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Submillimeter H_2O maser emission from water fountain nebulae

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Abstract. We present the results of the first detection of submillimeter water maser emission toward water-fountain nebulae. Using APEX we found emission at 321.226 GHz toward two sources: IRAS 18043−2116, and IRAS 18286−0959. The submillimeter H_2O masers exhibit expansion velocities larger than those of the OH masers, suggesting that these masers, similarly to the 22 GHz masers, originate in fast bipolar outflows. The 321 GHz masers in IRAS 18043−2116 and IRAS 18286−0959, which figure among the sources with the fastest H_2O masers, span a velocity range similar to that of the 22 GHz masers, indicating that they probably coexist. 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 is $T_k > 1000$ K. We propose a simple model invoking the passage of two shocks through the same gas that creates the conditions for explaining the strong high-velocity 321 GHz masers coexisting with the 22 GHz masers in the same region.

Keywords. submillimeter, ISM: jets and outflows, stars: AGB and post-AGB, masers

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1. Introduction

Water maser emission from the transition $6_{16} \rightarrow 5_{23}$ at 22 GHz has proven to be a valuable tool to study the kinematics of the gas in the circumstellar envelope (CSE) of evolved stars. In the envelopes of AGB stars, the 22 GHz H_2O masers exhibit typical expansion velocities of $\sim$10 km s^{-1} and trace clumpy spherical structures located at a distance of $\sim$100 AU from the star, where the stellar wind is accelerated (e.g. Richards *et al.* 2012). In the water-fountain nebulae (wf-nebulae), a subgroup of post-asymptotic giant branch (post-AGB) objects, the water masers trace collimated structures at larger distances from the star ($\gtrsim$500 AU) and they expand with larger velocities ($\gtrsim$100 km s^{-1}; Likkel & Morris 1988; Imai *et al.* 2002). From the expansion velocity and proper motion of the maser spots in wf-nebulae, it has been calculated a kinematical time scale for the jet-like outflows in these sources of $\sim$100 years, assuming that the expansion velocity has been constant. In some cases, the masers seem to be tracing a precessing jet. This phenomenon has been attributed to a binary companion (e.g. Imai *et al.* 2002). The magnetic field that is thought to be responsible for the collimation of the jet-like outflows has been measured via the Zeeman effect on the H_2O masers by Vlemmings *et al.* (2006). Despite of the valuable information that 22 GHz H_2O masers have revealed, due to the particular excitation conditions, they do not probe the entire physical conditions of the CSE.

Apart from the H_2O ($6_{16} \rightarrow 5_{23}$) line, other 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; Melnick *et al.* 1993; Patel *et al.* 2007). Some transitions of

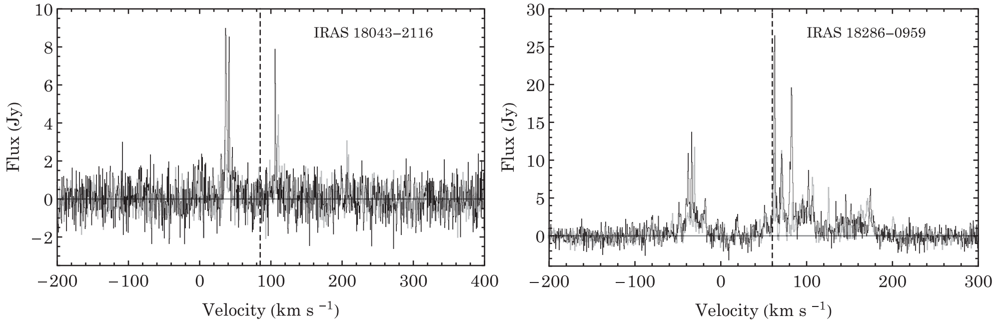

Figure 1. Spectra of the H_2O ($10_{29} \rightarrow 9_{36}$) maser emission in two water-fountain nebulae. The gray line indicates the spectrum obtained in the epoch May 15, 2013, and the black line indicates the spectrum obtained in the epoch July 6, 2013. The systemic velocity reported in the literature is indicated with a vertical dashed line.

the 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 can be used as tools to trace dense gas with relatively high temperatures.

