Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
Proceedings IAU Symposium No. 380, 2024
T. Hirota, H. Imai, K. Menten, & Y. Pihlström, eds.
doi:10.1017/S1743921323001916

Water Fountain Sources Monitored in FLASHING

Hiroshi Imai[1,2], Kei Amada[3], José F. Gómez[4], Lucero Uscanga[5], Daniel Tafoya[6], Keisuke Nakashima[7], Ka-Yiu Shum[7], Yuhki Hamae[7], Ross A. Burns[8,9], Yosuke Shibata[7], Rina Kasai[7], Miki Takashima[7] and Gabor Orosz[10]

[1]Amanogawa Galaxy Astronomy Research Center, Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima 890-0065, Japan. email: hiroimai@km.kagoshima-u.ac.jp

[2]Center for General Education, Institute for Comprehensive Education, Kagoshima University, 1-21-30 Korimoto, Kagoshima 890-0065, Japan; e-mail: hiroimai@km.kagoshima-u.ac.jp

[3]Graduate School of Science and Engineering, Kagoshima University, Kagoshima 890-0065, Japan

[4]Instituto de Astrofísica de Andalucía, CSIC, Granada E-18008, Spain

[5]Departamento de Astronomía, Universidad de Guanajuato, Guanajuato 36000, Mexico

[6]Department of Space, Earth and Environment, Chalmers University of Technology, Onsala 439 92, Sweden

[7]Faculty of Science, Kagoshima University, Kagoshima 890-0065, Japan

[8]National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

[9]RIKEN, Wako, Saitama 351-0198, Japan

[10]Joint Institute for VLBI ERIC, Dwingeloo 7900, Netherlands

Abstract. We have investigated the spectral evolutions of H_2O and SiO masers associated with 12 "water fountain" sources in our FLASHING (Finest Legacy Acquisitions of SiO-/H_2O-maser Ignitions by Nobeyama Generation) project. Our monitoring observations have been conducted using the Nobeyama 45 m telescope every 2 weeks–2 months since 2018 December except during summer seasons. We have found new extremely high velocity H_2O maser components, breaking the records of jet speeds in this type of sources. Systematic line-of-sight velocity drifts of the H_2O maser spectral peaks have also been found, indicating acceleration of the entrained material hosting the masers around the jet. Moreover, by comparing with previous spectral data, we can find decadal growths/decays of H_2O maser emission. Possible periodic variations of the maser spectra are further being inspected in order to explore the periodicity of the central stellar system (a pulsating star or a binary). Thus we expect to see the real-time evolution/devolutions of the water fountains over decades.

Keywords. masers, stars: AGB and post-AGB, stars: mass loss, stars: winds, outflows

1. Introduction

The FLASHING project is dedicated to intensive single-dish monitoring observations of 22 GHz H_2O and 43 GHz SiO masers associated with "water fountain" sources (WFs), which are classified as sources with H_2O maser emission tracing high-velocity, collimated outflows or jets driven by stars in the transition of the AGB to post-AGB phase (Desmurs 2012; Gómez *et al.* 2017). The origin of the collimated outflows from dying stars is a clue

Table 1. Observation specification and setup.

Frequency range (GHz)	Receiver Name	Spectral window width (km s^{-1})	Velocity resolution (km s^{-1})	Beam size (FWHM) (arcsec)	Aperture efficiently (%)	Typical system noise temperature (K)
20 – 24	H22	±820†	0.41	73–74	61‡	100 to 70 §
42.5 – 44.5	H40	±420	0.41 – 0.43	39	55‡	150
40 – 46	Z45	±420	0.41 – 0.43	38	49¶	100

† With three spectrum windows. ‡ Aperture efficiency in the 2018 season. § Improved from 100 K to 70 K since the 2022–2023 season.
¶ Aperture efficiency in the 2022–2023 season in the H22+Z45 mode.

to explore the mechanism of their extreme stellar mass loss at a rate of up to 10^{-3} $M_{\odot}$yr^{-1} for a period shorter than <200 yr (Khouri *et al.* 2021). The common envelope evolution is one of the most plausible scenarios of such mass loss (Khouri *et al.* 2021). Because of such possible short-lived events and periodic behaviors, it is expected to see some evolution and/or systematic variation in the WF masers over decades.

