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WATER MASER EMISSION FROM THE ACTIVE NUCLEUS IN M51

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ABSTRACT

At 22 GHz, water vapor "kilomaser" emission is reported from the central region of the Whirlpool galaxy M51 (NGC 5194). The redshifted spectral features ($V_{\rm LSR} \sim 560$ km s^{-1}), flaring during most of the year 2000, originate from a spatially unresolved maser spot of size $\lesssim$30 mas ($\lesssim$1.5 pc), displaced by $\lesssim$250 mas from the nucleus. The data provide the first direct evidence for the association of an H_2O kilomaser with an active galactic nucleus. In early 2001, blueshifted maser emission ($V_{\rm LSR} \sim 435$ km s^{-1}) was also detected. Red- and blueshifted features bracket the systemic velocity asymmetrically. Within the standard model of a rotating Keplerian torus, this may suggest the presence of either a highly eccentric circumnuclear cloud or red- and blueshifted "high-velocity" emission from a radially extended torus. Most consistent with the measured H_2O position, however, is an association of the redshifted H_2O emission with the northern part of the bipolar radio jet. In this scenario, the (weaker) northern jet is receding while the blueshifted H_2O emission is associated with the approaching southern jet.

Subject headings: galaxies: individual (M51) — galaxies: nuclei — masers — radio lines: galaxies

1. INTRODUCTION

The discovery of a thin molecular Keplerian torus surrounding a supermassive object at the center of NGC 4258 has proved that high-resolution imaging of water maser emission from active galaxies is a powerful method for investigating the dynamics of the circumnuclear region of an active galactic nucleus (AGN; Miyoshi et al. 1995; Herrnstein et al. 1999). About 20 water megamasers are known to date (e.g., Braatz, Wilson, & Henkel 1997), all of which associate with Seyfert 2 or LINER nuclei. However, not all megamasers form part of a circumnuclear torus (e.g., Claussen et al. 1998; Gallimore et al. 2001; Hagiwara et al. 2001), and there are also galaxies that are characterized by much less luminous H_2O emission. Toward the inner 40″ of the starburst galaxy NGC 253 and the nearby spiral galaxy M51 (NGC 5194), weak ($L_{\rm H_2O} \sim 0.1$–$1.0\ L_\odot$) water masers were observed, which were classified as "kilomasers" (Ho et al. 1987; Nakai & Kasuga 1988). Water masers with such intermediate luminosities are also observed in the Milky Way (e.g., W49N) and in the nearby galaxies IC 10, M33, and M82 and are associated with H II regions (Greenhill et al. 1990; Argon et al. 1994; Baudry & Brouillet 1996).

While all H_2O megamasers studied in detail were found to arise from the central few parsecs of active galaxies containing an AGN, it is an open question whether or not some of the H_2O kilomasers can also be linked to the nuclear activity of galaxies. Are H_2O megamasers only the most luminous members of a much larger but less conspicuous population of nuclear masers as suggested by Ho et al. (1987)? The H_2O kilomaser source M51 is one of the nearest galaxies with an active Seyfert 2/LINER nucleus (Terashima et al. 1998) and is thus a suitable target. To test the hypothesis of Ho et al. (1987), we present single-dish monitoring observations with the Effelsberg 100 m telescope and imaging observations with the Very Large Array.

2. OBSERVATIONS

2.1. *MPIfR* 100 m *Radio Telescope*

The Effelsberg 100 m telescope, operated by the Max-Planck-Institut für Radioastronomie, was used on several occasions between 1995 June and 2001 January. Between 1995 and 1997, observations of the 22 GHz H_2O line were made in a position-switching mode with offsets of 300″, employing a *K*-band maser receiver with $T_{\rm sys} \sim 75$ K on an antenna temperature (T_A^*) scale. The back end was an autocorrelator covering a bandwidth of 25 MHz with 1024 channels, yielding a velocity spacing of 0.33 km s^{-1} per channel. Since 2000, we used a dual-channel *K*-band HEMT receiver with $T_{\rm sys} \sim 60$ K (after averaging both channels) on a T_A^* scale. The observing mode was dual-beam switching with a beam throw of 121″ and a switching frequency of ∼1 Hz, providing baselines of high quality. The back-end digital correlator consisted of eight modules (four for each orthogonally polarized channel), each of them providing 512 channels and a bandwidth of 40 MHz (1.05 km s^{-1} channel separation). Amplitude calibration was obtained by repeated measurements of 3C 286 (Baars et al. 1977; Ott et al. 1994). The beam efficiency of the telescope was ∼0.33 at 22 GHz. Pointing measurements were made toward the nearby continuum sources DA 251 and 3C 280; pointing errors were less than 15″.

