Episodic ejection from a low-mass young stellar object traced by H_2O masers

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ABSTRACT

We present the first results of the EVN observation of the **22 GHz H_2O maser** in **a prototypical low-mass protostellar system, IRAS 16293-2422**. The observation was conducted to characterize the cause of the newly discovered **enhanced maser activity** in the source and to study the source's ejection behavior as traced by maser emission. Single-dish monitoring and analysis of archival data indicate that the activity of the H_2O maser in IRAS 16293-2422 has **a cyclic character** and traces **episodic ejection events** in the source. **A new maser flare** was recently discovered in a spectral feature that has never shown such a significant increase in flux density before. The flare of this feature seems to indicate the beginning of a new cycle of activity.

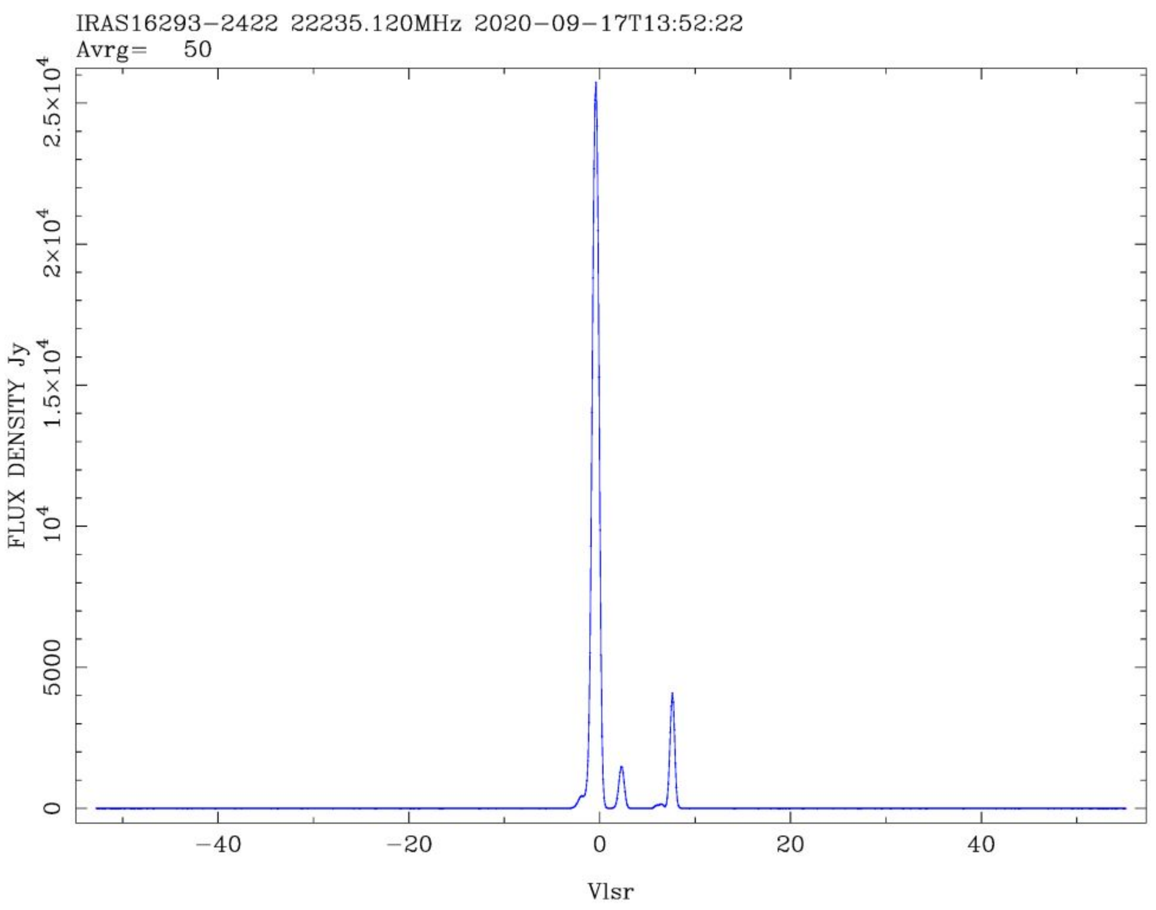


Figure 1. 22 GHz H_2O spectrum of IRAS 16293-2422 obtained on 2020, September 17th (M2O data, HartRAO).

