser lines in the millimetre/submillimetre (mm/submm) (e.g., Deguchi 1977; Neufeld & Melnick 1991; Yates et al. 1997; Humphreys et al. 2001; Gray et al. 2016). It is therefore believed that some mm/submm H_2O masers could occur from broadly the same regions as 22 GHz masers in AGN, and/or could probe unchartered regions of an AGN central engine, including regions closer to a black hole. Detection and study of mm/submm water masers could therefore make unique contributions to the study of disk and radio jet structure in AGN.

To date extragalactic mm/submm water maser emission has been detected for the 183 GHz transition towards NGC 3079 using the SMA (Humphreys et al. 2005), Arp 220 using the IRAM 30m and APEX (Cernicharo et al. 2006; Galametz et al. 2016), and for the 321 GHz transition towards Circinus and NGC 4945 using ALMA (Hagiwara et al. 2013; Pesce et al. 2016; Hagiwara et al. 2016). There has also been a tentative, 5σ detection of 439 GHz H_2O water maser emission towards NGC 3079 using the JCMT (Humphreys et al. 2005).

NGC 3079, Circinus and NGC 4945 display 22 GHz megamaser emission, and the mm/submm water maser emission towards these targets has been interpreted as also arising from the AGN central engine. However, there is no 22 GHz detection towards Arp 220 and in this case the 183 GHz water megamaser

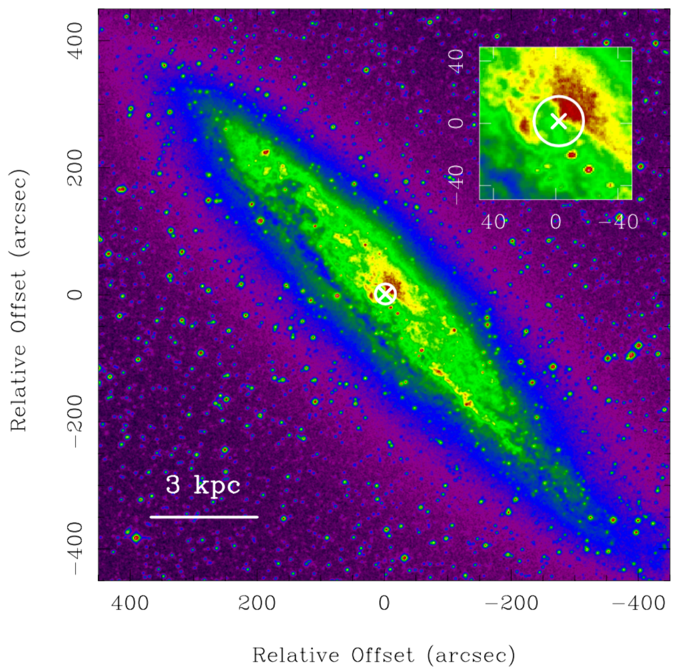

Fig. 1. Image of NGC 4945 from the Palomar Sky Survey[1]. The cross marks the position for NGC 4945 used in our APEX SEPIA Band 5 observations: α_{2000} =13:05:27.28, δ_{2000}= −49:28:04.4. The circle marks the half-power beamwidth (HPBW) of the APEX observations. At a sky frequency of 182.981 GHz this corresponds to 31.8″, or 570 pc at a distance of 3.7 Mpc.

emission is interpreted as arising from $\sim 10^6$ star-forming cores (Cernicharo et al. 2006) i.e. an environment similar to that giving rise to OH megamaser emission.

In this Letter, we report the first detection of 183 GHz H_2O megamaser emission towards southern Seyfert 2 galaxy NGC 4945. The velocities quoted throughout this work are radio definition, local standard of rest. The distance used is 3.7 Mpc (Tully et al. 2013) and the systemic velocity adopted is 556 kms^{-1}, based on CO observations (Dahlem et al. 1993).

2. Observations

The data were taken as part of programme 096.F-9312(A) using the APEX SEPIA[2]Band 5 receiver (Billade et al. 2012). The observations were performed on 3 March 2015 at 03:40 UTC with a native channel width of 0.125 kms^{-1}. The water line, of rest frequency 183.310 GHz from the para-H_2O $3_{13} - 2_{20}$ transition, was tuned to the USB, which covered a frequency range of 181.306 to 185.313 GHz, while the LSB covered 169.285 to 173.292 GHz. The upper level of the $3_{13} - 2_{20}$ transition lies at an energy, E_u/k, of 205 K. For comparison, that of the 22 GHz H_2O maser lies at 644 K. The observations were made in wobbler mode with an off position 140″away in azimuth, and a frequency of 0.5 Hz. Figure 1 indicates the position and the HPBW of the observations.