2.2. *Very Large Array*

The NRAO[3] Very Large Array (VLA) was used in its A configuration on 2001 January 23 to observe the 22 GHz H_2O line toward M51. The observations were made under good seeing conditions employing a single intermediate-frequency band of width 12.5 MHz divided into 64 channels of width 2.63 km s^{-1} each. The band was centered at $V_{\rm LSR} = 560$ km s^{-1}, which is ∼90 km s^{-1} redshifted to the systemic velocity of the galaxy. Considering filter roll-off at the edges of the passband, the usable velocity range was 495–625 km s^{-1}. Given that at the time of our VLA observations, H_2O emission at velocities lower than the systemic velocity had not yet been detected and considering the constraints imposed by the VLA's spectral line correlator modes, our setup did not cover the $V_{\rm LSR}$ range of that low-velocity H_2O emission. During the local sidereal time interval of $12^{\rm h}\!.5$–$15^{\rm h}$, the nuclear position of M51 was observed in a sequence of 5 minute scans, interspersed

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with 2 minute scans of the calibrator source J1419+543 for which we used a position of $(\alpha, \delta)_{J2000} = 14^h19^m46\overset{s}{.}5974$, $+54°23'14\overset{''}{.}787$, determined with submilliarcsecond precision by Johnston et al. (1995). The resultant integration time on M51 is about 100 minutes. The flux density scale S was determined by observations of 3C 286 and is estimated to be accurate to within 10%, assuming that S(3C 286) = 2.54 Jy at 22.2 GHz. The data were calibrated and mapped in the standard way using the NRAO's AIPS. The synthesized beam has a FWHM size of $0\overset{''}{.}102 \times 0\overset{''}{.}096$, corresponding to a linear scale of ~5 pc at $D \sim 10$ Mpc, and a position angle (P.A.) of $-7\overset{\circ}{.}6$. Maps of the H_2O emission were made for each velocity channel. These "channel maps" have a typical 1 σ rms noise level of about 4 mJy beam^{-1}. We also produced a map of the H_2O emission integrated over the velocity range over which significant emission was found in the channel maps, i.e., between 538 and 590 km s^{-1}. This map has an rms noise level of 2.8 mJy beam^{-1}.

3. RESULTS

Figure 1 shows the spectra obtained between 1995 and 2001. The upper panel displays single-dish profiles showing particularly strong maser emission in spring 1997 and 2000. The latter flare lasted until almost the end of the year. Most of the emission is seen redshifted relative to the systemic velocity ($V_{sys, LSR} = 469 \pm 5$ km s^{-1}; Kuno et al. 1995). For the first time, blueshifted emission is also observed: clearly seen at the end of 2001 January, the strongest component at V_{LSR} = 430.5 km s^{-1} is also visible in the 2000 December spectrum. The blueshifted emission covers a range of 410–440 km s^{-1}, or −60 to −30 km s^{-1} relative to V_{sys}, while the redshifted emission is observed between 538 and 592 km s^{-1}, or about 70–120 km s^{-1} relative to V_{sys}. Integrated intensities determined for the velocity intervals of 410–440 and 538–592 km s^{-1} are not correlated. Although not shown, all seven epochs include the velocity range near 690 km s^{-1}, where Nakai et al. (1995) detected emission in early 1995. No H_2O feature is seen at their velocity in our spectra.

