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The Discovery of H_2O Maser Emission in Seven AGN and at High Velocities in the Circinus Galaxy

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ABSTRACT

We report the discovery of H_2O maser emission at 1.35 cm wavelength in seven active galactic nuclei (at distances up to < 80 Mpc) during a survey conducted at the 70-m diameter antenna of the NASA Deep Space Network near Canberra, Australia. The detection rate was $\sim 4\%$. Two of the maser sources are particularly interesting because they display satellite high-velocity emission lines, which are a signature of emission from the accretion disks of supermassive black holes when seen edge on. Three of the masers are coincident, to within uncertainties of $0\farcs2$, with continuum emission sources we observed at about $\lambda 1.3$ cm. We also report the discovery of new spectral features in the Circinus galaxy H_2O maser that broaden the known velocity range of emission therein by a factor of ~ 1.7. If the new spectral features originate in the Circinus accretion disk, then molecular material must survive at radii ~ 3 times smaller than had been believed previously (~ 0.03 pc or $\sim 2 \times 10^5$ Schwarzschild radii).

Subject headings: galaxies: active — galaxies: individual (NGC2824, NGC2979, NGC5643, NGC6300, NGC6926, ESO269-G012, IRASF19370−0131, Circinus galaxy) — galaxies: Seyfert — ISM: molecules — masers

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1. Introduction

Water maser emission (λ1.35 cm in the rest frame) is known to trace warm, dense gas at radii of 0.1 to 1 pc in the accretion disks surrounding supermassive black holes in galactic nuclei (e.g., Moran, Greenhill, & Herrnstein 1999). It can also trace material heated by jet activity (e.g., Claussen et al. 1998) and wide-angle nuclear winds (Greenhill et al. 2001). Emission from disks is visible when they are viewed close to edge-on and amplification paths are longest. Several have been mapped with Very Long Baseline Interferometry (VLBI): NGC 4258 (Miyoshi et al. 1995), NGC 1068 (Greenhill & Gwinn 1997), and the Circinus Galaxy (Greenhill et al. 2001). "Maser disks" may also exist in IC 2560 (Ishihara et al. 2001), NGC 5793 (Hagiwara et al. 2001), and Mrk 1419 (Henkel et al. 2002), though confirmation awaits further study.

Triply peaked spectra characterize emission from accretion disks that are well populated by masers. Emission close to the systemic velocity of the host galaxies (i.e., low-velocity emission) occurs where orbital motion is transverse to the line of sight. High-velocity emission is symmetrically offset by the disk orbital velocities and arises in regions where the disk motion is parallel to the line of sight. Velocities as high as $\sim$ 1100 km s^{-1} have been observed (i.e., in NGC 4258).

Water maser sources in active galactic nuclei (AGN) are important astrophysical tracers in part because VLBI can provide maps of resolved disk structure (e.g., warping) and dynamics (e.g., rotation curves and proper motions), as in Herrnstein et al. (1999). Unfortunately, only $\sim$ 30 H_2O masers are known in AGN, and few of these exhibit triply peaked spectra. The discovery of new masers is a priority and a challenge. First, the emission is typically weak, and surveys must invest substantial time observing each target with the largest available apertures (e.g., 1 hour with a 100 m diameter antenna). Second, mean detection rates in surveys are typically $\ll 10\%$ for Seyfert II galaxies closer than $cz \sim 7000$ km s^{-1} (Braatz et al. 1997). Third, because the orbital speeds of disks (and concomitant velocity range of maser emission) cannot be known in advance, surveys must have instantaneous bandwidths of thousands of km s^{-1}. Sufficiently broadband observing systems have become available to the general community only recently.

We report the detection of seven new masers obtained in a high sensitivity, broad bandwidth survey of 160 nearby AGN ($cz < 8100$ km s^{-1}). The survey was unusual for two reasons. First, we used a 70-m antenna of the NASA Deep Space Network (DSN) to achieve high sensitivity (see also Greenhill et al. 1997a). Second, we used a custom built, portable, 5350 km s^{-1}-wide spectrometer. The survey, which is ongoing at DSN facilities in the Northern and Southern Hemispheres, and the hardware will be discussed in detail elsewhere.

