Revista Mexicana de Astronomía y Astrofísica, **50**, 137–143 (2014)

A SENSITIVE SEARCH FOR METHANOL LINE EMISSION TOWARD EVOLVED STARS

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Received 2013 December 11; accepted 2014 January 24

RESUMEN

Presentamos una búsqueda muy sensible de emisión de líneas de metanol a 1 cm en estrellas evolucionadas, con el fin de detectar, por primera vez, máseres de metanol en este tipo de objetos. Nuestra muestra incluye estrellas post-AGB y nebulosas planetarias (NP) jóvenes, cuyos procesos de pérdida de masa y sus estructuras circunestelares se asemejan a los de objetos estelares jóvenes (OEJ), en los que se detectan máseres de metanol. Buscamos máseres de Clase I en 73 objetos y de Clase II en 16. No encontramos ninguna detección. La ausencia de detecciones de máseres de Clase I indica que la producción de metanol en granos de polvo, o el incremento de su abundancia en las zonas de choque de objetos evolucionados no es tan eficiente como en OEJs. Proponemos que las NPs relativamente más evolucionadas podrían tener una mayor probabilidad de detección de máseres de Clase II.

ABSTRACT

We present a sensitive search for methanol line emission in evolved stars at 1 cm, aiming to detect, for the first time, methanol masers in this type of objects. Our sample comprised post-AGB stars and young planetary nebulae (PNe), whose mass-loss processes and circumstellar structures resemble those of young stellar objects (YSOs), where methanol masers are detected. Class I masers were searched for in 73 objects, whereas Class II ones were searched in 16. No detection was obtained. The non-detection of Class I methanol masers indicated that methanol production in dust grains and/or the enhancement of its gas-phase abundance in the shocked regions of evolved objects are not as efficient as in YSOs. We suggest that relatively more evolved PNe might have a better probability of harboring Class II masers.

Key Words: ISM: molecules — masers — stars: AGB and post-AGB

1. INTRODUCTION

The methanol molecule is rich in transitions with frequencies in the radio regime (mm to cm wavelengths), of which more than 20 are known to emit as masers (Sobolev 1993). Methanol masers are found in many star-forming regions, usually associated with high-mass young stellar objects (YSOs) (see, e.g., Haschick, Menten, & Baan 1990; Menten 1991a; Pestalozzi, Minier, & Booth 2005; Pratap 2008), but they are also present around a few low-mass ones (Kalenskii et al. 2006, 2010). However, there is no reported detection of methanol lines (either thermal or maser) toward evolved objects, despite several searches (Bachiller et al. 1990; Latter & Charnley 1996a,b; Charnley & Latter 1997). A possible exception may be IRAS 19312+1950 (Deguchi, Nakashima, & Takano 2004), although the nature of the object and whether the methanol lines are really associated with it, or with a nearby molecular cloud, is still unclear. Other prospective cases of methanol in evolved stars (Walsh et al. 2003; Urquhart et al. 2013) have been refuted by Breen et al. (2013).

The non-detection of *thermal lines* of methanol ruled out chemistry models (Charnley, Tielens, &

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Kress 1995; Marvel 2005) that invoked an injection of CH_4 from the inner to the outer circumstelar envelope, as a way to explain the high abundance of HCN observed in some oxygen-rich asymptotic giant branch (AGB) stars (Bujarrabal, Fuente, & Omont 1994; Bieging, Shaked, & Gensheimer 2000). These models predicted an enhancement of methanol abundance that should have resulted in flux densities of its thermal lines above the sensitivity limit of the observations.

Moreover, the absence of *methanol masers* in evolved stars suggests that the energy input and/or the physical conditions of density or temperature necessary to maintain the inversion of population, are not met in this type of objects, in contrast with YSOs. Alternatively, it is possible that the physical conditions are appropriate for maser pumping, but the methanol molecule is not abundant enough to produce any significant emission. This situation is significantly different from the case of other molecular species, such as SiO, OH, and H_2O, whose maser emission is detected toward both young and evolved objects (Elitzur 1992).

Searches for methanol in evolved stars have focused on AGB stars, which is understandable because they have dense circumstellar envelopes, and the detection rates of SiO, OH, and H_2O masers are much higher than in subsequent phases (Lewis 1989; Gómez, Moran, & Rodríguez 1990). However, the next evolutionary stages may provide more adequate targets. In post-AGB stars and early planetary nebulae (PNe) the structure of the circumstellar medium and the physical processes are similar (at least qualitatively) to those of YSOs (see, e.g., Shu, Adams, & Lizano 1987). They often display collimated jets (Sahai & Trauger 1998; Gómez et al. 2011), circumstellar disks (Kwok, Hrivnak, & Su 2000; Bujarrabal et al. 2005), and thick envelopes surrounding the whole system (Imai et al. 2009; Ramos-Larios et al. 2009; Rizzo et al. 2013).

