Draft Version 1.0, LOS
Preprint typeset using LaTeX style emulateapj v. 11/10/09

DISCOVERY OF THE FIRST METHANOL (CH_3OH) MASER IN THE ANDROMEDA GALAXY (M31)

Loránt O. Sjouwerman
National Radio Astronomy Observatory, P.O. Box 0, Lopezville Rd. 1001, Socorro, NM 87801

Claire E. Murray
Department of Physics and Astronomy, Carleton College, One North College Street, Northfield, MN 55057 and
National Radio Astronomy Observatory, P.O. Box 0, Lopezville Rd. 1001, Socorro, NM 87801

Ylva M. Pihlström[1]
Department of Physics and Astronomy, University of New Mexico, MSC07 4220, Albuquerque, NM 87131

Vincent L. Fish
Massachusetts Institute of Technology, Haystack Observatory, Route 40, Westford, MA 01886

and

Esteban D. Araya
Physics Department, Western Illinois University, 1 University Circle, Macomb, IL 61455

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ABSTRACT

We present the first detection of a 6.7 GHz Class II methanol (CH_3OH) maser in the Andromeda galaxy (M31). The CH_3OH maser was found in a Very Large Array (VLA) survey during the fall of 2009. We have confirmed the methanol maser with the new Expanded VLA (EVLA), in operation since March 2010, but were unsuccessful in detecting a water maser at this location. A direct application for this methanol maser is the determination of the proper motion of M31, such as was obtained with water masers in M33 and IC10 previously. Unraveling the three-dimensional velocity of M31 would solve for the biggest unknown in the modeling of the dynamics and evolution of the Local Group of galaxies.

Subject headings: masers — galaxies: individual (M31) — galaxies: ISM — Local Group

1. INTRODUCTION

The discovery of 22 GHz water masers in galaxies of the Local Group contributed to the study of the content, dynamics and evolution of individual star forming complexes in their host galaxies (e.g., Churchwell et al. 1977; Huchtmeier et al. 1988; Brunthaler et al. 2006a). More importantly, the microarcsecond (μas) accuracy provided by VLBI observations of these masers enabled measurements of the galactic rotation around the nucleus of their host galaxies, as well as the proper motion of their galaxies as a whole (e.g., Brunthaler et al. 2006b). A dynamical model of the history and mass distribution of the Local Group is within reach with accurate knowledge of the absolute distances and three-dimensional motions of its members.

The Milky Way and Andromeda (M31), together with M31's companion M33, are the dominant constituents of the Local Group and are responsible for the largest dynamic forces therein. Obtaining M31's geometric distance and its transverse velocity would resolve the largest unknown, its three-dimensional velocity, in the modeling of the Local Group (e.g., Peebles et al. 2001; Loeb et al. 2005; van der Marel & Guhathakurta 2008).

Water masers in star forming complexes are probably the brightest masers available, and their relatively high frequency is an advantage in proper motion studies as the accuracy scales with wavelength. On the other hand, the higher frequency implies smaller beam sizes, making a large area survey relatively expensive. Most often water maser searches are targeted toward compact HII regions, where massive star formation might be expected.

Current studies of the kinematics of the Local Group of galaxies include measuring the transverse motions of water maser complexes in galaxies such as M33 and IC10 with an accuracy of up to 3 μas yr^{-1}, i.e, about 10 km s^{-1} with a time baseline of 3 years (Greenhill et al. 1993; Brunthaler et al. 2005, 2007). The anticipated transverse motion of M31 is >80 km s^{-1} (Loeb et al. 2005; van der Marel & Guhathakurta 2008), occasionally quoted as large as ~150-160 km s^{-1} (Peebles 1994; Peebles et al. 2001). Unfortunately, no water masers are found in targeted observations toward M31 (Greenhill et al. 1995; Imai et al. 2001, M. Claussen, priv. comm.) leaving a major uncertainty in the dynamical history and mass distribution of the Local Group due to the undetermined transverse velocity of M31.

We therefore embarked on a systematic survey for Class II 6.7 GHz methanol masers in M31 to find sources for proper motion studies. Class II methanol masers are radiatelively pumped and believed to be signposts of an early phase of massive star formation. These methanol

lsjouwer@nrao.edu
[1] Y. M. Pihlström is also an Adjunct Astronomer at the National Radio Astronomy Observatory

masers represent the second brightest known Galactic maser transition, only surpassed by 22 GHz water vapor masers. The astrometry at 6.7 GHz is about a factor of three worse than at 22 GHz, in principle requiring three times as long a time baseline in order to measure proper motions to the same accuracy. However, tropospheric errors are much less problematic at 6.7 GHz than at 22 GHz, partly compensating this disadvantage.