2. Observations

The 70-m DSN antenna located at Tidbinbilla, near Canberra, is equipped with a cooled 18 to 26 GHz HEMT receiver. The left circular polarization channel is limited by a selectable 600 MHz bandpass filter and downconverted to a band centered at 321.4 MHz. A second downconversion and bandpass filter deliver a 400 MHz baseband (~ 5350 km s^{-1} at $\lambda 1.35$ cm) at the input of a 2-bit, four-level, 4096-lag digital autocorrelator.

Survey observations were conducted between 2002 May and September. The zenith system temperature was typically 40 K under good winter observing conditions, and zenith opacities were typically ~ 0.05. The temperature was calibrated with respect to an ambient load. The peak aperture efficiency was $48 \pm 5\%$, and we determined its dependence on elevation through antenna temperature measurements of PKS 1830−211 (6.3 ± 0.3 Jy) and PKS 1921−293 (10.9 ± 0.4 Jy). We calibrated these flux densities against 3C286 (2.6 Jy at 21.8 GHz) with the Australia Telescope Compact Array (ATCA) [5] on 2002 September 9 and 12. We measured and corrected for pointing errors (at the 70-m antenna), which were under most circumstances on the order of $4''$ or 8% of the half-power beamwidth. As a result, we estimate the flux density calibration of spectra is uncertain by $\lesssim 10\%$.

To construct total-power spectra for each AGN, we nodded the antenna between signal and reference positions. Switching times of 30 or 45 s were usually sufficient to produce flat baselines in the spectra. We removed residual fluctuations by subtracting a running mean computed over intervals of 256 channels (~ 337 km s^{-1}). Heliocentric velocities were computed from sky frequencies determined by the digital tuning of receiver elements, using the radio definition of Doppler shift. This calibration should be accurate to better than 0.1 km s^{-1}. We checked it by observing the H66α radio recombination line in W 33, which has a known Local Standard of Rest velocity of 36.2 ± 0.2 km s^{-1} (Wilson, Bieging, & Wilson 1979), and for which we measured a velocity of 36.3 ± 0.2 km s^{-1}.

3. Detections of New Sources

We observed 160 AGN with the Tidbinbilla antenna and obtained typical noise levels of 10 to 20 mJy (1σ) with 30 minutes of on-source integration. We discovered seven new H_2O masers (Table 1, Figure 1). Each detection has been confirmed through observation on more than one day. We have also measured positions for six of the new masers with the Very

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[5] The Australia Telescope Compact Array is part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

Large Array (VLA) of the National Radio Astronomy Observatory (NRAO)[6] or the ATCA. These observing tracks were also used to estimate continuum flux density levels from the underlying AGN at about λ1 cm (Table 1). Where we detected continuum emission, it was coincident with the maser emission, to within estimated uncertainties ($0\farcs2$).

Six masers lie in Seyfert II objects, and one lies in a nucleus whose classification is ambiguous (NGC 2824; Veron-Cetty & Veron 2001). The masers in NGC 5643 and NGC 6300 lie in galaxies that had been targeted in previous searches. Greenhill et al. (2002) reported noise levels of 59 to 87 mJy for NGC 5643 and 59 mJy for NGC 6300 in ~ 0.8 km s^{-1} wide channels, after Hanning smoothing. Braatz et al. (1996) report noise levels of 119 and 109 mJy for the two galaxies respectively, with 0.8 km s^{-1} wide channels. At the strength we measured ($\sim$ 300 mJy in a 1.3 km s^{-1} channel without Hanning smoothing), the maser emission in NGC 5643 would have been detected at the 3 to 5σ level by these earlier observations, from which we conclude the maser emission varies significantly with time. The emission in NGC 6300 is sufficiently weak that it would not have been detected by the earlier observations.