The lower panel shows the VLA spectrum taken on 2001 January 23. These are the first molecular data from M51 taken with subarcsecond resolution. Both with respect to flux density and line shape, the spectrum is consistent with the single-dish data from 2000 December and 2001 January. The 540, 566, and 578 km s^{-1} components are all seen. Within the limits of noise, there is no missing flux. The emission arises from a spatially unresolved maser spot of size ≲100 mas at a position of $(\alpha, \delta)_{J2000} = 13^h29^m52\overset{s}{.}7085 \pm 0\overset{s}{.}0004$, $+47°11'42\overset{''}{.}796 \pm 0\overset{''}{.}013$. The quoted uncertainty is the quadratic sum of the error due to the thermal noise in the map and the upper bound of the systematic error caused by the fact that the calibrator source and M51 are at different positions in the sky. This upper bound, which dominates the error budget, was determined by producing a map of 3C 286 by applying calibration solutions determined from J1419+543 scans and by determining the offset between 3C 286's centroid position in that map and its true position. Since the angular separation between J1419+543 and 3C 286 is significantly greater than the separation between J1419+543 and M51, and since M51 was observed over a much wider hour angle range than 3C 286, we consider the above offset as a conservative upper bound on the position error of the M51 H_2O emission. The absolute position errors of J1419+543 and 3C 286 are negligible (see, e.g., Johnston et al. 1995 and Ma et al. 1998).

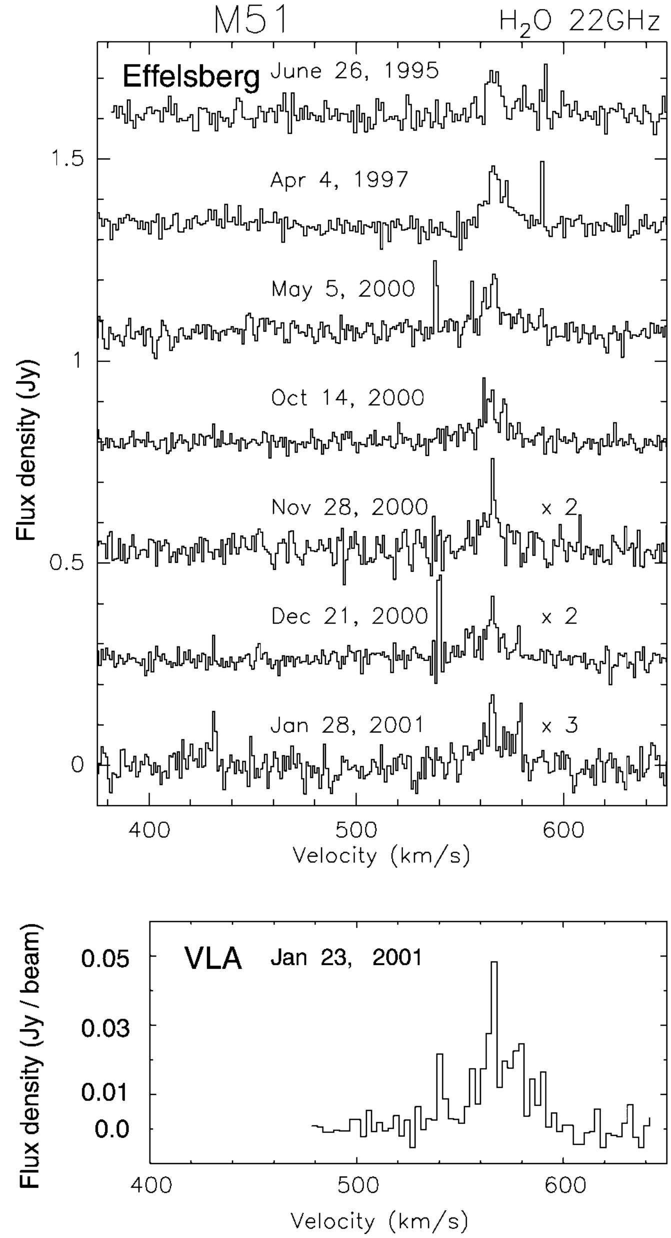

FIG. 1.—*Upper panel*: 22 GHz H_2O spectra taken with the Effelsberg 100 m telescope between 1995 June and 2001 January from M51. Note the enlargement of the temperature scale by factors of 2 or 3 for the most recent spectra marking the end of the flare. For the first two epochs, channel spacings are 1.3 km s^{-1}; for the other spectra, the spacing is 1.05 km s^{-1}. The 1 σ noise levels are, in chronological order, 22, 17, 28, 15, 15, 13, and 9 mJy. *Lower panel*: VLA spectrum from January 23. For details, see § 2.2.