The detection rate for extragalactic methanol masers seems to be very sensitive to the metallicity of the host galaxy (Beasley et al. 1996; Green et al. 2008). Other than the Milky Way, the only other galaxy in which methanol masers have been detected is the Large Magellanic Cloud (LMC; Green et al. 2008, and references therein). No methanol masers have been detected in the low-metallicity Small Magellanic Cloud (Green et al. 2008) or M33 (Goldsmith et al. 2008). In contrast, the high metallicity of M31 makes it an excellent target for a methanol maser search.

We will report on the full results of our systematic survey in a forthcoming paper. Here we report on the detection of the first 6.7 GHz methanol maser in M31. We also searched this location for a potential 22 GHz water maser.

2. OBSERVATIONS

The Very Large Array (VLA) was tuned to observe a rest frequency of 6668.518 MHz at a heliocentric (optical) velocity of about -275 km s^{-1}. The VLA correlator was processing a 3.125 MHz (140 km s^{-1}) Doppler tracked dual polarization bandwidth divided in 128 frequency channels of 24.4 kHz (1.1 km s^{-1}) each. Typical on-source times were about 2 hours per pointing, yielding typically 2.7 mJy beam^{-1} rms noise per frequency channel over most of the band. Over the lower $\sim$0.5 MHz, the noise was exponentially increased to about twice this value due to aliasing effects caused by feeding EVLA receiver electronics into the VLA correlator. The observations took place during a period of transition from the VLA to the Expanded VLA (EVLA), with the result that the number of telescopes with 4–6 GHz C band receivers varied by epoch. Also the number of new polarizers deployed on these receivers varied per observation. However, no fewer than 16 out of 27 possible receivers (by late 2010) were used for any of the observations. Several candidate masers with peaks over 5σ were cataloged.

We obtained exploratory time on the EVLA, in operation since March 2010, to follow up with a confirming observation on one of the candidate masers in July 2010. By this time 25 antennas were equipped with the new, final 4-8 GHz C band receivers of which typically 23 produced usable data. Apart from, e.g., the new receivers and receiver range of the EVLA, the EVLA also utilizes the new WIDAR correlator. Our EVLA observations used one of the standard modes available during the WIDAR commissioning period, using 2 MHz (90 km s^{-1}) bandwidth with 256 dual polarization channels (7.8 kHz, 0.35 km s^{-1}). In total 8 hours were spent to observe the candidate maser over four runs around the end of July 2010, yielding about 1.5 mJy beam^{-1} rms noise per channel in the robust weighted image, but with much narrower channel separation compared to the earlier VLA observations. Doppler *setting* was used, where the observing frequency was calculated to center the observation at -240 km s^{-1} at the start of the observation and then kept fixed. This contributed a negligible spectral broadening of less than 0.1 km s^{-1}, or about a third of a channel. The pointing and frequency were also adjusted compared to our VLA survey to place the candidate maser closer to the center of the beam and the center of the observing band.

After confirmation of the methanol maser, we also obtained exploratory time to search for a potential 22.23508 GHz water maser. The observation was taken at the end of August 2010, lasted for 2 hours and used an 8 MHz (100 km s^{-1}) bandwidth with 256 dual polarization channels (31.25 kHz, 0.42 km s^{-1}). The channel rms noise achieved in the naturally weighted image was 4.8 mJy beam^{-1} using data from 25 antennas.

All VLA and EVLA observations were taken when the interferometer was in its most compact "**D**" configuration. The angular resolution at 6.7 GHz of about 10$''$ corresponds to about 38 pc at the distance of M31 ($\sim$800 kpc, Stanek & Garnavich e.g., 1998), leaving any candidate maser spatially unresolved. The 2.8$''$ angular resolution at 22 GHz corresponds to about 10 pc at the distance of M31. All observations were exclusively reduced using the standard NRAO Astronomical Imaging Processing System (AIPS) procedures where a new Obit[2] task `BDFIn` filled the native Science Data Model data into AIPS.