Two of the new maser sources exhibit discrete line complexes above and below the systemic velocity, which probably correspond to the high-velocity emission that is a characteristic of maser action in the accretion disks of supermassive black holes. ESO 269-G012 displays red and blueshifted high-velocity emission, symmetrically offset by $\sim$ 650 km s^{-1} from a narrow line near the systemic velocity of the galaxy (Figure 2). The inferred orbital speed is exceeded only by that of NGC 4258 among known maser hosts. The high-velocity line complexes extend over $\sim$ 100 km s^{-1}, which may be due to the radial distribution of emitting gas. If the rotation curve is "Keplerian" ($v \propto r^{-0.5}$), then the outer radius of the molecular material in the disk would be $\sim$ 1.4 times the inner radius. NGC 6926 exhibits high-velocity emission that is symmetrically offset by up to $\sim$ 200 km s^{-1} from the systemic velocity (Figure 1). Because the blueshifted emission is relatively weak, we have used the VLA to confirm it is real. If the masers in ESO 269-G012 and NGC 6926 lie in disks at radii of 0.1 pc, which is the radius of the innermost masers in NGC 4258, then the enclosed mass is on the order of 10^6 to 10^7 $M_\odot$. The corresponding centripetal acceleration in the ESO 269-G012 disk (v^2/r), which would be manifested by a secular velocity drift in the low-velocity emission, is $\sim$ 4 km s^{-1} yr^{-1}, which is large enough to measure readily within one year.

The maser in NGC 2824 lies in an early-type galaxy and displays an anomalously broad line profile ($\sim$ 150 km s^{-1} half power full width). Broad lines are also seen toward other

[6]The National Radio Astronomy Observatory is a facility of the U.S. National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

early-type galaxies that host maser sources (e.g., NGC 1052, Mrk 348), where the emission is seen toward radio jets rather than accretion disks (Claussen et al. 1998; Peck et al. 2001). However, any correspondence between Hubble-type and maser characteristics is tentative. For example, the maser in IRAS F01063−8034 is broad (Greenhill et al. 2002), but the galaxy is believed to be type Sa (though it is difficult to classify because it is edge-on). In NGC 1386 and IRAS F22265−1826, the relative positions of the masers and jets therein are unknown because the jets are undetected at about λ1.3 cm (Sand, Braatz, & Greenhill 1999). For NGC 2824, we have established a 1 mJy (5σ) upper limit on continuum emission at λ1.3 cm (Table 1).

4. New High-Velocity Gas in Circinus

Previously reported H_2O maser emission in the Circinus galaxy comprises two broad complexes of lines that bracket the systemic velocity ($\sim$ 439 km s^{-1}; Freeman et al. 1977), with spectral features offset by as much as $\sim$ 200 km s^{-1} (Nakai et al. 1995; Braatz et al. 1996; Greenhill et al. 1997b). VLBI images ($\sim$ 15 mJy 1σ noise) resolve a warped accretion disk and show emission with somewhat larger $\sim \pm 260$ km s^{-1} Doppler shifts (Greenhill et al. 2001, 2003). This is the maximum detected orbital speed, and it corresponds to a radius of $\sim$ 0.11 pc.

We have detected weak ($\ll$ 0.1 Jy) high-velocity emission that establishes a $\sim$ 50 to $\sim$ 900 km s^{-1} range of emission (i.e., Doppler shifts up to $\sim$ 460 km s^{-1}). The rotation curve of the Circinus accretion disk is approximately Keplerian (Greenhill et al. 2001). If the new emission arises in the accretion disk, then it lies at $\sim$ 0.03 pc radius (2×10^5 Schwarzschild radii for a 1.7×10^6 $M_\odot$ black hole), and future VLBI studies will be able to map the rotation curve and warp of the accretion disk over an expanded range of radii.

5. Summary

We have detected new H_2O maser sources in seven AGN, as well as new high-velocity emission components in the Circinus galaxy. Two of the new masers exhibit high-velocity emission, indicative of emission from accretion disks. It should be possible to map these two disks with VLBI, trace their rotation curves, and weigh the central engines that bind them. Ultimately, it may be possible to measure geometric distances to the two host galaxies, which would be significant because both lie in the Hubble Flow. One of the new masers lies in an early-type galaxy, and we speculate that it might therefore be associated with an as yet undetected jet. We have also discovered new high-velocity water maser emission in the Circinus galaxy, VLBI observation of which could greatly improve our understanding of its accretion disk.

