Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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The Astrometric Animation of Water Masers toward the Mira Variable BX Cam

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Abstract. We report VLBI monitoring observations of the 22 GHz H_2O masers toward the Mira variable BX Cam. Data from 37 epochs spanning $\sim$3 stellar pulsation periods were obtained between May 2018 and June 2021 with a time interval of 3–4 weeks. In particular, the VERA dual-beam system was used to measure the kinematics and parallaxes of the H_2O maser features. The obtained parallax, 1.79±0.08 mas, is consistent with *Gaia* EDR3 and previous VLBI measurements. The position of the central star was estimated relied on *Gaia* EDR3 data and the center position of the 43 GHz SiO maser ring imaged with KVN. Analysis of the 3D maser kinematics revealed an expanding circumstellar envelope with a velocity of 13 ± 4 km s^{-1} and significant spatial and velocity asymmetries. The H_2O maser animation achieved by our dense monitoring program manifests the propagation of shock waves in the circumstellar envelope of BX Cam.

Keywords. masers—stars: individual (BX Cam)—stars:evolved, astrometry, kinematics

1. Introduction

The long-period variables (LPVs), such as Mira variables, are stars of low to intermediate masses that have reached the late stage of the asymptotic giant branch (AGB) phase. They are characterized by long-period (>100 d) variations in radius, brightness, and temperature, and exhibit an intense mass-loss phenomenon. Numerous details of the physics of late-stage stellar mass loss remain poorly understood, ranging from the wind launching mechanism(s) to the geometry and timescales of mass loss. Fundamentally, material on the surface of an evolved star gets colder and forms dust as it moves into interstellar space. The newly formed dust is accelerated by the stellar radiative pressure and forms an expanding envelope. However, such processes are complicated because the related phenomena occur in a dynamically and physically unstable region, including radial pulsations, shocks, magnetic fields, opacity changes due to dust and molecule formation, and large-scale convective segments in the stellar interior. One of the major challenges in understanding AGB winds is that mass loss often exhibits significant asymmetry on very different spatial (1–10^4 AU) and temporal scales (a few months to a few 10^4 years) (see the review of Höfner & Olofsson 2018 and their references therein).

Circumstellar SiO and H_2O masers are located, respectively, at the innermost part and the acceleration zone of the circumstellar envelope (CSE) around a typical oxygen-rich star (Richards 2012). The maser structures are composed of clusters of compact maser features (isolated gas clumps with sizes of ∼1 AU), enabling us to measure the three-dimensional velocity field of the CSE using Very Long Baseline Interferometry (VLBI) with ultra-high spatial resolution (Imai et al. 2003). VLBI maser observations offer one of the most powerful tools to measure the dynamics and physical conditions of the stellar atmosphere, as demonstrated by a 78-epoch "movie" of the SiO masers in a Mira variable covering three pulsation cycles (∼5 yr) (Gonidakis et al. 2013). Such a maser movie needs a reference frame for registering individual maps. Since the animated SiO masers formed an almost perfect ring, the maser maps could be registered with the fitted center of the ring. However, this is very challenging for most of the CSE masers with broken structures, e.g., H_2O masers.

We are tracing the asymmetric maser motions with the astrometric approaches with VLBI and *Gaia* (Gaia Collaboration et al. 2021), as demonstrated by the first "movie" of the H_2O masers in the Mira variable star BX Camelopardalis (BX Cam) (Xu et al. 2022). A maser animation derived based on astrometric steps enables us to visualize a radial expansion of the CSE masers and identify deviations of the maser motions from constant-velocity motions, such as radial accelerations, rotations, etc.

2. Observations and Methods

The monitoring observations of H_2O and SiO masers around BX Cam are carried out with the East Asian VLBI Network (EAVN) (Akiyama et al. 2022), as a part of the EAVN Synthesis of Stellar Maser Animations (ESTEMA) project. ESTEMA aims at intensive VLBI monitoring observations of CSE masers associated with LPVs of different pulsation periods (300—1000 d) over a few stellar pulsation cycles. The time cadence for a single observational epoch is 3–4 weeks, which is approximately equal to a time resolution of 1/20 stellar pulsation cycles of BX Cam (∼22 d). The reported H_2O data of 37 epochs in

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total were obtained from 2018 May to 2021 June, spanning approximately three stellar pulsation periods (P =∼440 d).

