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Letter to the Editor

Submillimeter H_2O masers in water-fountain nebulae*

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ABSTRACT

We report the first detection of submillimeter water maser emission toward water-fountain nebulae, which are post-AGB stars that exhibit high-velocity water masers. Using APEX we found emission in the ortho-H_2O ($10_{29} \to 9_{36}$) transition at 321.226 GHz toward three sources: IRAS 15445−5449, IRAS 18043−2116, and IRAS 18286−0959. Similar to the 22 GHz masers, the submillimeter water masers are expanding with higher velocity than do OH masers, suggesting that these masers also originate in fast bipolar outflows. In IRAS 18043−2116 and IRAS 18286−0959, which figure among the sources with the fastest water masers, the velocity range of the 321 GHz masers coincides with the range of the 22 GHz masers, indicating that they probably coexist. Toward IRAS 15445−5449, the submillimeter masers appear in a different velocity range, indicating that they trace different regions. The intensity of the submillimeter masers is comparable to the 22 GHz masers, implying that the kinetic temperature of the region where the masers originate should be $T_k > 1000$ K. We propose that the passage of two shocks through the same gas can create the conditions for explaining the strong high-velocity 321 GHz masers coexisting with the 22 GHz masers in the same region.

Key words. masers – stars: AGB and post-AGB – submillimeter: stars

1. Introduction

Water-fountain nebulae are thought to represent a group of post-asymptotic giant branch (post-AGB) stars where the formation of the bipolar and multipolar morphologies observed in the planetary nebula phase has recently been triggered. In these sources, the water masers trace high-velocity, collimated outflows. It has been proposed that they appear as a result of an episode of collimated mass loss in the post-AGB phase that modifies the morphology of the circumstellar envelope (CSE; Likkel et al. 1988). To date, the water maser emission that has been observed in these objects arises from the $J_{K_aK_c} = 6_{16} \to 5_{23}$ transition at ~22 GHz. Since the physical conditions for inverting this transition require high densities (~10^8–10^{10} cm^{-3}) and kinetic temperatures T_k ~ 200–2000 K (Yates et al. 1997), it has been proposed that this emission arises from shocked dense material that has been swept up by the collimated wind that pierces the CSE (e.g., Imai 2007). To better constrain the physical conditions of the gas within which the masers originate and to reveal the characteristics of the collimated wind that provides the energy, observations of other transitions of water maser emission toward these types of sources are necessary.

In addition to the H_2O ($6_{16} \to 5_{23}$) line, several water maser lines, most of them at submillimeter wavelengths, have been detected toward star-forming regions and late-type stars (Menten et al. 1990a, b; 2008; Melnick et al. 1993; Patel et al. 2007). Some transitions of the submillimeter water masers have upper levels with energies above the ground state higher than for the 22 GHz masers, for which $E/k = 643$ K. In particular, the upper level of the 321 GHz water maser transition has an energy $E/k = 1861$ K above the ground state; consequently, these masers trace dense gas with relatively high temperatures. In the star-forming region Cepheus A, Patel et al. (2007) find 321 GHz water masers that are aligned with the bipolar outflow seen in this source. This indicates that these submillimeter masers arise in material that has been shocked and heated up by the jet. In late-type stars, the physical conditions for efficiently pumping the 321 GHz water masers ($n_{H_2} = 8 \times 10^8$–4×10^9 cm^{-3}; $T_k > 1000$ K; Yates et al. 1997) are found in the inner CSE, with the strongest 321 GHz emission confined to a distance closer to the star than the region traced by strong 22 GHz masers (Humphreys et al. 2001). The 22 GHz water masers in water-fountain nebulae are associated with high-velocity collimated outflows.

We searched for submillimeter H_2O maser emission toward a group of water-fountain nebulae that exhibit relatively strong 22 GHz water maser emission. In this letter we report the first detection of H_2O ($10_{29} \to 9_{36}$) maser emission at 321.226 GHz toward three of these sources.

2. Observations

The observations were carried out in two epochs using the 12 m Atacama Pathfinder Experiment (APEX) telescope. We made

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single-pointing observations using the heterodyne receiver APEX-2 centered at the rest frequency of the H_2O ($10_{29} \rightarrow 9_{36}$) transition, ν_0 = 321.22568 GHz. The system temperature ranged from 260 K to 430 K, except when we observed the source IRAS 18450−0148 for which $T_{\rm sys}$ ∼ 1100 K. The calibration was performed using the chopper wheel technique. The conversion factor from antenna temperature to flux density at ∼345 GHz is 41 Jy K^{-1}. We reduced the data using the package CLASS of GILDAS, averaging individual spectra of each scan and subsequently subtracting a fitted baseline of first order to the emission-free channels. We smoothed the resulting averaged spectra to a final velocity resolution of ∼0.6 km s^{-1}. On May 4, 2013 we also carried out observations of the para-H_2O ($5_{15} \rightarrow 4_{22}$) transition, ν_0 = 325.1529 GHz, with APEX. However, we did not detect emission in any of the sources above an rms noise of 2 Jy.