BACKGROUND

The life cycles of stars follow patterns based mostly on their initial mass. In this sense, all stars can be divided into three classes: low-, intermediate-, and high-mass stars. Comparison of the physical parameters of protostar envelopes of different masses hints that the transition between them seems to be smooth, and the formation processes and triggers are similar (although massive stars evolve much more rapidly) [Crimier et al. 2010]. Disk-mediated accretion accompanied by episodic accretion bursts is thought to be a common mechanism of star formation across the entire stellar mass spectrum. However, the accretion process itself is poorly understood due to scarce observational evidence.

Much progress in the study of high-mass star formation has been made recently with the study of masers, which have proven to be a powerful tool for locating "bursting" massive young stellar objects (MYSOs) that are undergoing accretion events (see Brogan et al. 2019, Burns et al. 2020, and other publications of the Maser Monitoring Organisation (M2O) - a global co-operative of maser monitoring programs).

During accretion events in MYSOs, multiple maser species and transitions flared, and rare maser transitions were detected (e.g. Szymczak et al. 2018, MacLeod et al. 2018, Brogan et al. 2019). Masing occurs only over certain ranges of physical conditions of the gas and radiation field (e.g. Ellingsen et al. 2007 and Breen et al. 2019), hence the spatial distribution of masers can reveal the temperature, density and radiation enhancements in the region, while the kinematics of the maser spots can indicate gas motions.

According to theory and observation [Caratti o Garatti et al. 2015, 2017], there is a correlation between ejection and accretion rates, so major outflow events can be linked to major accretion events (bursts). Under this hypothesis the accretion history of a star can be inferred by its ejection history traced by symmetric pairs of ejection bow shocks at ever increasing distances from the central object [Burns et al. 2016, 2017]. The morphology of the jets/outflows (radius, curve shape) traced by H_2O masers may indicate timescales of the accretion process in young stellar objects (YSOs) as well as reveal the collimation properties of the jet and the density of the ambient material.

IRAS 16293-2422

is a low-mass protostellar system, showing bright and active H_2O maser emission.

The source is **known for its very rich chemistry**, several complex molecules have been discovered in it for the first time ever: glycolaldehyde, the simplest sugar molecule [Jørgensen et al. 2012]; methyl socyanate, a prebiotic complex organic molecule [Martín-Doménech et al. 2017, Ligterink et al. 2017]; and freon-40, the first stable organohalogen detected in interstellar medium [Fayolle et al. 2017].

The source is a **binary system**, usually referred to as **sources A and B**, separated by 5'' (600 AU, considering the distance to the source of 140 pc) [Wootten 1989, Mundy at el. 1992]. Sources A and B have properties of Class 0 objects, YSOs in their very early stages of the stellar evolution. Component B appears to be a single source, while component A was resolved into two subcomponents: A1 (an ionized region produced by shocks between an outflow and nearby dense gas) and A2 (a protostar powering a radio jet) [Chandler et al. 2005, Loinard et al. 2007]. Pineda et al. (2012) studied the kinematics of the gas in the IRAS 16293-2422 system using methyl formate (CH_3OCHO) lines and found an almost edge-on rotating disk around source A and signs of infall evidenced by inverse P Cygni profile around source B. The latest multi-epoch continuum VLA observations of the system confirm that **A2 is a protostar driving episodic mass ejections** [Hernández-Gómez et al. 2019].

Source A2 shows highly variable but bright 22 GHz H_2O maser emission with the flux density of tens kJy during flares and no less than 100 Jy in a stable state [Colom et al. 2016]. The flaring features appear alternately at blueshifted and redshifted velocities with respect to the cloud velocity of ~4 km/s, typically in the velocity range of -5-10 km/s. **Recently a new maser flare was detected** in a blueshifted feature at the velocity of -1.5 km/s (Fig. 1); this is **the brightest flare in this feature ever observed**.