The total time on science target was 175 minutes, however the first portion of the data was discarded due to high PWV (> 0.6 mm) leaving 88 minutes on target. In the remaining data, the water line could be seen in individual scans (5303 to 5309). Two later scans were discarded due to an apparent loss of phase lock during this time. The total time remaining on science target was 58 minutes.

The remaining scans were averaged in time and a baseline subtracted of polynomial order 2 in the GILDAS CLASS package[3]. We used a Jy/K factor of 34 to convert between antenna temperature T_A^* and flux density[4], with an estimated uncertainty in the flux scale of 50%.

3. Results

The detection of 183 GHz water emission obtained using APEX SEPIA Band 5 is shown in Figure 2 for two different smoothings. For the spectrum binned to a velocity resolution of 40 kms^{-1}, the 1σ rms of the observations is 0.2 Jy and the peak is ~1.8 Jy. The emission is dominated by three main peaks at 505, 680 and 1084 kms^{-1}. This spectrum was binned to emphasise the weaker red-shifted feature at 1084 kms^{-1}. For the spectrum binned to a velocity resolution of 25 kms^{-1}, the 1σ rms of the observations is 0.24 Jy and the peak is ~3 Jy. This binning is shown to indicate the emission peak is stronger when less smoothing is applied (typical for maser spectra in which individual strong spikes could have FWHM as narrow as ~1 kms^{-1}).

4. Discussion

4.1. Nature of the detected emission

We note that isotropic luminosity is not likely to be a meaningful physical quantity when it comes to maser emission, which can be highly beamed, however traditionally this has been used for megamaser classification purposes. The isotropic luminosity of the 183 GHz line is given by:

$$\frac{L}{[L_\odot]} = 1.04 \times 10^{-3} \frac{\nu_{rest}}{[\mathrm{GHz}]} \frac{D^2}{[\mathrm{Mpc}^2]} \frac{\int S\,dv}{[\mathrm{Jykms}^{-1}]} \qquad (1)$$

where ν_{rest} = 183.310 GHz. Performing a single Gaussian fit to the blended maser emission between 400 and 800 kms^{-1} gives **an estimate (lower limit)** of the integrated line area of 11.606 K kms^{-1} or 394.6 Jy kms^{-1}. Using a distance to NGC 4945 of 3.7 Mpc, then this gives **an isotropic luminosity of** 1029 $L_\odot$. If emission from the redshifted feature at 1084 kms^{-1} is added in, then **this becomes 1303±652 $L_\odot$ where the uncertainty quoted is wholly based on the uncertainty in the fluxscale**.

A water megamaser should have an isotropic luminosity of a million times greater than a typical Galactic star-formation water maser, and at 22 GHz this is 10^{-4} $L_\odot$ (Lo 2005) (and likely less at 183 GHz), in which case the 183 GHz emission observed towards NGC 4945 certainly falls into the megamaser category. Indeed we note that famous 22 GHz megamasers towards NGC 4258 and NGC 1068 have isotropic luminosities of 120 and 450 $L_\odot$ respectively (Lo 2005). **We note that the isotropic luminosity for the 183 GHz transition found here is much higher than that found for 321 GHz emission towards NCC 4945 at ~ 10**

[1] The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.

[2] SEPIA is the *Sweden-ESO PI Instrument for APEX*, a PI instrument built in collaboration between the Group for Advanced Receiver Development, Chalmers University of Technology, and ESO.