3. Results and discussion

We observed seven water-fountain nebulae with relatively strong 22 GHz maser to search for submillimeter H_2O maser emission. The three sources in which we detected 321 GHz water emission are listed in Table 1. Their spectra are shown in Fig. 1. Although the emission showed variability by a factor of up to ∼10 in some spectral features, it was detected toward the three sources in both observation epochs. The sources with no detection are listed in Table 2. The 321 GHz water emission from IRAS 18043−2116 and IRAS 18286−0959 consists of clusters of spectral lines spread over ≳200 km s^{-1}. The narrow width of the lines suggests that the emission is indeed amplified by the maser effect. The emission from IRAS 15445−5449 shows a broader line width. However, thermal emission of the H_2O ($10_{29} \rightarrow 9_{36}$) transition has not been reported before. Additionally, the spectrum also exhibits the narrow spectral features typical of maser emission.

In the following sections we describe the characteristics of the maser emission from each source.

3.1. IRAS 15445−5449

The 321 GHz water emission in this source comprises a broad spectral feature that covers the velocity range from ∼−240 km s^{-1} to ∼−110 km s^{-1} (see Fig. 1a). It did not exhibit significant variability between the two epochs of our observations. In this source, the 22 GHz maser emission reported by Deacon et al. (2007) and Pérez-Sánchez et al. (2011) appears over the velocity range from ∼−150 km s^{-1} to ∼−75 km s^{-1}. In addition, the OH maser emission consists of a broad spectral feature that covers the velocity range from ∼−200 km s^{-1} to ∼−110 km s^{-1} (Deacon et al. 2007). Thus, the 321 GHz H_2O maser emission has a velocity range in better agreement with the range of the OH maser emission do the 22 GHz water masers.

Since the OH maser emission does not show the typical double peak characteristic of AGB stars, the systemic velocity of this source is not well known. Deacon et al. (2007) adopted a systemic velocity equal to the midpoint of the OH profiles, near a velocity of $\upsilon_{\rm LSR} = -150$ km s^{-1} (see Fig. 1a). This would imply that most of the submillimeter masers are blue-shifted with respect to the source. Thus, they might be tracing the blue-shifted part of the bipolar outflow seen in this source (Legadec et al. 2011; Pérez-Sánchez et al. 2013). Another possibility is that, given the double-peak of the profile of the 321 GHz line emission, the systemic velocity is closer to $\upsilon_{\rm LSR} = -185$ km s^{-1}. This would indicate that both the OH and the 22 GHz masers are red-shifted with respect to the star.