We have conducted single-dish monitoring observations of these maser sources in FLASHING with the new capability of simultaneous 22 GHz- and 43 GHz-band observations using the Nobeyama 45 m telescope (Okada *et al.* 2020). Some of them and the masers visible only in the southern hemisphere have also been observed with the Australia Telescope Compact Array (ATCA) (Uscanga *et al.* 2023). If new maser features are detected, follow-up interferometric observations are crucial for their localization (e.g., Imai *et al.* 2020; Uscanga *et al.* 2023).

2. FLASHING observations

Table 1 gives the typical specifications of the observed frequency bands in FLASHING. Spectra of 22 GHz H_2O and 43 GHz SiO (v =1, 2, 3 $J = 1 \rightarrow 0$) maser lines, as well as some thermal lines in the 22 GHz- and 43 GHz-bands, were simultaneously obtained in 16 spectral windows in total using the SAM45 digital spectrometer.

The FLASHING observations have been conducted since 2018 December, except during summer seasons. At first, a combination of the H22 (IEEE right- and left-hand circular polarization, or RHCP and LHCP) and the H40 (LHCP only) receivers was used. In the season of 2018 December–2019 May, the observations were conducted in the "Back-up Program", in which the opportunities of the observations were available in only when weather conditions were invalid for observations at higher frequency bands, due to too strong winds or too high humidity. However, some of the WFs could be monitored approximately every two weeks. In the seasons in 2019 December–2022 March, the observation sessions were allocated in a regular cadence (3–4 weeks). Since 2022 September, a combination of the H22 and the Z45 (two orthogonal linear polarization) receivers has been adopted. The integration time has been set so as to obtain typically a root-mean-square (rms) noise level of 0.1 Jy in the H_2O maser spectra in the velocity resolution of $\sim$1 km s^{-1}. As a result, the rms noise levels were yielded to be $\sim$0.2 Jy in the SiO maser spectra with the H40 receiver and $\sim$0.1 Jy with the Z45 receiver.

3. Early results of FLASHING

Through the FLASHING monitoring, we have tracked the evolution of H_2O maser spectra. Such evolution has been reported in IRAS 18286−0959 (Imai *et al.* 2020) and IRAS 18043−2116 (Imai *et al.* 2020; Uscanga *et al.* 2023), in which new spectral peaks of H_2O masers have broken the records of the top speed of the WF jets (up to $\sim$280 km s^{-1}). They may indicate the growth of the jet as clearly demonstrated in IRAS 18286−0959, in which the length of the distribution of H_2O maser features has doubled in a decade

https://doi.org/10.1017/S1743921323001916 Published online by Cambridge University Press

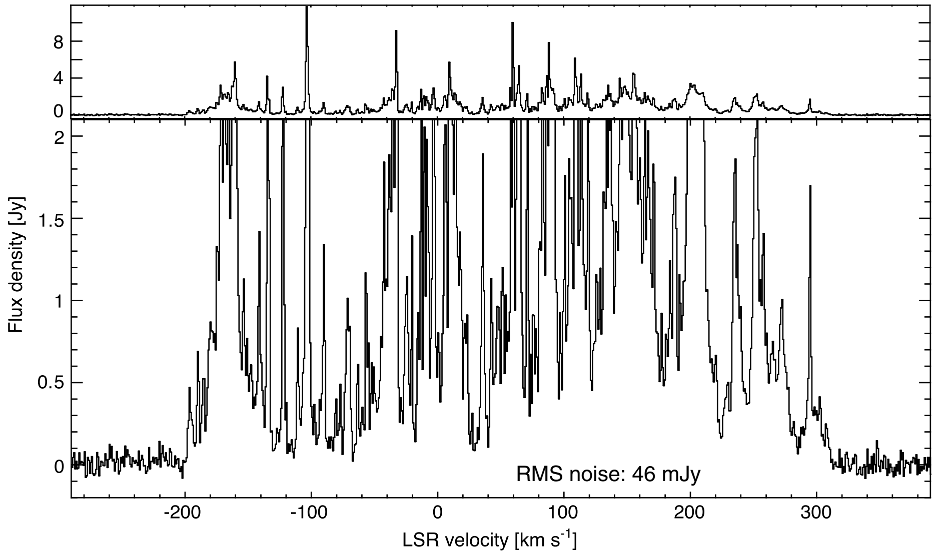

Figure 1. Spectrum of H_2O masers in IRAS 18286−0959 taken on 2023 March 30. The velocity components at the local-standard-of-rest (LSR) velocities higher than 200 km s^{-1} and lower than −100 km s^{-1} have appeared in only the recent FLASHING observations.