EAVN enables us to simultaneously monitor four to eight lines of H_2O and SiO masers at four frequency (22/43/86/129 GHz) bands with the sub-array KVN (Korean VLBI Network). The absolute positions, proper motions, and annual parallaxes are determined using the dual-beam astrometry of the sub-array VERA (VLBI Exploration of Radio Astrometry) for masers (Nagayama et al. 2020) and using Gaia for the central star. We can only measure the absolute positions of the bright masers of BX Cam with the VERA dual-beam bona-fide astrometry, then propagate this to all of the maser spots in the EAVN image by registering the bright masers in the pair of images. The stellar position with respect to the H_2O maser distribution is also astrometrically registered by a ring of SiO masers using the source-frequency phase-referencing (SFPR) technique (Dodson et al. 2014) from the KVN data. After subtracting the position offset and amotion of the central star, the asymmetric maser maps can be registered on the reference frame accurately.

3. Results

3.1. *Periodic variation of the H_2O masers*

ESTEMA observations allow us to study the variability and periodicity of maser intensity on timescales of a few weeks to a few years, investigating the possible correlation with stellar pulsation. The American Association of Variable Star Observers (AAVSO) reported a period of 486 d† for BX cam, however, we (Xu et al. 2022) and Matsuno et al. (2020) determined a period of 440 d by reanalyzing the AAVSO database. The peaks of the H_2O maser intensity exhibit an average delayed time-lag ∼25±9 days or phase-lag ∼0.06±0.02 related to the peaks of optical intensity. The averaged time interval of H_2O maser peak intensity is ∼447±11 days, which fits the period 440d better than 486d (AAVSO).

We investigated the spatial and velocity variation of maser features at different epochs. The shapes in the maser structures reveal the complex variation of the interior structure, such as rotation, expansion of the shape, flashing sub-structure, and changes in direction. The relative proper motions are not necessarily consistent between different cycles for some maser features. Almost all of the maser features exhibit radial velocity drifts that are not consistent between different cycles, indicating gradual behaviors related to the pulsation phases. We find that the light curves of the individual maser features or groups have different time lags relative to the optical light curve.

3.2. *Astrometry*

Few maser features can be detected with VERA Bona-Fide astrometry alone. Using the brightest maser feature (MF1 in Figure 1), we found different deviations from a common constant proper motion and conservatively obtained a parallax value of 1.79±0.08 mas, which is consistent with 1.76±0.10 mas from *Gaia* EDR3 (Gaia Collaboration et al. 2021) and 1.73±0.03 mas from the previous VERA result (Matsuno et al. 2020) within a 1-sigma level. The absolute positions of the bright and compact maser spots with VERA astrometric data were obtained and used to register the VERA and EAVN maps with an accuracy of ∼0.1 mas. Then, we estimated the proper motion results for all maser features with the EAVN data.

Gaia EDR3 provided the stellar position in optical astrometry; however, there may exist some position uncertainty for this AGB star (Xu et al. 2019). We registered the maps of the H_2O and SiO masers with the map taken with the KVN data using the SFPR