VLBI studies of the spatial distribution of the 22 GHz H_2O maser emission in the source showed that there are two separate clusters: maser spots with blueshifted velocities are found to the north, and redshifted spots are found to the south [Imai et al. 1999, 2007, Dzib et al. 2018]. While early papers propose to associate the detected H_2O maser clusters with a rotating-infalling disk [Imai et al. 1999], later works argue that maser emission trace outflows [Imai et al. 2007, Colom et al. 2016, Dzib et al. 2018]. Single-dish monitoring of maser emission in the source suggests that the H_2O maser flares are most probably linked to motions of shocked gas [Colom et al. 2016].

Our analysis of the literature and a comparison of the VLBI data obtained in different epochs indicates that H_2O masers in IRAS 16293-2422 could trace shocks excited by a precessing outflow system (see Fig. 2). Although the general segmentation of maser emission into two spatial clusters persists from epoch to epoch, the distance and alignment between them vary.

The elongated morphology and bipolar outward motions of water masers suggest that they are associated with an ejection event from the YSO. Particularly noteworthy is the fact that the distance between clusters increases.

There is a correlation between kinematic age and outflow length (the angular separation between the lobes) of H_2O maser jets: very young bipolar H_2O maser jets/outflows are very compact. VLBA observations of the intermediate-mass YSO LkHα 234 reveal a remarkably compact ~0.2 arcsec (~180 AU) H_2 maser jet with a kinematic age of ~40 yr [Torrelles et al. 2014]. Also the structure of bow shocks decay over time due to turbulence, young jets show the more evident morphology.

Note that observation of Alves et al. (2012) (see Fig. 2) was made during a quiescent state of the maser and blueshifted features were not detected. Monitoring of Colom et al. (2016) indicated that the activity of the H_2O maser in IRAS 16293-2422 has a cyclic character, and the period of 2006-2008 was one of the longest maser emission minima. Thus, it is possible that the shocks traced by the H_2O maser and detected in Imai et al (1999, 2007) and Dzib et al. (2018) no longer exist, and with VLBI observation of the maser emission associated with the new flare, **we can catch the launch of young ejection bow shocks.**