In none of the channel maps (see § 2.2) does the centroid position of the H_2O emission significantly deviate from the position determined for the integrated emission. From the measured peak flux density and the beam size, we obtain a lower limit to the maser's brightness temperature of 10^4 K. Assuming Gaussian distributions for both the H_2O emission and the beam, deconvolution yields a maser source size of ≲30 mas and a peak brightness temperature of ≳10^5 K.

To search for 22.2 GHz continuum emission, we made a map from a (u, v)-database obtained by averaging the line-free channels. No continuum emission was detected at a 1 σ noise level of 0.52 mJy beam^{-1}.

4. DISCUSSION

4.1. H_2O *Maser versus Radio Continuum Peak Position*

The most important result of our observations is the determination of an absolute position of the maser with a 1 σ accuracy of ∼15 mas. A comparison of this maser position with an 8.4 GHz VLA A-array continuum peak position [$(\alpha, \delta)_{J2000}$ = $13^h29^m52^s.7101 \pm 0^s.0016$, $+47°11'42''.696 \pm 0''.026$; M. E. Kaiser, W. A. Baan, & L. D. Bradley III 2001, in preparation) shows that the water kilomaser arises from a hot spot ∼100 mas (5 pc at $D = 10$ Mpc) north of the radio continuum peak that marks the nuclear position of the galaxy (e.g., Grillmair et al. 1997, 1998). A comparison with a 5 GHz VLA A-array continuum map of slightly lower angular resolution by Crane & van der Hulst (1992) also shows good agreement; in this case, the position of the continuum peak is $(\alpha, \delta)_{J2000} = 13^h29^m52^s.706$, $+47°11'42''.55$ (no errors given); i.e., the maser is located ∼25 mas east and ∼250 mas north of the compact continuum source. From even lower resolution 5 GHz VLA B-array and 15 GHz C-array data, Turner & Ho (1994) determined a continuum peak position of $(\alpha, \delta)_{J2000} = 13^h29^m52^s.711$, $+47°11'42''.61$; an absolute positional uncertainty of 100–500 mas is quoted. A comparison with our data suggests that the maser is arising from a position 25 mas to the west and 185 mas to the north of the continuum peak. Since the registration of one map to another is problematical when different calibrators and frequencies are involved, we should consider the quoted individual position errors with utmost caution. A better approach is to compare the three offsets derived: with an average offset of 180 ± 80 mas, this is the first direct evidence for a *kilomaser* located *in the vicinity of an AGN.*

4.2. *Extended Molecular Complex, Nuclear Torus, or Nuclear Jet?*

The nuclear region of M51 is complex. CO $J = 1$–0 and 2–1 interferometric data (Scoville et al. 1998; Aalto et al. 1999) show an ∼2″ sized centrally located molecular cloud with a bulk velocity that is redshifted with respect to V_{sys}. Is this peculiar cloud responsible for the predominance of redshifted H_2O maser features? This is not likely. The average velocities of the main CO subcomplexes are in the range 462 km s^{-1} < V_{LSR} < 545 km s^{-1} (Scoville et al. 1998) and do not cover the velocity range seen in H_2O (Fig. 1). At $V_{LSR} \sim 565$ km s^{-1}, the characteristical H_2O velocity of the redshifted features, Scoville et al. (1998) find CO $J = 2$–1 emission 1″ southwest of the nucleus, well outside the positional error bars of our data (§ 4.1). According to Scoville et al. (1998; their § 3), the asymmetry in the CO distribution is significant, with the bulk of the emission being redshifted with respect to the systemic velocity and arising from western offsets with respect to the nuclear position.