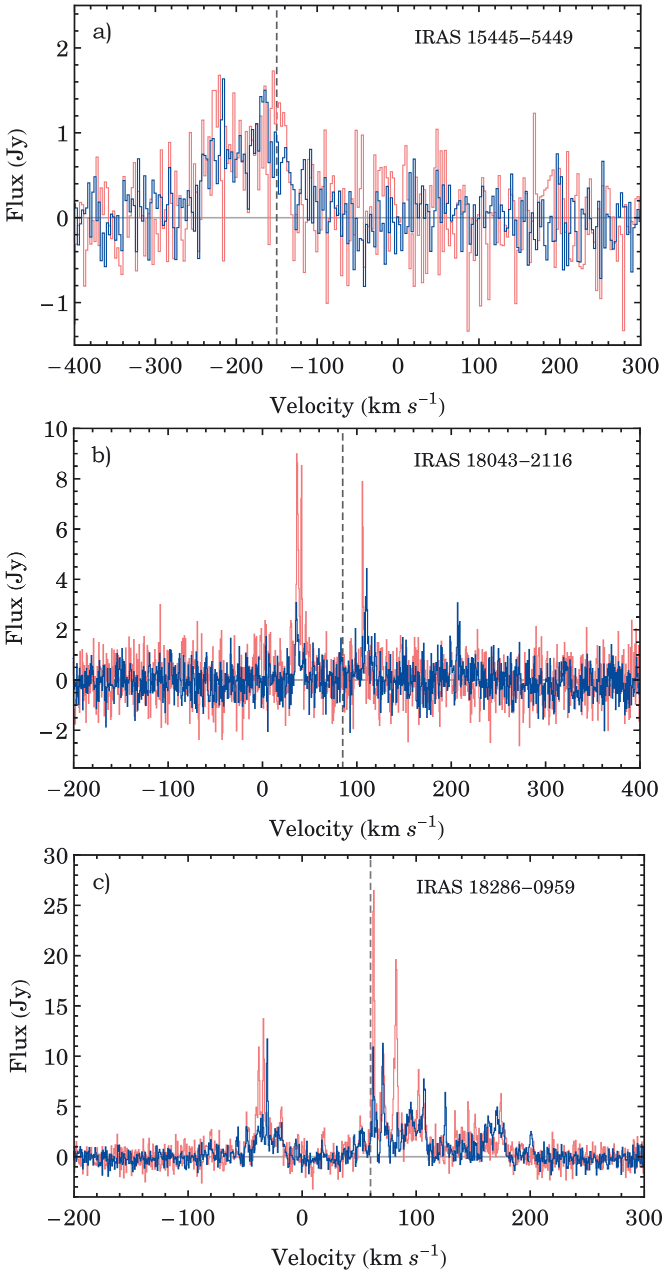

Fig. 1. Spectra of the H_2O ($10_{29} \rightarrow 9_{36}$) maser emission in three water-fountain nebulae. The red line indicates the spectrum obtained in the epoch May 15, 2013, and the blue line indicates the spectrum obtained in the epoch July 6, 2013. The systemic velocity reported in the literature is indicated with a vertical dashed line. The velocity and flux ranges are different for each source.

3.2. IRAS 18043−2116

The velocity range covered by the 321 GHz water emission extends from ∼30 km s^{-1} to ∼210 km s^{-1}, which falls within the velocity range of the 22 GHz masers reported by Walsh et al. (2009). In this source the 321 GHz maser emission exhibits at least three spectral features at $\upsilon_{\rm LSR}$ ∼ 40 km s^{-1}, ∼110 km s^{-1}, and ∼210 km s^{-1}. The last one only appears in the July 6 observation epoch, indicating the high variability of this emission (see Fig. 1b). Comparing our spectrum with

Table 1. Sources with detected 321 GHz water maser emission

Source	RA(J2000)	Dec(J2000)	Line peak (epoch 1)	rms (epoch 1)	Line peak (epoch 2)	rms (epoch 2)
IRAS name	h m s	° ′ ″	Jy	Jy	Jy	Jy
15445−5449	15 48 19.37	−54 58 21.2	1.6[a]	0.4[a]	1.6[a]	0.3[a]
18043−2116	18 07 21.10	−21 16 14.2	8.5	0.9	4.2	0.7
18286−0959	18 31 22.93	−09 57 19.8	25.2	1.0	11.1	0.7

Notes. Line peak and rms noise values for a spectral resolution of 0.6 km s^{-1}. [(a)] Values for a spectral resolution of 2.6 km s^{-1}.

Table 2. Sources with non-detected 321 GHz water maser emission.

Source	RA(J2000)	Dec(J2000)	rms noise
IRAS name	h m s	° ′ ″	Jy
15103−5754	15 14 18.45	−58 05 20.3	0.8
16342−3814	16 37 39.91	−38 20 17.3	0.9
18113−2503	18 14 27.27	−25 03 00.5	0.7
18450−0148	18 47 40.97	−01 44 55.4	2.6[a]

Notes. rms noise for a spectral resolution of 0.6 km s^{-1}. [(a)] Value for a spectral resolution of 2.5 km s^{-1}.

those obtained by Deacon et al. (2007), Walsh et al. (2009), and Pérez-Sánchez et al. (2011) we note that, in general, the intensity of the submillimeter masers is similar to that of the 22 GHz masers. The systemic velocity of this source is around $\upsilon_{\rm LSR}$ = 85 km s^{-1} (Sevenster & Chapman 2001), implying that the submillimeter masers arise in gas expanding with velocities of at least 125 km s^{-1}.