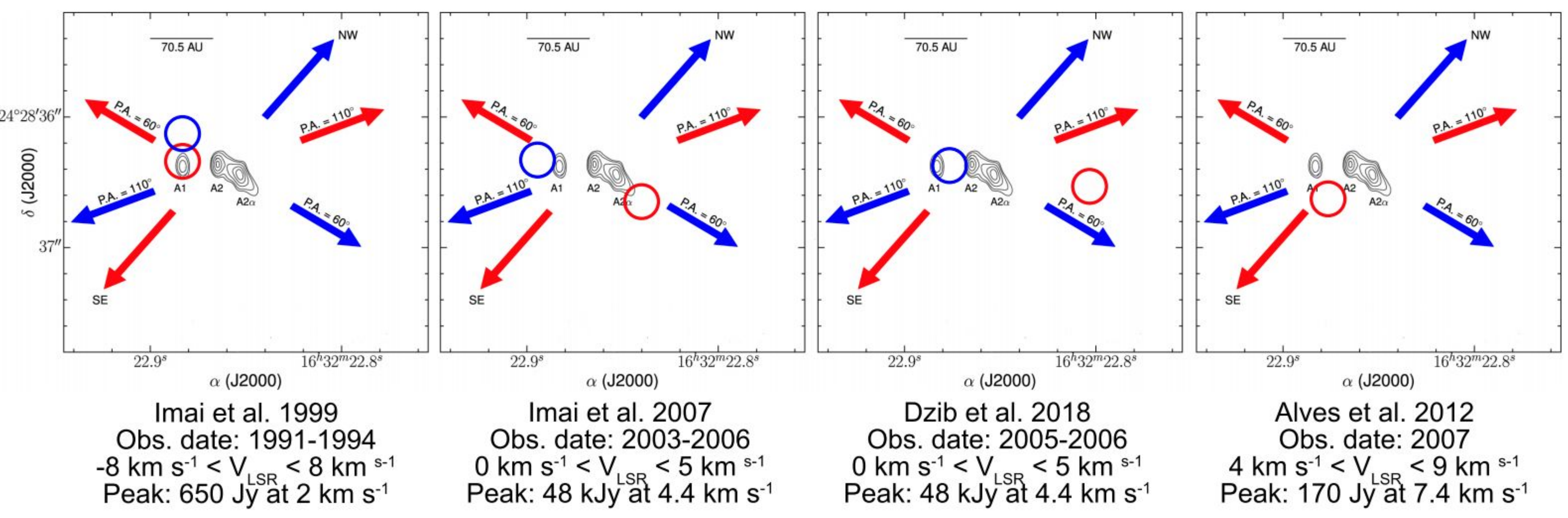


Figure 2. Evolution of the 22 GHz H_2O maser special distribution in IRAS 16293-2422. Background image is taken from Dzib et al. 2018: A1 and A2 - the sources composing this system; blue and red arrows mark the directions of the three outflows in the system. The blue and red circles mark the average positions of blueshifted and redshifted H_2O maser features, respectively. For each observation epoch (see the reference under each map), the velocity range of the detected H_2O maser features with the peak flux and velocity is indicated.

OBSERVATIONS

In order to characterise the cause of enhanced maser activity and to study the ejection behaviour of IRAS 16293-2422 as it traced by maser emission, we requested EVN observation of K-band masers in the source.

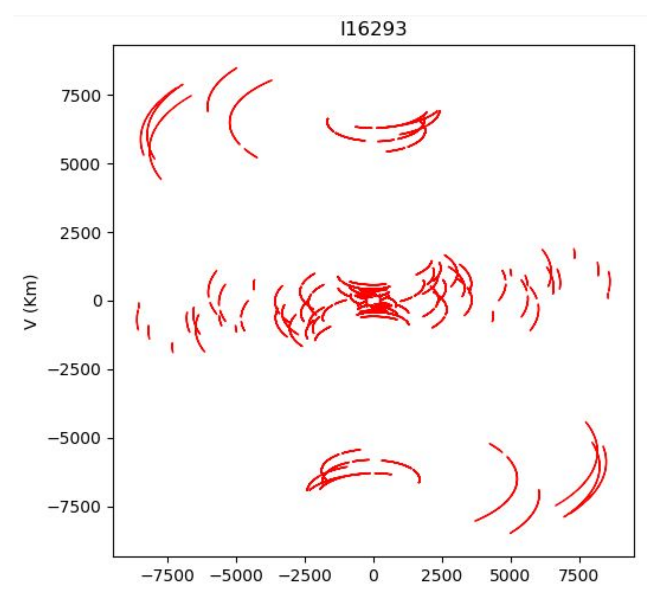
The EVN phase referencing observation of the source was conducted on March 11, 2021 (project code EB084). 13 EVN stations participated in the observation. Unfortunately, the e-MERLIN out-stations did not record successfully for the K-band user experiments during this EVN session, thus the observation lacks short inter-e-MERLIN baselines, crucial for picking up more extended maser emission.

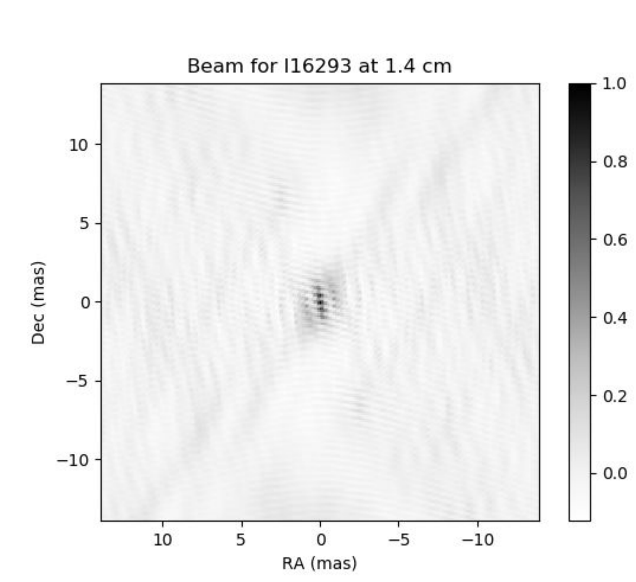
The total time of the observation was 10 hours, and it is justified by the need to obtain a good UV coverage (the high flux density of the target ensures the detection even taking into account the expected correlated flux of about 10% of the total flux). Note that the elevation of the source is close to the EVN declination limit, but the obtained UV coverage still seems to be sufficient to meet our scientific goals.