† https://www.aavso.org/vsx/index.php?view=detail.top&oid=4634

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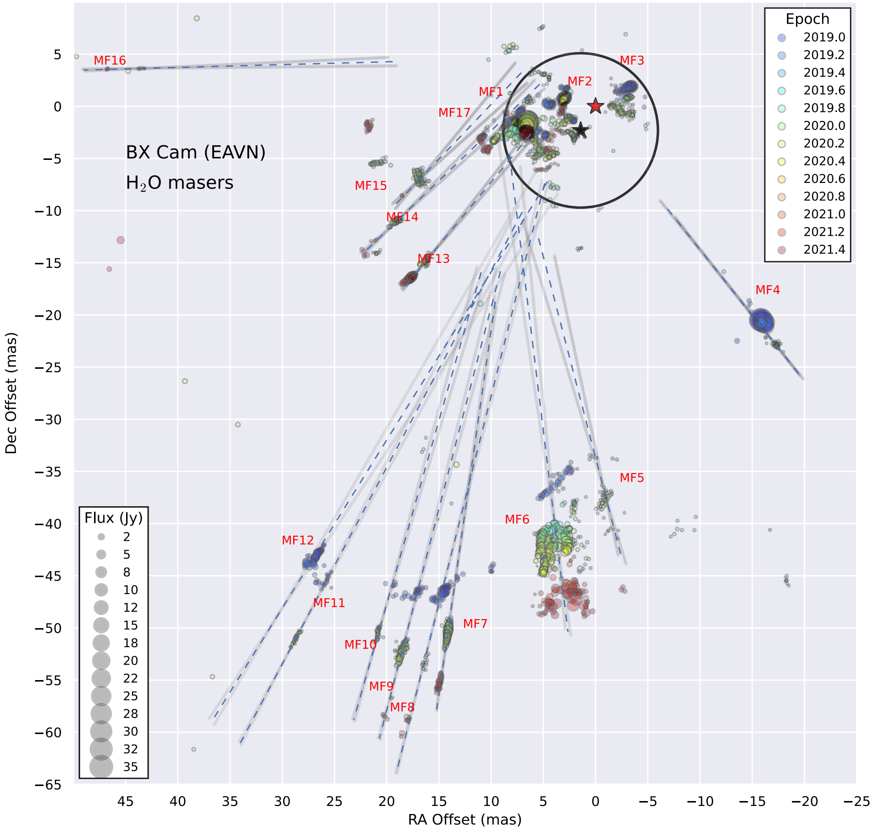

Figure 1. The BX Cam flow traced by H_2O maser features (MF#). The positional reference is *Gaia* EDR3 (red star). The black circle represents the fitted ring of SiO masers. The maser spots are shown in different colors to indicate different epochs, which have been astrometrically fixed. An auxiliary dashed line illustrates a possible trajectory of a maser feature from 2012 to 2022, assuming a constant velocity vector.

calibration technique (Dodson et al. 2014). We obtained the position of the central star, indicated as the center of the solid circle of the SiO maser ring. The differences between the estimated position and the *Gaia* EDR3 result are 1.4 mas (∼3 sigma) in the east direction and 2.3 mas (∼5 sigma) in the north direction on January 10, 2020.

3.3. *The expansion of the BX Cam flow traced by H_2O masers*

The constant velocity proper motions and spoke-like maser features in BX Cam 'point back' towards the central star (see Figure 1). However, the point-back directions of the maser features in different groups may converge into different areas, which may also have offsets from the location of the central star and the ring of SiO masers. Using the VERA data from 2012 to 2014, Matsuno et al. (2020) obtained a three-dimensional velocity of 14.8±1.4 km s^{-1} with three collimated flows. However, our result shows a wider range of 9 km s^{-1} (inner radii) to 19 km s^{-1} (outer radii) in different directions. These differences may be caused by the different pulsation phases originating from the characteristics of BX Cam, which trace the different expanding shells. The expansion velocity of H_2O masers is estimated to be 13.0 ± 3.7 km s^{-1}. The outer masers roughly exhibit radial expansions and are located at similar distances from the central star, with roughly a

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constant expansion velocity. However, there are some significant deviations from the spherical flow for the inner masers projected closely to the central star in the sky.

4. Conclusion

We have demonstrated the role of astrometry in the maser animation, which is crucial for registering the maser images at different epochs and extracting the intrinsic motions of maser features associated with the CSE. Further investigation will be conducted to explore the detailed maser kinematics of the CSE around BX Cam. This will involve analyzing multiple maser-line movies with SiO masers and discussing the possibility of maser clump acceleration.

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