[3] http://www.iram.fr/IRAMFR/GILDAS

[4] https://www.eso.org/sci/activities/apexsv/sepia/sepia-band-5.html

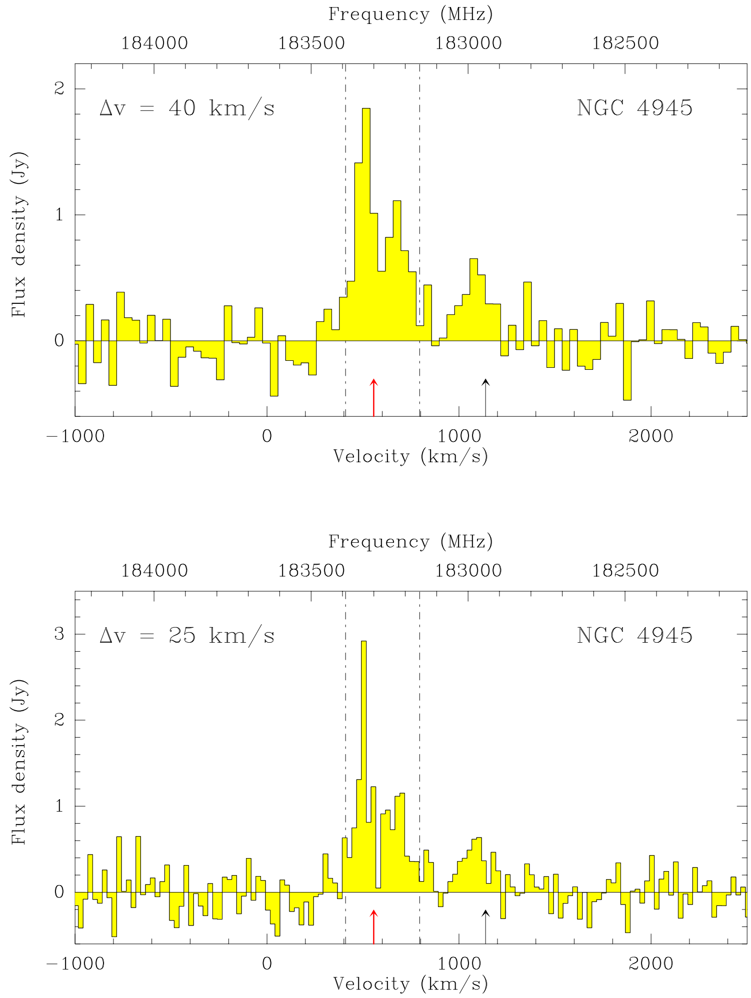

Fig. 2. 183 GHz H_2O emission towards NGC 4945: *(top)* data have been binned to 40 kms^{-1} resolution; *(bottom)* data have been binned to 25 kms^{-1} resolution. The red arrow marks the approximate galactic systemic velocity of 556 kms^{-1}. The dashed lines mark the velocity range of 22 GHz H_2O megamaser emission determined by Greenhill et al. (1997), about 410 to 800 kms^{-1}. We note that the velocities are radio heliocentric in Greenhill et al. (1997) and so we use $v_{LSR} = v_{hel}$ - 4.6 kms^{-1} to convert velocities. The black arrow marks the velocity of a marginally significant feature in the 321 GHz spectrum reported by Hagiwara et al. (2016) (the strongest features at 321 GHz occurred between about 650 to 750 kms^{-1}). The velocity scale is radio LSR.

$L_\odot$ (Pesce et al. 2016; Hagiwara et al. 2016). We speculate that this is due to the very different energy requirements of the two lines. Whereas the upper level of the 183 GHz transition lies at an E_u/k = 205 K above ground state, the 321 GHz line originates from a transition at E_u/k = 1862 K. The difference between the isotropic luminosities may indicate that the physical conditions needed to pump the 183 GHz water maser are more prevalent in the NGC 4945 central region than the conditions required to produce strong 321 GHz water maser emission. For comparison, the 22 GHz line arises from a transition of E_u/k = 644 K.

4.2. Does the emission originate from the AGN central engine?

There are now three extragalactic targets reported in the literature with detections of 183 GHz water maser emission: NGC 3079 attributed to arising from an AGN central engine as for the 22 GHz emission (Humphreys et al. 2005), Arp 220 attributed to a starburst origin (Cernicharo et al. 2006; Galametz et al. 2016), and this new detection for NGC 4945. What is the likely physical origin of the newly-detected maser emission in NGC 4945?

Towards NGC 4945 Greenhill et al. (1997, G97) mapped the 22 GHz H_2O emission from 409 kms^{-1} to 714 kms^{-1} using a subset of the VLBA (although weak/marginal emission was detected up to about 800 kms^{-1}). It was found to originate from a linear structure extending about 40 mas (~0.7 pc at a distance of 3.7 Mpc), interpreted as a portion of the AGN circumnuclear disk. G97 used the observations to estimate a black hole mass of M_{BH}=1.4 × 10^6 $M_\odot$. Since 183 GHz and 22 GHz emission can be produced by similar sets of physical conditions, and since the velocity range of the 183 GHz emission extends across the range detected at 22 GHz by G97, we believe it to be likely that the two maser lines originate from similar locations in NGC 4945, either entirely or predominantly from the AGN central engine. This can be verified by future high spatial resolution observations, which only ALMA can provide.