3. RESULTS

Figure 1 shows the primary beam corrected spectra of the VLA candidate maser and the EVLA maser confirmation along with a MSX infrared image outlining the location of the maser in M31. We could identify the methanol maser in all four EVLA observing chunks ("Scheduling Blocks"), but the signal-to-noise in the individual scheduling blocks was insufficient to derive a statement on short time scale variability. The spectra compare in shape, line width ($\sim$5 km s^{-1}), peak flux ($\sim$8 mJy beam^{-1}) and central line-of-sight velocity (-242 km s^{-1}). Their measured positions are within 2$''$ (less than one pixel) of each other (at RA $00^h44^m19.2^s$, Dec 41°19$'$30$''$ in J2000; X=+13$'$.66, Y=+11$'$.96 following Baade & Arp 1964). The location of the maser is at a projected distance of 18.13$'$, which corresponds to a deprojected distance of about 12.7 kpc from the nucleus. No "VLBI-bright" water maser complex was found at this location with a (2σ) detection limit of 10 mJy beam^{-1} per 0.42 km s^{-1} channel.

Nearby peaks in CO (near area #13, Dame et al. 1993) and infrared radiation (IRAS 00416+4104, 3.17 Jy at 60 μm) are present. The narrow velocity range of the methanol emission is within the wide velocity range of the CO emission in that region, but a clear relation cannot be derived due to the low resolution of the CO and infrared data.

4. DISCUSSION

We have found and confirmed the first 6.7 GHz methanol maser in M31, making it the second (and most distant) galaxy outside the Milky Way known to host a

