Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Evolution of the outflow traced by water masers in the evolved star IRAS 18043−2116

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Abstract. We present the spectral and spatial evolution of H_2O masers associated with IRAS 18043−2116, a well-known water fountain hosting a high-velocity collimated jet, which has been found in the observations with the 45 m telescope of Nobeyama Radio Observatory and the Australia Telescope Compact Array. We found new highest velocity components of the H_2O masers, with which the resulting velocity spread of $\simeq 540$ km s^{-1} breaks the speed record of fast jets/outflows in this type of sources.

Keywords. masers — stars: AGB and post-AGB — stars: individuals (IRAS 18043−2116)

1. Introduction

Water fountains (WFs) are evolved stars, mostly in the post-asymptotic giant branch (post-AGB) phase that show H_2O maser emission tracing high-velocity collimated jets when they are observed at high-angular resolution (Imai 2007; Desmurs 2012). The velocity spread in their H_2O maser spectra is typically > 50 km s^{-1}, and can be as large as $\simeq$ 500 km s^{-1} (Gómez *et al.* 2011). Their H_2O maser emission thus traces significantly faster motions than the typical expansion velocities of circumstellar envelopes (CSEs) during the AGB phase (10–30 km s^{-1}; Sevenster *et al.* 1997). The short dynamical ages of the maser jets (5−100 yr; Imai 2007; Tafoya *et al.* 2020) may indicate that WFs represent one of the first manifestations of collimated mass-loss in evolved stars.

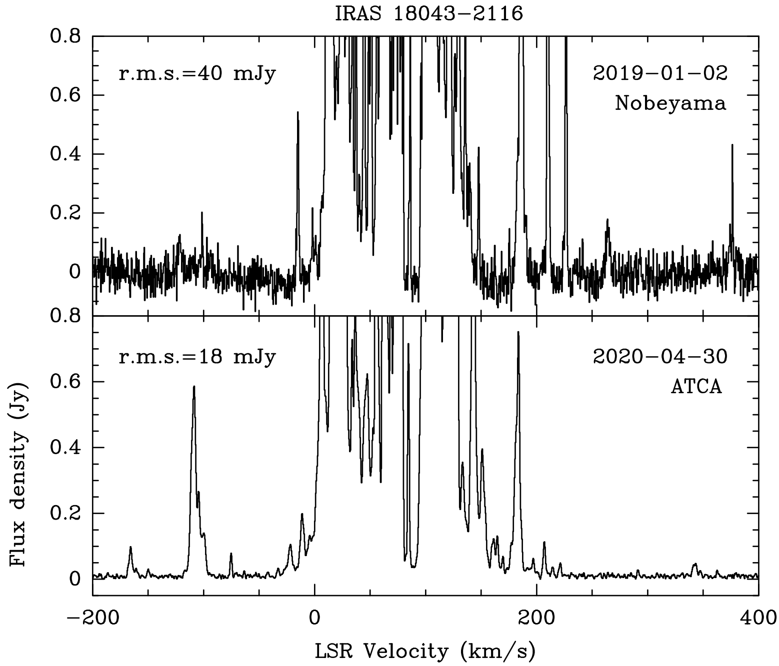

Figure 1. Selected spectra of H_2O masers in I18043 taken with ATCA and NRO telescopes. The root-mean-square (RMS) noise levels are indicated in each spectrum. Note the new highest velocity components at $V_{\rm LSR} \simeq 376$ km s^{-1} (top) and $V_{\rm LSR} \simeq -165$ km s^{-1} (bottom).

Previously, the H_2O maser spectra of IRAS 18043−2116 (hereafter I18043) presented a velocity spread of nearly 400 km s^{-1} (Walsh *et al.* 2009; Pérez-Sánchez *et al.* 2017). Here we present new detections of the highest velocity components of the masers in this WF yielded with the 45 m telescope of Nobeyama Radio Observatory (NRO) and the Australia Telescope Compact Array (ATCA), breaking the record of the top speed of the jet in I18043.

2. Observations

We observed I18043 within the monitoring program called FLASHING (Finest Legacy Acquisitions of SiO- and H_2O-maser Ignitions by the Nobeyama Generation). FLASHING is described in detail within this volume by Imai *et al.* (2023). Here we analyzed FLASHING observations of H_2O masers conducted during 2019 January – 2020 April (eight epochs), as well as a follow-up with the ATCA from 2020 April to 2021 March (four epochs). Observations with NRO had a total velocity coverage of ∼1600 km s^{-1} with a velocity resolution of 0.41 km s^{-1} while for ATCA observations the total velocity coverage was ∼3453 km s^{-1} with a similar velocity resolution of 0.42 km s^{-1}. Single-dish and interferometric observations of H_2O masers in WF sources are able to trace the evolution of the collimated jet or even measure directly the growth of the WF outflow. We complemented these studies with ALMA observations taken on 2019 January to estimate the systemic velocity of I18043 and compare the spatio-kinematical distribution of the masers with that of the molecular material.