Considering these similarities, we have carried out a search for methanol masers focused on post-AGB and young PN candidates, using two of the most sensitive single-dish radio telescopes in the world working at centimeter wavelengths. We have searched for emission in four different transitions, pertaining to the two different classes of methanol masers, commonly known as Class I and II (Batrla et al. 1987; Menten 1991b).

2. SOURCE SAMPLE

We have used two different samples in our observations. The Class II masers were searched for in some post-AGB stars and PNe from the catalogue of Suárez et al. (2006) that fulfilled at least one of these criteria: (a) they had a previous detection of either H_2O or OH masers, (b) they were classified as "transition objects" in Suárez et al. (2006), or (c) they were PNe of low excitation. In addition, we included some post-AGB stars and PNe that were not included in Suárez et al. (2006), but that showed SiO masers (Nyman, Hall, & Olofsson 1998).

The second sample used for the Class I maser search comprises most of the northern sources in Ramos-Larios et al. (2009). They are post-AGB stars and PN candidates with the IRAS color criteria of Suárez et al. (2006), and with signs of strong optical obscuration.

3. OBSERVATIONS

3.1. *Robledo de Chavela*

The Class II $2_1 - 3_0$ E transition of methanol (rest frequency = 19967.3961 MHz) was observed with the DSS-63 antenna, located in the Madrid Deep Space Communications Complex (MDSCC), near Robledo de Chavela, Spain. The antenna has a diameter of 70 m, providing a half-power beam width of $46''$ at this frequency. The observations were carried out between September 2002 and June 2005, using two different backends depending on the observing dates. In 2002 and 2003 we used a 256-channel spectrometer covering a bandwidth of 10 MHz, which provided a velocity resolution of $\simeq$0.59 km s^{-1}. In 2005 we used a 384-channel spectrometer covering a bandwidth of 16 MHz ($\simeq$216 km s^{-1} with $\simeq$ 0.63 km s^{-1} resolution). Spectra were taken in position-switching mode with the 384-channel spectrometer and in frequency switching mode, with a switch of 5 MHz when using the 256-channel one, thus providing in the latter case an effective velocity coverage of $\simeq$ 202 km s^{-1} (15 MHz). Only left-circular polarization was processed. The total integration time was typically 20 minutes per source in frequency-switching mode and 30 minutes (on + off) in position-switching mode The rms pointing accuracy was better than $10''$. The data reduction was performed using the CLASS package, which is part of the GILDAS software. Spectra were corrected for the elevation-dependent gain of the telescope and for atmospheric opacity.

3.2. *Green Bank Telescope*

We observed three Class I methanol transitions of the J_2−J_1 E series: $2_2 - 2_1$, $3_2 - 3_1$, and $4_2 - 4_1$, with rest frequencies 24934.382, 24928.707, and 24933.468 MHz, respectively, using the Robert C.

TABLE 1

ROBLEDO OBSERVATIONS

IRAS name	RA(J2000) (h:m:s)	Dec(J2000) (°:′:″)	rms[a] (Jy)	Date[b] (yyyy-mm-dd)	V_0[c] (km s^{-1})
06530−0213	06:55:32.07	−02:17:30.1	0.03	2003-05-16	+28.0
16559−2957	16:59:08.22	−30:01:40.8	0.18	2003-05-16	+56.0
17086−2403	17:11:38.76	−24:07:33.5	0.04	2005-06-16	−0.3
17291−2402	17:32:12.98	−24:05:00.8	0.04	2005-06-16	−0.3
17347−3139	17:38:01.28	−31:40:58.1	0.07	2005-06-16	−68.3
17395−0841	17:42:14.08	−08:43:21.6	0.12	2003-05-16	+85.0
18061−2505	18:09:12.54	−25:04:35.5	0.05	2005-06-17	+3.8
19016−2330	19:04:43.21	−23:26:11.0	0.05	2005-06-17	−0.2
19154+0809	19:17:50.68	+08:15:06.0	0.10	2002-10-11	0.0
19255+2123	19:27:43.99	+21:30:03.0	0.05	2002-09-05	+25.0
"	"	"	0.25	2002-10-11	+25.0
19590−1249	20:01:49.77	−12:41:17.2	0.04	2005-06-17	84.8
20406+2953	20:42:45.95	+30:04:06.0	0.12	2002-10-11	+15.0
20462+3416	20:48:16.64	+34:27:24.2	0.08	2002-09-05	0.0
21546+4721	21:56:33.03	+47:36:13.0	0.07	2002-09-05	0.0
22023+5249	22:04:12.24	+53:03:59.9	0.05	2002-09-05	0.0
22036+5306	22:05:30.63	+53:21:32.6	0.13	2002-10-11	−40.0

[a]One-sigma rms noise level of the spectra, after correction by elevation-dependent gain and atmospheric opacity.