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Table 1. Newly Discovered H_2O Masers

Galaxy	V_{sys} [a] (km s^{-1})	Date[b] (DOY)	α_{2000} (hhmmss)	δ_{2000} [c] (ddmmss)	T [d] (s)	1σ noise[e] (mJy)	Continuum[f] (mJy)
NGC 2824	2735	170	09 19 02.22	+26 16 12.0	2370	12	< 1
NGC 2979	2695	152	09 43 08.65	−10 23 00.0	4050	6.6	···
NGC 5643	1194	252	14 32 40.70	−44 10 27.8	3840	6.8	4.1
NGC 6300	1106	185	···	···	3465	5.7	···
NGC 6926	5851	183	20 33 06.11	−02 01 38.9	5490	5.1	2.9
ESO 269-G012	4868	152	12 56 40.51	−46 55 34.4	4905	6.5	0.6
IRAS F19370-0131	6060	208	19 39 38.91	−01 24 33.2	4995	5.8	< 2.8
Circinus	439	168	14 13 09.95	−65 20 21.2[g]	13068	5.1	···

[a] Heliocentric velocity, assuming the radio definition of Doppler shift.

[b] Discovery date. Expressed as day-of-year (2002).

[c] Maser positions measured with the ATCA (ESO 269-G012, NGC 5643) or VLA. Uncertainties are $\pm 0\farcs2$. The masers lie within the 1σ error circles associated with optical or infrared positions of nuclei, except for NGC 2979 where the maser-optical RA offset is $+2\farcs3$.

[d] Total integration time on-source.

[e] Noise levels are for a ~ 98 kHz (~ 1.3 km s^{-1}) channel. The flux density scale is corrected for elevation dependence of antenna gain and referenced to outside the atmosphere.

[f] Continuum flux densities, measured with the VLA, at 22.435 and 22.485 GHz, or the ATCA, at 21.056 GHz. The upperlimits reflect five times the RMS noise. The half-power beamwidths for the two arrays were $\sim 0\farcs4$ and $\sim 0\farcs8$, respectively, and the sources were unresolved.

[g] VLBI position (Greenhill et al. 2001).