3. Results

Figure 1 shows two spectra of H_2O masers of I18043 taken with the NRO 45 m telescope and ATCA on 2019 January 2 and 2020 April 30, respectively. Here the new high

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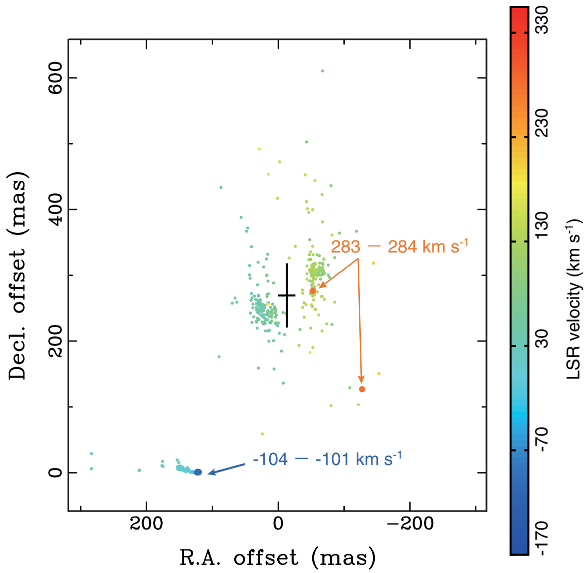

Figure 2. Map of H_2O masers in I18043 taken with ATCA on 2021 March 30. The maser distribution has a larger positional uncertainty in declination offset (up to 200 mas). The new blue-shifted components ($V_{LSR} \sim -102$ km s^{-1}) and the red-shifted components ($V_{LSR} \sim 284$ km s^{-1}) are highlighted in bigger filled circles. The position and the size of a black cross indicate the position and statistical error (3σ) of the continuum source. The synthesized beam is 1.42 arcsec×0.41 arcsec at a position angle of $-1.27°$ (Uscanga *et al.* 2023).

velocity components are clearly seen, red-shifted with respect to the systemic velocity of $V_{LSR} \simeq 87.0$ km s^{-1} km s^{-1} (Deacon, Chapman, & Green 2004) at $V_{LSR} \simeq 376$ km s^{-1} and blue-shifted at $V_{LSR} \simeq -165$ km s^{-1}. The new velocity spread ($\simeq 540$ km s^{-1}) is the largest ever detected in the spectra of H_2O masers of WFs, surpassing the case of IRAS 18113−2503 (velocity spread $\simeq$500 km s^{-1}; Gómez *et al.* 2011).

The spatial distribution of the H_2O masers observed with ATCA on 2021 March 30 is presented in Figure 2. Two main clusters of maser components can be distinguished. A continuum source toward the center of the maser distribution was also detected at 22 GHz with a flux density of $S_\nu = 0.97 \pm 0.09$ mJy. This continuum source exhibits an increase in the flux density, i.e., $S_\nu = 0.75 \pm 0.05$ mJy on 2020 April 30. Note that the new high velocity components ($V_{LSR} \sim -102$ km s^{-1}, $V_{LSR} \sim 284$ km s^{-1}) are farther away from the continuum source in right ascension (see Figure 2). The same behaviour was seen in other new high velocity components ($V_{LSR} \sim -165$ km s^{-1}, $V_{LSR} \sim 344$ km s^{-1}, Uscanga *et al.* 2023).

Figure 3 (left) shows the spectrum of the CO(J=2→1) emission observed with ALMA. The line consists of a strong central component and high-velocity wings. From the velocity of line peak of the central component, we derived a systemic velocity of $V_{LSR,sys} = 87 \pm 1$ km s^{-1} for I18043. This value is compatible with the systemic velocity obtained by Deacon, Chapman, & Green (2004) using OH maser observations. The locus of the CO(J=2→1) emission peak in each bin with a velocity width of 6 km s^{-1} is shown in Figure 3 (right). The observed dispersion of the locus in the R.A. offset indicates a wide-angle of the outflow. We note that there exists a clear velocity gradient in the R. A. offset of the CO emission from −20 to 20 km s^{-1} with respect to the systemic velocity. The wanders of the peak positions in the blue- and red-shifted CO emission components, for $V_{offset} = 10 - 70$ km s^{-1} are roughly consistent with the ones of H_2O masers. This