[2] Available from http://www.cv.nrao.edu/$\sim$bcotton/Obit.html

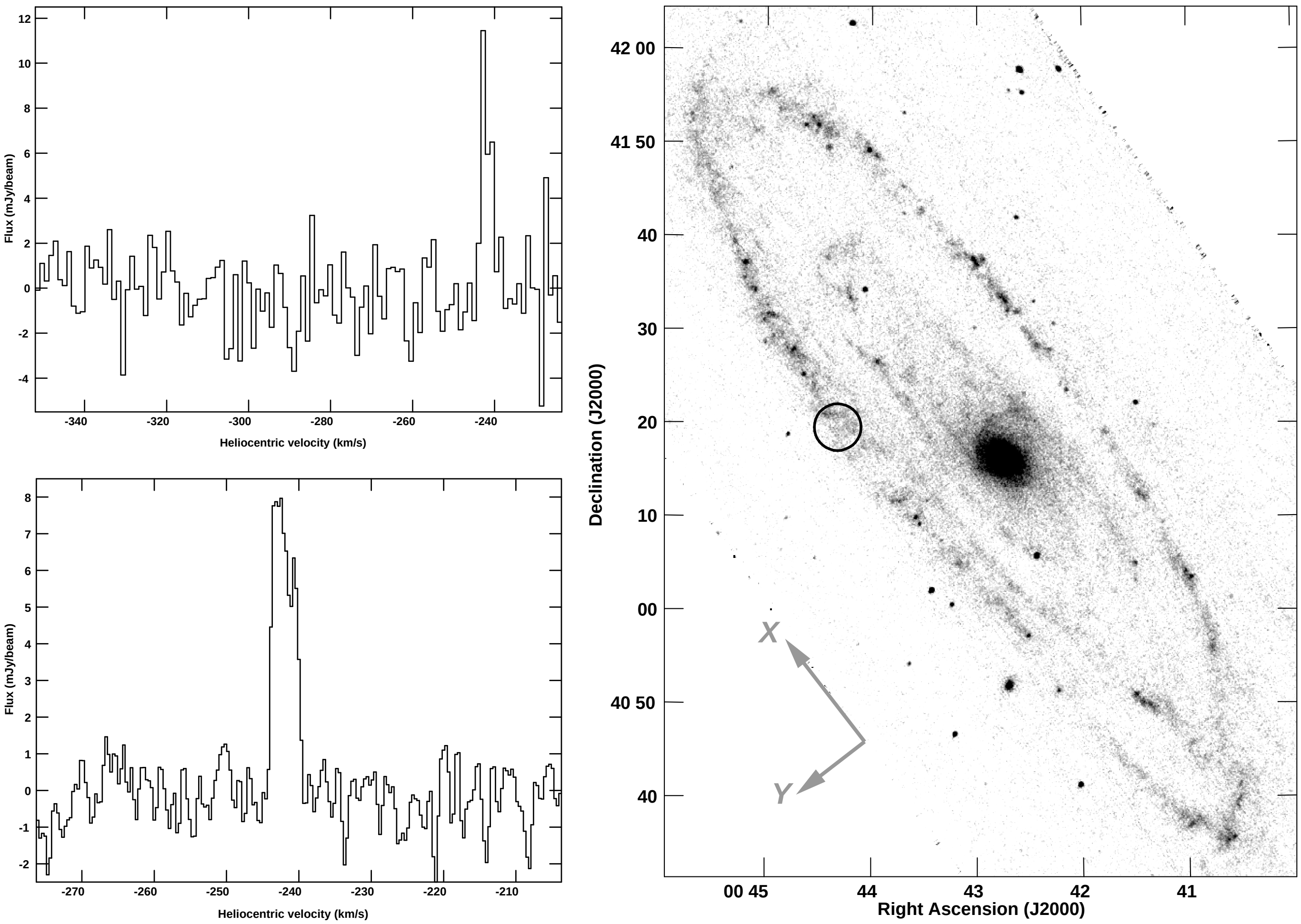

FIG. 1.— Top left: original spectrum of the first methanol maser in M31, taken with the VLA correlator using EVLA receivers. Bottom left: Smoothed confirmation spectrum, taken using the EVLA and the WIDAR correlator. Right: MSX 8 μm infrared image of M31 (Moshir et al. 1997; Kraemer et al. 2002) locating the methanol maser in an inconspicuous part of the $\sim$10 kpc molecular ring (circle). The directions of the axes of the X,Y coordinate system (where the origin should be in the nucleus) of Baade & Arp (1964) are indicated.

methanol maser. It is also the first maser of any type detected in M31.

Interstellar methanol is found in massive star forming regions in the Milky Way, mostly in the spiral arms peaking at around 5 kpc galactocentric distance, but not being necessarily associated with compact HII regions (Pandian et al. 2010). Galactic 6.7 GHz methanol masers can be as bright as a few thousand Jy (e.g., Pestalozzi et al. 2005). The maser peak flux density of about 8 mJy beam^{-1} for the maser found in M31 compares to masers on the high-end tail of the 6.7 GHz methanol maser distribution in the Milky Way (see derivation in Goldsmith et al. 2008). The brightest Galactic methanol maser with a very accurate distance measurement is W3(OH): $\sim$3700 Jy at 2.0 kpc (Pestalozzi et al. 2005; Hachisuka et al. 2006). At this distance, the M31 detection would measure $\sim$1300 Jy, while the brightest maser in the LMC would be $\sim$3000 Jy (e.g., Beasley et al. 1996). Thus, it is plausible that M31 may host brighter methanol masers than the one reported here.

For the purpose of astrometry and proper motion measurements, higher frequency masers may be better suited than the here presented 6.7 GHz methanol maser. For example, a similar but higher frequency Class II methanol maser may be present. A likely candidate would be the 12.2 GHz maser, which can be very bright ($\sim$1100 Jy) but is usually (though not always) fainter than the brightest 6.7 GHz maser in a given source (Caswell et al. 1995).

On the other hand, of the four known 6.7 GHz methanol masers in the LMC, one was found to have an accompanying water maser. While the LMC appears to be under-abundant in masers due to its low metallicity (e.g., Beasley et al. 1996; Green et al. 2008), there might be a fair chance of detecting a water maser near the methanol maser in a metal-rich galaxy such as M31. The maser detection in M31 is not in the immediate vicinity ($<$50 pc) of a known star forming region, an Hα emission line region, or a compact HII region; regions typically targeted when searching for water maser emission in the Magellanic Clouds, M31 and M33.

Assuming that the 6.7 GHz methanol masers are the highest frequency masers to be found in M31, a conservative estimate of the expected astrometric accuracy for a low signal-to-noise feature with VLBI instruments would be about a tenth of the beam size, or about 100 μas. When we ignore galactic rotation and take the anticipated lower limit for the transverse motion of M31 of 80 km s^{-1} (Loeb et al. 2005; van der Marel & Guhathakurta 2008), which is much higher than an undetermined random motion of the maser in the galaxy, the expected angular displacement of M31 would be in the order of 20 μas yr^{-1} (at 800 kpc). This is measurable with about ten years of observations.

A survey for potential similarly bright or brighter methanol masers, as described in our full survey paper, will allow us to determine more than one proper motion and derivation of the high-end tail of the methanol maser distribution. As M31 has a well determined inclination, the proper motions of a few masers will allow the derivation of an accurate geometric distance to M31. In that respect it would be very interesting if these maser proper motions could be linked to a proper motion measurement of M31*, the ∼50 μJy beam^{-1} (at 6 GHz) nuclear supermassive black hole in M31. We anticipate follow-up observations, e.g., with the European VLBI Network, for this purpose.

ACKNOWLEDGMENTS

CEM acknowledges support from the "Research Experiences for Undergraduates" program, which is funded by the National Science Foundation. The Very Large Array and the Expanded Very Large Array are operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Facilities: VLA (), EVLA ()

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