The frequency settings was 8 BBCs of 16 MHz, dual-polarisation, with 2 bit Nyquist sampling, leading to a data rate of 1024 Mbps. At correlation we requested 512 frequency channels for the continuum and 2048 channels for the line pass.

The target source was calibrated using the phase-reference source J1625-2527. 3C454.3, J1751+0939, and J1159+2914 were also observed as calibrators and fringe finders.

The achieved UV coverage and beam size are presented in the figures to the right (the plots are prepared using the EVN Observation Planner).





THE FIRST RESULTS

Fundamentally, our project aims **to provide comparison between low- and high-mass formation by investigating of outflow behaviour for a prototypical low-mass protostellar system.**

Analysis of archival data suggests that the maser emission in the source marks episodic ejection events that can be linked to the source accretion activity. According to the latest M2O update, there is currently **a bright flare** ongoing in blueshifted feature at the velocity of -1.5 km s^{-1} which has never shown such an increase in flux density before. The activity of the H_2O maser in the source is known to be **periodic**, and the flare of this feature seems to indicate t**he beginning of a new cycle of activity**, i.e. a possible new ejection episode.

The high 'flaring' flux density of the source ensured detection in the presented VLBI observation even considering the elevation of the source and reduced number of the participated telescopes. Comparison of the EVN cross-correlation spectra and the M2O single-dish data shows that only **~10%** of the maser emission is recovered with the synthesized beam of the EVN (see Fig. 3). The signal from the central flaring spectral feature **is detected with the longest EVN baselines** (Europe-South Africa), therefore the masing region from which the flare originates is **very compact**. At the moment, we are preparing images of the maser emission in the source to answer the main question of our project: **where does the new maser flare come from?**

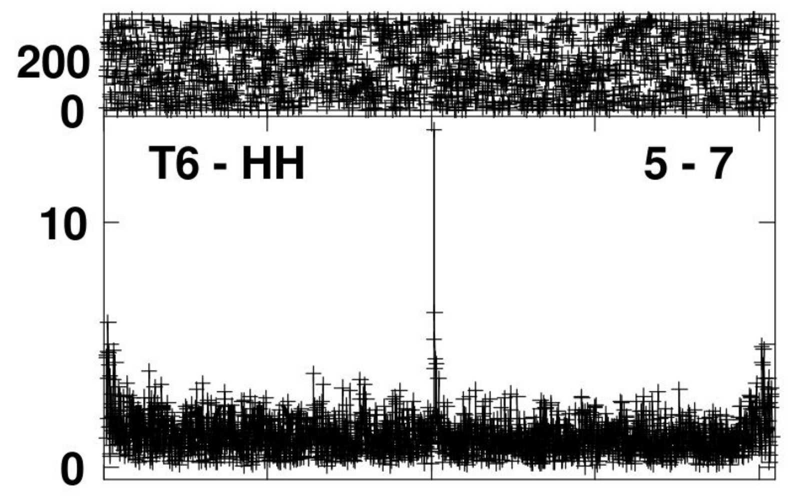


Figure 3. An example of cross-correlation spectrum of IRAS 16293-2422 obtained with a long EVN baseline between Tianma 65-m (China) and Hartebeesthoek (South Africa).

THE STORY BEHIND

The PI of the project, Zs. M. Szabó, is a student of Eötvös Loránd University (Hungary) and a participant of the JIVE summer student programme 2020. Under the supervision of JIVE support scientists Olga Bayandina, Zsófia was supposed to work on a project dedicated to the study of maser flares associated with accretion bursts in MYSO. Unfortunately, the summer student programme was canceled due to the COVID-19 situation.

The proposed study was planned as a substitutional project, but expanded in the first joint work of the Konkoly Observatory Structured ACCREtion Disks (SACCRED) Research Group and the M2O. Both collaborations study star formation and accretion bursts in YSOs, but the first group focuses on low-mass YSOs, while the second - on high-mass objects. The project attracted attention of single-dish telescopes participating in the M2O to the monitoring of maser sources associated with low-mass YSOs, and will be the first VLBI study for the Konkoly Observatory collaboration.