3.3. IRAS 18286−0959

This source exhibits a very rich 22 GHz water maser spectrum with emission spread over a velocity range ≳200 km s^{-1} and distributed in a double-helix pattern (Deguchi et al. 2007; Yung et al. 2011). The 321 GHz water emission also extends over a wide velocity range from ∼−50 km s^{-1} to ∼200 km s^{-1}, similar to the range of the 22 GHz masers. The 321 GHz spectrum shows a complex ensemble of spectral lines that seem to be grouped in at least three broad features (see Fig. 1c). There is weak submillimeter water emission at ∼200 km s^{-1} with no counterpart in the 22 GHz emission. The brightest 321 GHz maser emission corresponds to the strongest lines at 22 GHz, although the spectra changed significantly between the two epochs of observation. The systemic velocity of this source has been adopted as $\upsilon_{\rm LSR}$ = 50 km s^{-1} by Yung et al. (2011) and $\upsilon_{\rm LSR}$ = 60 km s^{-1} by Imai et al. (2013). Thus, the submillimeter masers exhibit expansion velocities of at least ∼140 km s^{-1}.

3.4. The origin of the 321 GHz water masers

Theoretical works indicate that the excitation mechanism of the astronomical water masers must be collisional (de Jong 1973; Deguchi 1977; Cooke & Elitzur 1985; although see Yates et al. 1997). These works also show that in addition to the $J_{K_aK_c} = 6_{16} \rightarrow 5_{23}$ transition several other lines should be amplified by the maser effect. Among the predicted maser lines was the H_2O ($10_{29} \rightarrow 9_{36}$) at ∼321 GHz, which was detected for the first time by Menten et al. (1990a) in a group of sources that also exhibit 22 GHz masers. Neufeld & Melnick (1990) estimated the physical conditions under which these two masers can coexist in the same volume of gas. In general, they showed that the values of density and temperature under which the 321 GHz masers are pumped are more constrained than those for the 22 GHz masers. These results were confirmed and extended in a more comprehensive work by Yates et al. (1997), who found that strong inversion of the 321 GHz transition is optimized in kinetic temperatures, $T_{\rm k}$ > 1000 K, and densities, ($n_{\rm H_2}$ = [4–6] × 10^8 cm^{-3}). At higher densities, the 321 GHz emission can be stronger than the 22 GHz maser.

The 321 GHz maser emission in the detected water-fountain nebulae shows spectral characteristics that indicate that it could have different origins. While in IRAS 15445−5449 the 321 GHz maser emission does not coincide with the 22 GHz masers, in IRAS 18043−2116 and IRAS 18286−0959 the 321 GHz masers cover velocity ranges similar to those of the 22 GHz masers. This suggests that the 321 GHz masers in IRAS 15445−5449 originate in a region different from where the 22 GHz are located, possibly at a distance closer to the star. However, we note that the velocity extent of the submillimeter masers, ∼130 km s^{-1}, is too large to be originating in the fossil CSE. We speculate that the water molecules in this source could be excited in the vicinity of the non-thermal jet detected by Pérez-Sánchez et al. (2013). In the other two sources, given that both masers span similar velocity ranges and that several spectral features appear at the same velocity, it is likely that the 321 GHz and 22 GHz masers originate in the same gas.

The models that explain the water maser emission in evolved stars assume that the emission originates in the expanding CSE created by the massive wind at the end of the AGB phase (Cooke & Elitzur 1985; Neufeld & Melnick 1990). However, the origin of the H_2O maser emission in water-fountain nebulae is associated to fast collimated outflows that interact with the slowly expanding CSE. Therefore, it is more appropriate to interpret the water maser emission in a similar way to that of the star-forming regions. Elitzur et al. (1989) explained the water maser emission in star-forming regions as the result of the passage of a dissociative shock ($\upsilon_{\rm s}$ ≥ 50 km s^{-1}) through the interstellar medium (see also Hollenbach et al. 2013 and references therein). Behind the shock, a layer of high-density gas with a temperature of ∼400 K forms, where the conditions for 22 GHz maser emission are optimal in that model. Neufeld & Melnick (1990) showed that under the physical conditions of the post-shock region described by Elitzur et al. (1989) 321 GHz emission can be produced with a luminosity ratio $L_{\rm p}$(22 GHz)/$L_{\rm p}$(321 GHz) ≳ 5. They also suggested that values of the ratio below five could be attained with slower non-dissociative shocks that would heat the molecules to temperatures up to $T_{\rm k}$ = 1000 K (Kaufman & Neufeld 1996).