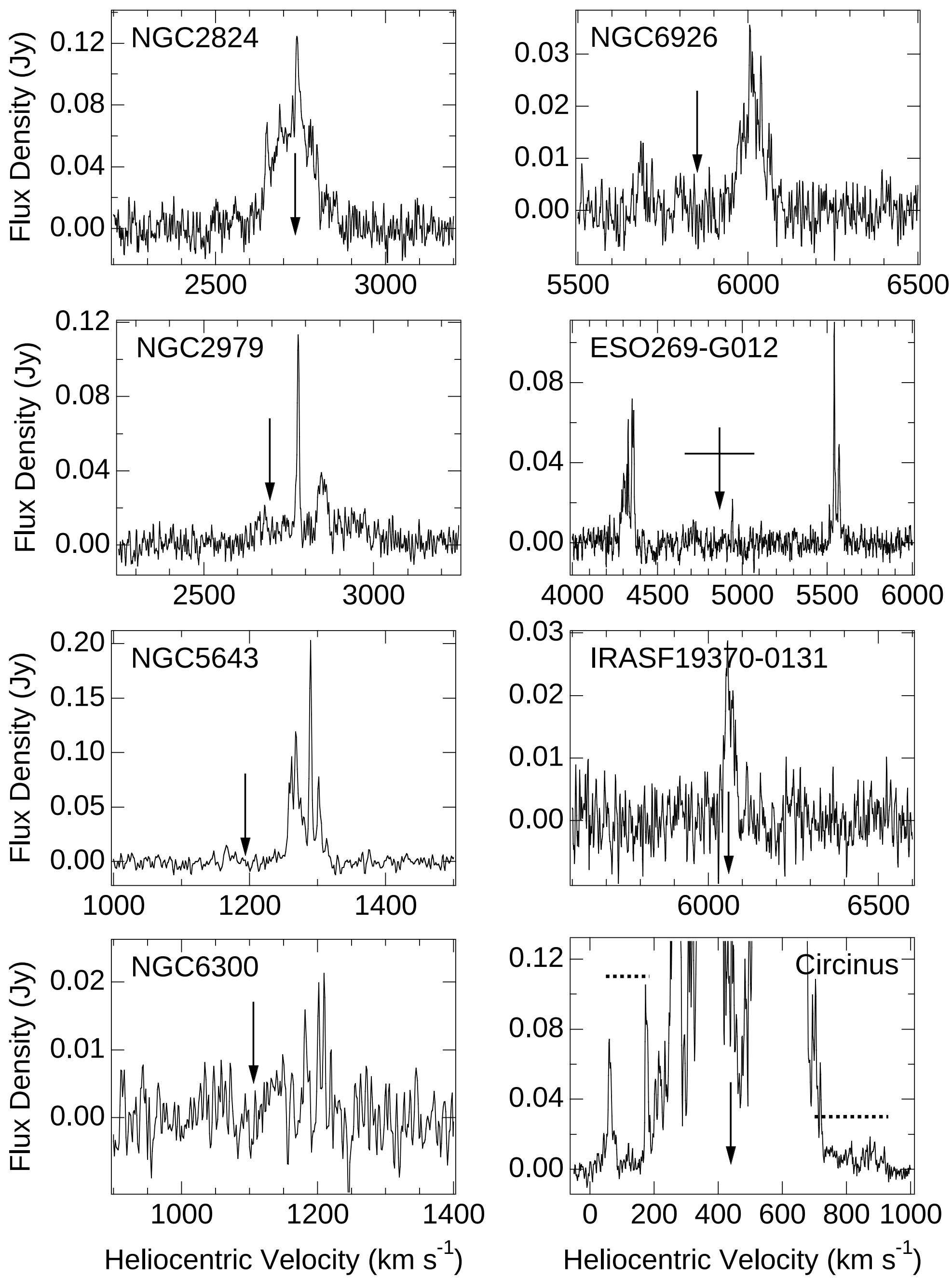

Fig. 1.— Spectra of H_2O maser emission discovered with the 70-m DSN antenna located at Tidbinbilla, near Canberra. Arrows show the systemic velocities of the galaxies (assuming the radio definition of Doppler shift). The systemic velocity of ESO 269-G012 is uncertain by 200 km s^{-1}, which is indicated by the horizontal error bar. The flux density scale for Circinus is expanded to show the newly discovered emission, whose velocity range is indicated by the heavy horizontal dashed lines. All spectra are Hanning smoothed to an effective resolution of 2.6 km s^{-1}. The spectra represent data collected on multiple days that were separated by up to about one month.

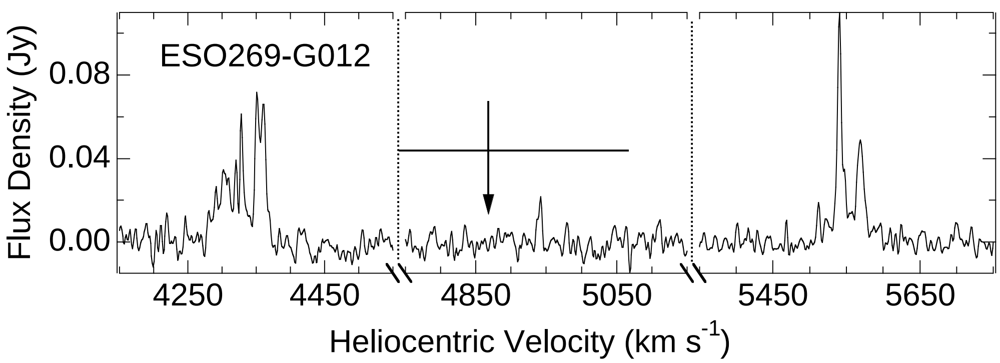

Fig. 2.— Expanded spectrum of the H_2O maser emission in ESO 269-G012. Note that the velocity axis is not continuous.