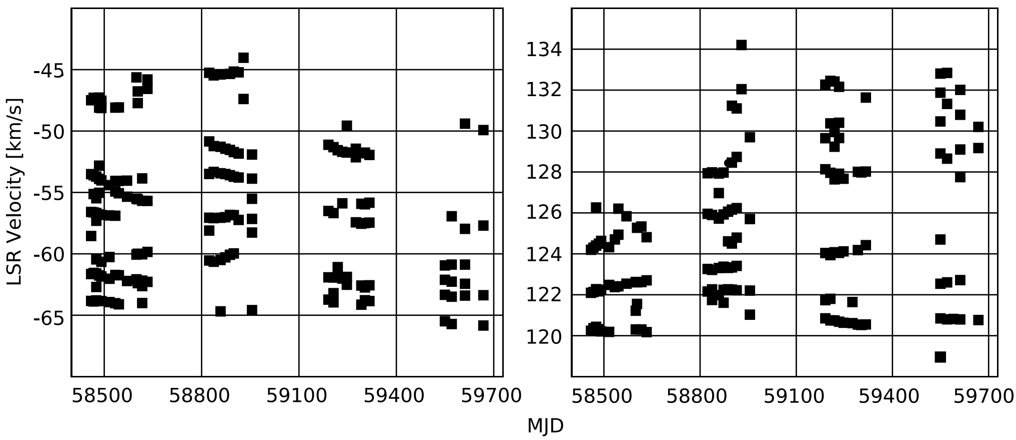

Figure 2. Spectral peak LSR velocities of the H_2O masers in the two major, high-velocity components in W 43A during 2018 December–2022 April. The drifts of the spectral peak velocities with respect to the systemic LSR velocity (∼35 km s^{-1}) indicate further accelerations of the maser clumps.

(Imai *et al.* 2020) and the total velocity width of the spectrum also has increased (Figure 1). On the other hand, due to too short visible duration of the spectral peaks, it is challenging to see the possible rapid changes in their velocities expected from the jet deceleration (Orosz *et al.* 2019).

If groups of the spectral peaks are changing their velocities in some systematic trends, they may indicate a specific dynamics of the outflow. Such an example has been found in W 43A (Figure 2), suggesting that the entrained material hosting the masers may be accelerated by the faster jet as suggested (Tafoya *et al.* 2020).

Note that we are also monitoring the devolution of the WFs, namely fading of H_2O and SiO masers: SiO masers in W 43A and H_2O masers in IRAS 17291−2147, OH 12.8−0.9, IRAS 18596+0315, IRAS 19134+2131, and K3−35 (H_2O masers in a planetary nebula).

https://doi.org/10.1017/S1743921323001916 Published online by Cambridge University Press