If the 183 GHz emission does originate from the circumnuclear disk, we can estimate the radius of emission of the highest velocity feature at 1084 kms^{-1}, i.e. that closest to the black hole. For an edge on disk and for emission arising from the disk midline (the line perpendicular to the line of sight to the black hole) the linear radius of the feature from the black hole is given by $r_{feature} = GM_{BH}/\Delta v^2 = 0.022$ pc or 1.6×10^5 Schwarzschild radii. We note that Hagiwara et al. (2016) detected marginally significant high-velocity emission at 321 GHz towards NGC 4945 at $v_{optical,LSR}$ = 1138.6 kms^{-1}. 22 GHz maser spectra in the literature do not display velocities much above 1000 kms^{-1} (e.g. G97; Pesce et al. 2016; Hagiwara et al. 2016).

4.3. Physical conditions leading to the emission

Multiple maser radiative transfer models provide the conditions leading to 183 GHz H_2O maser emission appropriate to evolved stars and star-forming regions. 22 GHz maser emission associated with the AGN central engine disk is believed to be pumped by X-rays from the central engine obliquely irradiating portions of the warped disk, causing heating (Neufeld et al. 1994). Assuming that this yields similar **gas/dust conditions** to galactic water masers, the presence of 183 GHz and 22 GHz emission likely indicates conditions found by Gray et al. (2016). For the 22 GHz transition, strongest emission occurs between T_k = 500 to 2500 K and **$n(H_2)=10^{9-11}$ cm^{-3}**. For the 183 GHz transition, strongest emission occurs between T_k = 500 to 2000 K and $n(H_2)=10^{8-10}$ cm^{-3}. Note the overlapping parameter space for strong emission at both frequencies, and also that Gray et al. (2016) did not investigate densities below 10^7 cm^{-3}.

For Arp 220, in which 183 GHz H_2O emission is observed in the absence of 22 GHz, Cernicharo et al. (2006) find that significantly lower gas densities must be giving rise to the emission (or else 22 GHz emission would also be detectable) i.e. $n(H_2) < 10^6$ cm^{-3} or $T_k < 40$ K. These are conditions found in galactic high-mass star formation, such that the Arp 220 183 GHz emission is proposed to be associated with the Arp 220 starburst rather than the AGN nuclei. We note that lack of variability of the Arp 220 183 GHz emission when observed with single-dishes supports this hypothesis, since the variability of the maser emission for individual star-forming cores could be washed out by beam-averaging (Galametz et al. 2016).

We note that the 183 GHz maser emission detected towards NGC 3079 had a significantly lower isotropic luminosity and narrower velocity range of emission than the emission detected towards NGC 4945, even though both are attributed to arising from the AGN. There may be many reasons for the difference. However, what appears to be the case in NGC 3079 is that the strongest 22 GHz emission occurs for a velocity range where 183 GHz emission is weak or absent. From the results of Gray et al. (2016), this may indicate that a significant proportion of the gas in the NGC 3079 central engine is too dense for strong 183 GHz emission to arise, while it can still produce strong 22 GHz emission (Humphreys et al. 2005, see Figure 2) i.e. $n(H_2) > 10^{10}$ cm^{-3}. In this scenario, the NGC 4945 AGN would have more molecular gas in the density range $n(H_2)=10^{8-10}$ cm^{-3} than NGC 3079.

5. Conclusions

1. We have made a first detection of 183 GHz H_2O maser emission towards NGC 4945 using APEX SEPIA Band 5.
2. The emission is strong, with a peak flux density of ∼3 Jy near to the galactic systemic velocity. The velocity range of the emission extends across several hundreds of kms^{-1}, from about 400 to 1100 kms^{-1}. The isotropic luminosity of the line classifies it as a megamaser.
3. Comparison of the 183 GHz spectrum with that observed at 22 GHz suggests that at least the bulk of the 183 GHz emission arises from a similar location in NGC 4945. From a VLBA map of the 22 GHz emission towards NGC 4945, we believe that 183 GHz emission is arising from the AGN central engine, from the circumnuclear disk.
4. Detection of high velocity emission at 1084 kms^{-1} (528 km s^{-1} from the galactic systemic velocity), if also associated with the disk, is closer to the black hole than 22 GHz emission detected to date for this target. For Keplerian rotation, the emission would be at only 0.022 pc from the black hole (1.6×10^5 Schwarzschild radii).
5. **Further study of this megamaser should be made using ALMA Band 5. On 15 km baselines, an angular resolution of 23 milliarcseconds could be achieved. Indeed we note that APEX now provides an ideal 183 GHz survey instrument for performing pathfinder observations of megamaser candidates, which can then form the groundwork for spatially resolved ALMA studies.**

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