[b]Date of observation.

[c]Central LSR velocity of the spectra.

Byrd Green Bank Telescope (GBT) of the National Radio Astronomy Observatory, in March 2010. The 1.3 cm receiver comprised four beams, arranged in two pairs that could be tuned independently. We used one such pair, with a separation of 178.8″ between the beams, to simultaneously observe an on- and off-source position in dual polarization. Antenna nodding between the two beams was used to subtract atmospheric and instrumental contributions. We selected two spectral windows, one comprising the three methanol lines (and centered on the frequency of the $4_2 - 4_1$ E transition), and the other centered on the water line at 22 GHz (whose results will be presented in Gómez et al. in preparation). The bandwidth of each spectral window was 50 MHz ($\simeq$601 km s^{-1} velocity coverage) sampled over 8192 channels ($\simeq$0.07 km s^{-1} velocity resolution). The half-power beam width of the telescope was 30″ at the frequency of the methanol lines. The integration time per source was $\simeq$4 minutes, and all of it was effectively on-source time, because of the use of the antenna-nodding with dual beams. The data reduction was carried out with the GBTidl package. Spectra were corrected for the elevation-dependent gain of the telescope and for atmospheric opacity. The rms pointing accuracy was better than 3″.

4. RESULTS AND DISCUSSION

No emission of methanol was detected with either telescope. Tables 1 and 2 give the (1σ) rms noise level of each spectrum. We consider that our upper limits for detections are $\simeq 3\sigma$ levels.

The non-detection of thermal emission from these transitions is not surprising, since an unreasonably high abundance of methanol would be required to obtain mensurable emission. We have calculated upper limits to the abundance of methanol with respect to hydrogen, following the formulation in Charnley & Latter (1997), and assuming physical parameters appropriate for circumstellar envelopes expelled in the AGB phase (see, e.g., Charnley & Latter 1997; Marvel 2005): expansion velocity of 15 km s^{-1}, temperature of 30 K, mass loss rate of $10^{-5}\ M_\odot$ yr^{-1}, and distance from the star to the peak of molecular emission of 10^{16} cm. The solar distance is unknown for most of these objects, but we have assumed 8 kpc in our calculations, since a significant fraction are in the direction of the Galactic bulge. The more restrictive

TABLE 2

GBT OBSERVATIONS[a]