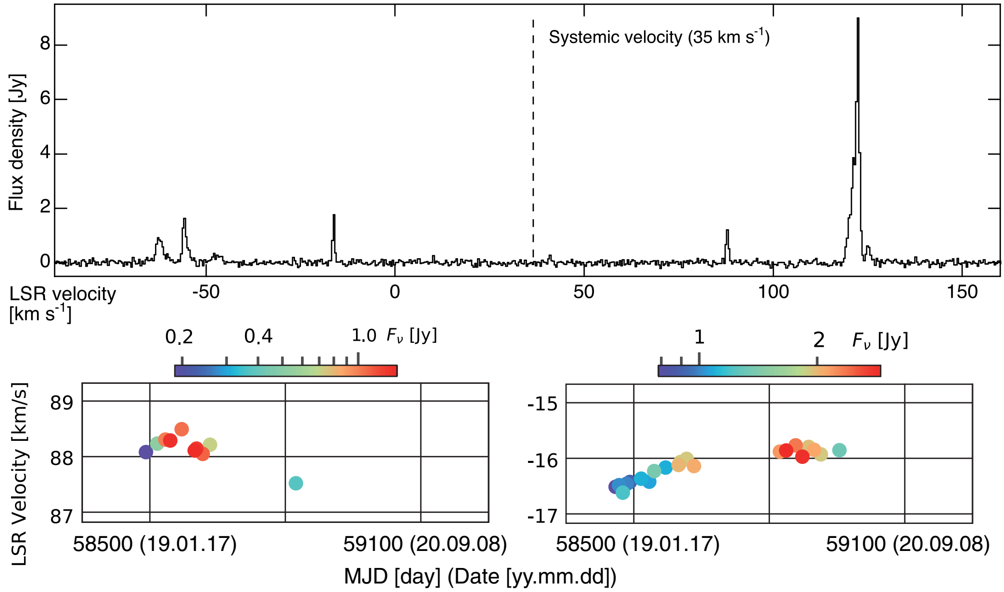

Figure 3. Top: Spectrum of H_2O masers in W 43A on 2019 April 30. One can see two or three pairs of double spectral peaks whose center velocities are well consistent with the systemic velocity of W 43A ($\sim$35 km s^{-1}, Tafoya *et al.* 2020). Bottom: Spectral peak LSR velocities of the H_2O masers in the two low-velocity components in W 43A during 2018 December–2020 May. The two components are located symmetrically with respect to the systemic LSR velocity ($\sim$35 km s^{-1}). A possible coherent flux density variation is found between the two components.

Such devolution is consistent with the predicted rate of WF emergences about every decade (Khouri *et al.* 2021). SiO masers are also unique targets for exploring the central stellar system driving the WFs (Amada *et al.* 2022).

4. Future perspectives

Periodicity of the maser spectra will be found if the central stellar system of the WF is composed of a long period variable such as an OH/IR star or a binary system (Tafoya *et al.* 2020; Khouri *et al.* 2021). The former case will be found in low velocity maser components, which may be associated with a relic of a spherical circumstellar envelope, as seen in W 43A (Figure 3) and IRAS 18286−0959 (Imai *et al.* 2013). They may indicate the WF hosted by the star that is still in the asymptotic giant branch (AGB) phase. The latter case will be found in some symmetry in the maser spectra and the spatial patterns. They have been confirmed in the VLBI maps of H_2O masers in W 43A (Tafoya *et al.* 2020), IRAS 18286−0959 (Imai *et al.* 2020), and IRAS 18113−2503 (Orosz *et al.* 2019). Localization of the dynamical center of the symmetric components will elucidate the origin of the periodicity and test the scenario of the common envelope evolution mentioned above. For such a test, imaging of thermal emission with the Atacama Large Millimeter-submillimeter Array (ALMA) will be crucial (Tafoya *et al.* 2020).

In both cases mentioned above, the complexity of the maser spectra affected by chaotic variation and the artificial periodicity due to time gaps of the monitoring program should be solved in future monitoring observations with higher cadence, say every several days. Even for a small number of the WFs ($\sim$15, Desmurs 2012; Gómez *et al.* 2017), it is challenging to sustain such observations with only one large telescope, such as the Nobeyama 45 m telescope. Therefore, it is indispensable nowadays to develop a collaboration of the

https://doi.org/10.1017/S1743921323001916 Published online by Cambridge University Press

large telescopes regularly monitoring the WFs, as conducted by the Maser Monitoring Organization (M2O).

References

Amada, K., Imai, H., Hamae, Y., *et al.* 2022, *AJ*, 163, 85
Desmurs, J.-F. 2012, *Cosmic Masers - from OH to* H_0, Proc. IAU Symposium 287, 217
Gómez, J. F., Suárez, O., Rizzo, J. R., *et al.* 2017, *MNRAS*, 468, 2081
Imai, H., Uno, Y., Maeyama, D., et al. 2020, *PASJ*, 72, 58
Imai, H., Nakashima, J., Yung, B. H. K., *et al.* 2013, *ApJ*, 771, 47
Khouri, T., Vlemmings, W. H. T., Tafoya, D., *et al.* 2021, *New Astron.*, 6, 275
Okada, N., Hashimoto, I., Kimura, K., *et al.* 2020, *PASJ*, 72, 7
Orosz, G., Gómez, J. F., Imai, H., *et al.* 2019, *MNRAS*, 482, L40
Tafoya, D., Imai, H., Gómez, J. F., *et al.* 2020, *ApJ*(Letters), 890, L14
Uscanga, L., Imai, H., Gómez, J. F., *et al.* 2023, *ApJ*, 948, 17