For the case of the water-fountain nebulae presented in this work, the expansion velocity of the 22 GHz and 321 GHz H_2O masers is ≳100 km s^{-1}, thus the shock must be dissociative. According to the model proposed by Elitzur et al. (1989), when the shocked material cools down, H_2 and H_2O molecules form in gas that is maintained at T_k = 400 K by the energy liberated when the H_2 molecules are released from the dust grains. As mentioned above, for this temperature the luminosity ratio L_p(22 GHz)/L_p(321 GHz) is expected to be $\gtrsim$5. Comparing the intensities of the 22 GHz masers (see Deacon et al. 2007; Walsh et al. 2009; Pérez-Sánchez et al. 2011; Yung et al. 2011) and the 321 GHz masers of IRAS 18043−2116 and IRAS 18286−0959, it can be seen that the luminosity ratio is close to unity. This implies a kinetic temperature T_k > 1000 K for the gas (Neufeld & Melnick 1990; Yates et al. 1997). But this temperature should indicate the presence of a relatively slow non-dissociative shock, in contradiction to the relatively high velocity of the masers. Therefore, to explain the coexistence of strong 321 GHz masers with 22 GHz masers, there should be a mechanism that accelerates the gas to the observed high velocities ($v_{\rm exp} \gtrsim 100$ km s^{-1}) and that favors the creation of water molecules while maintaining the gas at high temperatures (T_k > 1000 K).

The presence of high-velocity strong 321 GHz masers coexisting with 22 GHz masers in the same region could be explained if we invoke the passage of two shocks with different speeds through the same material. The first shock would be due to the collision between a fast collimated wind and the slowly expanding CSE, which produces a J-type dissociative shock (see above). If the post-shock density is much higher than for the pre-shock gas, then the velocity of the shocked gas would be very low in the frame of reference of the shock. Thus, in the frame of reference of the star, the shocked gas, where the 22 GHz water masers originate, would move almost at the same speed as the shock ($v_{\rm exp} \sim 100$ km s^{-1}). Subsequently, we consider a collision between the fast collimated wind and the shocked material. Since the shocked material is already moving at high speeds, the collision occurs at a slower relative velocity. This produces a slower C-type non-dissociative shock, which raises the temperature of the shocked gas to a higher value, where the 321 GHz transition is inverted more efficiently (Kaufman & Neufeld 1996). The 321 GHz water masers would move at the same velocity as the 22 GHz masers, which is the velocity of the shocked gas. If the temperature of the shocked gas reaches values of T_k > 1500 K, then the gain coefficient of the 22 GHz transition becomes smaller and the 321 GHz masers become dominant (Yates et al. 1997). If the C-type shock does not occur or if there is an efficient cooling mechanism in the shocked material then the 321 GHz maser emission will be negligible. Interestingly, the velocity range and strength of the 22 GHz maser emission of the sources with no detected submillimeter water masers are not fundamentally different from those in which submillimeter masers were detected. This may be due to the lack of the second slower shock or to the fact that the gas has already cooled down in the sources with no submillimeter maser detected. In this regard, the sources with strong, high-velocity 321 GHz water masers represent a subclass of post-AGB stars that could be referred to as *hot-water fountain nebulae*. It is clear that our observations pose a challenge for the current water maser excitation models.

It should be pointed out that our assumption of the coexistence of 321 GHz and 22 GHz in at least two of the sources is based on the correspondence of the velocity ranges of the maser emission at both frequencies. To confirm this assumption, simultaneous interferometric images of the maser emission at both frequencies are required. Patel et al. (2007) obtained maps of the 321 GHz and 22 GHz masers in the star-forming region Cepheus A. They find that, while the 22 GHz masers mainly trace an equatorial structure, the 321 GHz maser are aligned in the perpendicular direction, parallel to the bipolar jet. In the case of the water-fountain nebulae presented in this work, the high expansion velocity of the 321 GHz masers strongly suggests that they are tracing the same structures as the 22 GHz masers. Future observations with ALMA will reveal the spatial distribution of the 321 GHz masers in water-fountain nebula that will allow us to compare them with 22 GHz masers, which will help us elucidate their origin.

4. Conclusions

We detected submillimeter H_2O maser emission in three water-fountain nebulae for the first time. In a similar way to the 22 GHz water masers, the submillimeter water masers extend over a velocity range that is broader than for OH maser emission, indicating that they are also tracing fast bipolar outflows. In general, the kinetic temperature of the gas where the maser emission originates is required to be T_k > 1000 K. Such kinetic temperature can be due to a slow non-dissociative shock. However, the high velocities of the H_2O masers indicate the passage of a faster dissociative shock. To explain our observation we propose that the passage of a fast shock accelerates the material and that the water molecules are created behind it. Subsequently, a second slower shock heats up the shocked material to the temperates needed to invert the 321 GHz efficiently. Both higher angular observations with ALMA and more theoretical models are required to fully understand the presence of high-velocity 321 GHz masers in the subclass of hot-water fountain nebulae.

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