2. Pilot search for submillimeter water masers

In May (epoch 1) and July (epoch 2) 2013 we carried out observations with APEX toward seven wf-nebulae that exhibit relatively strong 22 GHz maser to search for submillimeter H_2O maser emission. 321 GHz water maser emission was detected for the first time in two wf-nebulae. The details of the observations and the results are reported by Tafoya *et al.* (2014). The peak fluxes and rms noise levels are listed in Table 1 and the spectra of the masers are shown in Fig. 1. Although the emission showed variability by a factor of up to ∼10 in some spectral features, the masers were clearly detected toward the two sources in both observation epochs. The sources with no detection are listed in Table 2 of Tafoya *et al.* (2014). The 321 GHz water emission from IRAS 18043−2116 and IRAS 18286−0959 consists of clusters of spectral lines spread over a velocity range of $\gtrsim$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 exhibits a broader line width (see Fig. 1a of Tafoya *et al.* 2014). Tafoya *et al.* (2014) proposed that the emission from the latter source is submillimeter water masers that originate in a region different from where the 22 GHz are located, possibly at a distance closer to the star.[†]

3. Discussion and conclusions

The most striking result from our observations is that both masers, 321 GHz and 22 GHz, span similar velocity ranges and that several spectral features appear at the same velocity. Thus, it is likely that these 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

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[†] From recent ALMA observations it has been confirmed that the emission in from IRAS 18043−2116 and IRAS 18286−0959 is maser, but the emission from IRAS 15445−5449 is thermal SO_2 ($18_{0,18} \rightarrow 17_{1,17}, v = 0$), ν_0=321.3301645 GHz, (Pérez-Sánchez in prep., private communication).

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
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}.

(Cooke & Elitzur 1985; Neufeld & Melnick 1990). However, the origin of the H_2O maser emission in wf-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 outflows in star-forming regions. According to Elitzur *et al.* (1989), the water maser emission in star forming regions arise after the passage of a dissociative shock ($v_s \gtrsim 50$ km s^{-1}) through the interstellar medium. 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. 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_p(22 GHz)/L_p(321 GHz)$\gtrsim$5. They also suggested that values of the ratio <5 could be attained with slower non-dissociative shocks that would heat the molecules to temperatures up to T_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}, implying a dissociative shock. 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. 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; Yung *et al.* 2011; Pérez-Sánchez *et al.* 2017) and the 321 GHz masers of IRAS 18043−2116 and IRAS 18286−0959, we find a luminosity ratio ≈1. This implies a kinetic temperature T_k>1000 K for the gas (Neufeld & Melnick 1990; Yates *et al.* 1997). But this temperature indicates 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_{exp}~100 km s^{-1}), favoring the creation of water molecules, while maintaining the gas at high temperatures (T_k>1000 K).

We propose scenario that includes the passage of two shocks with different speeds through the same material, as it is shown schematically in Fig. 2. The first shock is due to the collision between a fast collimated wind and the slowly expanding CSE, which produces a J-type dissociative shock. 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, moves almost at the same speed as the shock (v_{exp}~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 v_{exp}~100 km s^{-1}, 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

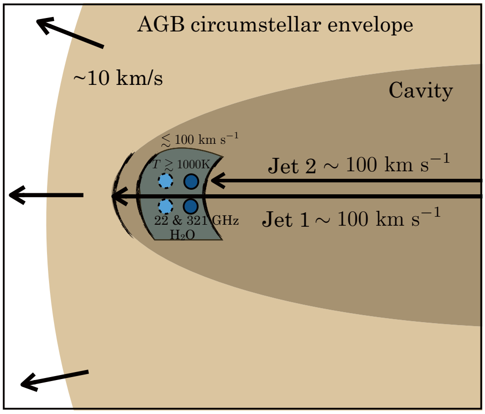

Figure 2. Schematic representation of the two jets scenario proposed to explain the coexistence of the 22 GHz and 321 GHz water masers. The circles with dashed lines represent the 22 GHz masers and the circles with solid lines represent the 321 GHz masers.

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 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, which would explain the non-detections toward the other wf-nebulae of our sample. 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. Higher angular resolution observations with ALMA and more theoretical models are required to fully understand the presence of high-velocity 321 GHz masers in these sources.

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