IRAS name	RA(J2000) (h:m:s)	Dec(J2000) (°:′:″)	rms[b] (Jy)	Date[c] (yyyy-mm-dd)
17021−3109	17 05 23.42	−31 13 18.4	0.04	2010-03-21
17021−3054	17 05 24.23	−30 58 14.4	0.04	2010-03-21
17149−3053	17 18 11.89	−30 56 40.8	0.04	2010-03-03
17175−2819	17 20 42.57	−28 22 36.8	0.03	2010-03-03
17233−2602	17 26 28.78	−26 04 57.8	0.03	2010-03-21
17291−2147	17 32 10.21	−21 49 58.9	0.014	2010-03-21
17301−2538	17 33 14.23	−25 40 23.5	0.03	2010-03-03
17348−2906	17 38 04.32	−29 08 22.7	0.03	2010-03-03
17359−2902	17 39 08.13	−29 04 06.1	0.03	2010-03-03
17360−2142	17 39 05.97	−21 43 51.8	0.021	2010-03-01
17382−2531	17 41 20.18	−25 32 53.3	0.03	2010-03-03
17385−2413	17 41 38.45	−24 14 40.9	0.020	2010-03-01
17393−2727	17 42 32.29	−27 28 28.2	0.03	2010-03-03
17404−2713	17 43 37.27	−27 14 46.4	0.03	2010-03-03
”	”	”	0.03	2010-03-21
17479−3032	17 51 12.59	−30 33 44.5	0.03	2010-03-03
17482−2501	17 51 22.55	−25 01 51.4	0.03	2010-03-03
17487−1922	17 51 44.78	−19 23 41.5	0.03	2010-03-21
17506−2955	17 53 49.42	−29 55 35.0	0.03	2010-03-03
17516−2525	17 54 43.45	−25 26 29.8	0.021	2010-03-01
17540−2753	17 57 14.06	−27 54 16.0	0.022	2010-03-01
17548−2753	17 57 57.94	−27 53 20.8	0.03	2010-03-03
17550−2120	17 58 04.30	−21 21 09.0	0.03	2010-03-03
17550−2800	17 58 10.72	−28 00 25.9	0.03	2010-03-03
17552−2030	17 58 16.37	−20 30 22.1	0.020	2010-03-01
17560−2027	17 59 04.61	−20 27 23.5	0.021	2010-03-01
18011−1847	18 04 02.81	−18 47 09.7	0.03	2010-03-21
18015−1352	18 04 22.28	−13 51 49.1	0.03	2010-03-21
18016−2743	18 04 45.89	−27 43 11.0	0.022	2010-03-01
18039−1903	18 06 53.36	−19 03 09.3	0.025	2010-03-01
18049−2118	18 07 54.93	−21 18 08.9	0.020	2010-03-01
18051−2415	18 08 12.87	−24 14 35.8	0.03	2010-03-03
18071−1727	18 10 05.97	−17 26 35.2	0.03	2010-03-01
18083−2155	18 11 18.85	−21 55 05.1	0.03	2010-03-01
18087−1440	18 11 34.66	−14 39 55.6	0.03	2010-03-03
18105−1935	18 13 32.33	−19 35 03.3	0.03	2010-03-01
18113−2503	18 14 26.37	−25 02 55.6	0.03	2010-03-03
”	”	”	0.03	2010-03-21
18135−1456	18 16 26.16	−14 55 13.4	0.03	2010-03-01
18183−2538	18 21 24.81	−25 36 35.2	0.021	2010-03-01
18199−1442	18 22 50.93	−14 40 49.4	0.024	2010-03-01
18229−1127	18 25 45.14	−11 25 55.7	0.03	2010-03-21
18236−0447	18 26 20.43	−04 45 41.8	0.025	2010-03-01
18355−0712	18 38 15.50	−07 09 52.3	0.023	2010-03-01
18361−1203	18 38 58.94	−12 00 44.3	0.024	2010-03-01
”	”	”	0.03	2010-03-21
18385+1350	18 40 52.25	+13 52 53.9	0.027	2010-03-07
18434−0042	18 46 04.46	−00 38 55.4	0.023	2010-03-01
18454+0001	18 48 01.62	+00 04 48.0	0.03	2010-03-01
18470+0015	18 49 39.16	+00 18 52.0	0.03	2010-03-01
18514+0019	18 53 58.08	+00 23 25.4	0.03	2010-03-01

TABLE 2 (CONTINUED)

IRAS name	RA(J2000) (h:m:s)	Dec(J2000) (°:′:″)	rms[b] (Jy)	Date[c] (yyyy-mm-dd)
18529+0210	18 55 26.37	+02 14 48.8	0.03	2010-03-03
”	”	”	0.03	2010-03-07
18580+0818	19 00 25.31	+08 22 47.1	0.024	2010-03-07
18596+0315	19 02 06.46	+03 20 15.1	0.025	2010-03-07
19006+1022	19 02 59.96	+10 26 35.1	0.024	2010-03-21
19011+1049	19 03 30.84	+10 53 53.3	0.024	2010-03-07
19015+1256	19 03 52.75	+13 01 20.9	0.024	2010-03-07
19071+0857	19 09 29.77	+09 02 23.3	0.017	2010-03-01
”	”	”	0.018	2010-03-03
”	”	”	0.023	2010-03-07
19075+0432	19 10 00.07	+04 37 06.2	0.3	2010-03-03
”	”	”	0.024	2010-03-07
19079−0315	19 10 32.56	−03 10 15.8	0.025	2010-03-21
19094+1627	19 11 44.72	+16 32 54.0	0.024	2010-03-07
19134+2131	19 15 35.46	+21 36 33.2	0.024	2010-03-07
19178+1206	19 20 14.24	+12 12 22.0	0.024	2010-03-07
19181+1806	19 20 25.28	+18 11 41.0	0.024	2010-03-07
19190+1102	19 21 25.37	+11 08 39.8	0.024	2010-03-07
19193+1804	19 21 31.65	+18 10 09.5	0.024	2010-03-07
19315+2235	19 33 41.75	+22 42 08.1	0.024	2010-03-07
19319+2214	19 34 03.51	+22 21 13.6	0.023	2010-03-07
19374+2359	19 39 35.48	+24 06 24.8	0.023	2010-03-07
20035+3242	20 05 29.74	+32 51 35.1	0.022	2010-03-07
20042+3259	20 06 10.73	+33 07 50.7	0.023	2010-03-07
20214+3749	20 23 19.29	+37 58 52.4	0.021	2010-03-07
20244+3509	20 26 25.48	+35 19 14.2	0.023	2010-03-21
20461+3853	20 48 04.65	+39 05 00.7	0.024	2010-03-21
21525+5643	21 54 15.14	+56 57 23.0	0.025	2010-03-21
21554+6204	21 56 58.35	+62 18 43.4	0.025	2010-03-21