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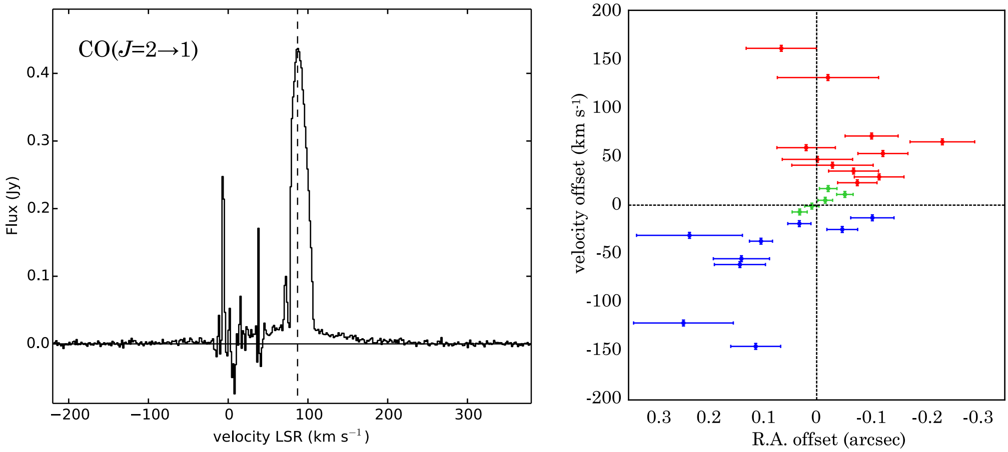

Figure 3. *Left*: ALMA spectrum of the CO(J=2→1) emission in I18043. The vertical dashed line indicates the systemic velocity of the source, $V_{\rm LSR,sys} = 87$ km s^{-1}. *Right*: Right Ascension offsets from the continuum peak position as a function of the velocity offset from the systemic velocity. The blue, green and red marks represent emission in the velocity ranges: $-170 < V_{\rm offset} < -20$ km s^{-1}, $-10 < V_{\rm offset} <$ 10 km s^{-1} and $10 < V_{\rm offset} <$ 170 km s^{-1}, respectively (Uscanga *et al.* 2023).

suggests that the H_2O masers are associated with the CO outflow itself, or possibly the shock regions in the outflow.

4. Discussion

Considering previous observations toward the WF I18043 (Walsh *et al.* 2009), we estimate that the spatial separation of the two main clusters of H_2O masers has doubled (45 mas vs 88 mas) in a period of about ≃12.5 yr. Interestingly, the new highest velocity components possibly located at the outer outflow lobes are farther away from the center, indicating a rapid growth of the outflow triggered by an increase in the maximum outflow velocity.

The spatio-kinematical characteristics of the H_2O masers in this WF are different from those found recently in IRAS 18286−0959, where new high velocity components (>200 km s^{-1}) have also been discovered within FLASHING program (Imai *et al.* 2020). These components are located closer to the central stellar system than other high velocity components (50200 km s^{-1}). Overall the components present a point-symmetric distribution that could be related to a precessing jet. Among the known WFs, there is a variety of high-velocity collimated outflows traced by the H_2O masers. Monitoring observations combining single-dish and interferometric studies, including proper-motion measurements are crucial to discover the enigmas of these outflows in this particular evolutionary stage of the low-mass evolved stars.

Regarding the CO emission, the CO velocity wanders indicate a large opening angle of the outflow, within which the locations of different velocity components are scattered due to an inhomogeneity of the outflow velocity. We estimated a full opening angle of the outflow of ∼60° (Uscanga *et al.* 2023). Using VLBA data, Orosz (2017) estimated a dynamical age of the outflow associted with I18043 to be $t_{\rm jet} \lesssim 30$ yr.

CO emission has been also mapped in other WFs, such as W 43A and IRAS 15103−5754. In the first one, the CO emission traces a highly collimated jet (Tafoya *et al.* 2020); while in the second one, the CO emission is confined within a biconical structure suggesting a wide-angle outflow quite similar to the case of I18043, but with a different

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spatio-kinematics (Gómez *et al.* 2018). It seems that there is a wide variety of outflows exhibiting CO emission in WFs that requires further investigation.

Related to the continuum emission, from previous data of Pérez-Sánchez *et al.* (2017), we deduce that the continuum emission is consistent with a fully-ionized collimated outflow. To determine whether it is a shock- or radiative-ionized region, further observations are needed.

Acknowledgements

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