HCN $J = 1$–0 line emission is weaker but traces gas of higher density and may thus be a more appropriate tracer of the warm dense molecular gas that gives rise to 22 GHz H_2O emission. In the HCN $J = 1$–0 line, an asymmetry favoring redshifted over blueshifted emission (as seen in CO) is not apparent. At the 3 σ level, Kohno et al. (1996) find HCN $J = 1$–0 emission at 551–582 km s^{-1} in the inner 5″ of M51 and identify a dense nuclear torus with $R \sim 70$ pc and an apparent $V_{rot} = 16$ km s^{-1} at its outer edge; the estimated inclination is $i \sim 50°$–80° (much higher than the inclination of the large-scale disk). Redshifted emission with respect to V_{sys} is seen to the west; blueshifted emission arises east of the nucleus. With an elongation along P.A. ∼ 70°, the rotation axis (P.A. ∼ 160°) is aligned with the nuclear jet. If the nuclear torus shows Keplerian rotation and if the very center dominates the mass (∼$10^7\ M_\odot$), $V_{rot} = V - V_{sys} \sim 95$ km s^{-1} (for the H_2O line velocities; see § 3) should be reached at $R \sim 2$ pc (40 mas). In view of the positional error bars (§ 4.1), this is not inconsistent with the observational data, but we note that H_2O emission from $V - V_{sys} \sim 95$ km s^{-1} would then arise from a location 40 mas west, not (as our data more likely suggest) ∼180 mas north of the nucleus. Assuming that the blue- and redshifted masers originate from those parts of the torus that are viewed tangentially, the asymmetry in $V - V_{sys}$ (§ 3) infers a dense warm torus that is radially extended or the existence of highly eccentric orbits. The position offset between red- and blueshifted features should be detectable with the A array of the VLA.

Instead of inferring that H_2O is tracing a nuclear torus, we may postulate that the emission is associated with the radio jet. As already mentioned, the radio jet and the rotational axis of the inner (HCN) torus are characterized by P.A. ∼ 160°–165°. The maser position determined in § 4 is not far from this axis (for the line connecting the 8.4 GHz continuum peak [M. E. Kaiser, W. A. Baan, & L. D. Bradley III 2001, in preparation] with the maser position, P.A. = $174° \pm 10°$). Agreement with measured positions is thus better than in the Keplerian disk scenario (for the 8.4 GHz peak, the distance to the jet axis is 15 ± 35 mas). In view of unifying schemes predicting a Doppler-boosted approaching and a Doppler-dimmed receding jet, it is likely that the southern jet is approaching, while the northern jet is receding. Within this context, the redshift of the H_2O emission is readily explained: entrainment of the molecular gas by the jet may offset the velocity from being systemic.

It is well known that 22 GHz H_2O emission is often associated with shocks (e.g., Elitzur 1995) that may raise not only kinetic temperatures but also H_2O abundances. Such shocks can be triggered (on small scales) by jets arising from young stellar objects or (on larger scales) by nuclear radio jets. Megamasers not oriented perpendicular but along the nuclear jets have already been observed toward NGC 1052 (Claussen et al. 1998), Mrk 348 (NGC 262; Peck et al. 2001), NGC 1068 (the "jet masers"; Gallimore et al. 2001), and Circinus (Greenhill et al. 2000) and may either arise from a fortuitously placed foreground cloud or, more likely, from a shocked dense region near the boundary of the jet. According to this latter scenario, the blueshifted features from M51 (see Fig. 1) should be associated with the southern jet. This can be checked observationally since position offsets should be large enough to be detected by VLA A-array observations.

4.3. *Conclusions*

Presenting the first direct evidence for a nuclear H_2O kilomaser, our data are not inconsistent with the suggestion of Ho et al. (1987) that there must be a family of weak nuclear "megamasers." *The kilomaser in M51 shows characteristic properties of megamasers*. Only the measured luminosity is smaller. Interpreting slight offsets between nuclear and maser position and postulating that the northern jet is receding, we conclude that the masers in M51 are most likely associated with the nuclear jet. Positional uncertainties, however, are too large to definitely rule out emission from a circumnuclear disk.

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