[a]All spectra were centered at $V_{\rm LSR} = 0$ km s^{-1} for the $4_2 - 4_1$ E transition.
[b]1σ rms noise level of the spectra, after correction by elevation-dependent gain and atmospheric opacity.
[c]Date of observation.

limit for the abundance is <0.03, obtained with the $4_2 - 4_1$ transition. Such an extremely high limit obviously does not give any useful information. Even taking into account the large uncertainties for the assumed parameters, far more restrictive upper limits to the methanol abundance in evolved stars have been obtained elsewhere with millimeter methanol lines, on the order of $5 \times 10^{-9} - 6 \times 10^{-7}$ (Charnley & Latter 1997; Marvel 2005).

However, more relevant here is the fact that no maser emission has been detected. As mentioned above, we have included lines pertaining to both types of methanol transitions (Class I and II). Class II methanol masers have been found exclusively toward high-mass YSOs (Breen et al. 2013). They tend to be closely associated with HII regions, and are believed to be excited by intense infrared radiation fields. In the particular case of the $2_1 - 3_0$ E transition we observed, its emission seems to be correlated with the flux density of the background radio continuum emission (Krishnan et al. 2013). Although young PNe in our sample also show free-free radio continuum emission, the non-detection of $2_1 - 3_0$ E masers may indicate that the radiation field from the central star is not enough to create population inversion, that the radio continuum emission is too weak to ignite the maser, or that methanol abundance is too low. It is possible that a search for this line emission in more evolved PNe, whose radio continuum flux density is stronger, would have a higher probability of finding detections.

On the other hand, Class I methanol masers are thought to be collisionally pumped. They are found in the neighborhood of both low- and high-mass YSOs, but their locations are offset from those of Class II masers. It is possible that Class I masers arise in post-shock gas in the lobes of bipolar outflows, where the abundance of methanol is enhanced due to grain mantle evaporation (Plambeck & Menten 1990), and the energy released inverts the populations of the molecule. One might expect that Class I masers could also be present in some post-AGB star, since they eject collimated jets in a similar way as low-mass YSOs (e.g., Sahai 2002). However, it is interesting that the conditions for water and OH maser pumping are met in both young and evolved objects, but this is not the case of methanol for the latter. In particular, we note that some post-AGB stars and young PNe show water maser emission, which in the case of "water fountains" trace jets with high velocities ($\gtrsim$50 km s^{-1}) and high degree of collimation. Water masers can originate in J-shocks, involving high-velocities ($>$40 km s^{-1}), in regions with densities $n \simeq 10^6 - 10^8$ cm^{-3}, but they are quenched at $n \gtrsim 10^8$ cm^{-3} (Hollenbach, Elitzur, & McKee 2013). Interestingly, these density conditions are very similar to those for the $J_2 - J_1$ E maser lines of methanol (Leurini 2004) that we observed with the GBT. The fact that water masers are detected, but methanol ones are not, strongly suggests that, although the methanol energy levels could be actually inverted, the column density of the molecule in shocked regions of post-AGB stars and young PNe is not large enough to produce detectable emission. This indicates that the production of methanol molecules in dust grains (Garrod et al. 2006; Breen et al. 2013) and/or the enhancement of its gas-phase abundance in the shocked regions of evolved objects are not as efficient as in YSOs.

JFG, OS, and IdG acknowledge support from MICINN (Spain) AYA2011-30228-C03 grant (including FEDER funds). L.U. acknowledges support from grant PE9-1160 of the Greek General Secretariat for Research and Technology in the framework of the program Support of Postdoctoral Researchers. JRR acknowledges support from MICINN grants CSD2009-00038, AYA2009-07304, and AYA2012-32032. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work is partially based on observations done at MDSCC (Robledo), under the Host Country Radio Astronomy program. Part of the data in this paper was reduced using the GILDAS software package (`http://www.iram.fr/IRAMFR/GILDAS/`).

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