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New 6.7 GHz imaging of the high-mass star-forming region Cep A HW2

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Due to high brightness and low interstellar extinction at 6.7 GHz, class II methanol masers are useful for studying the physical properties of massive young stellar objects. Since they usually originate within 1000 AU from the protostar and are pumped by IR photons, their variability can be a fairly good marker of protostellar activity. Our monitoring of the 6.7 GHz methanol masers in Cep A revealed quasi-periodic low-amplitude red-shifted flares. Thus we decided to examine this phenomenon in EVN projects RD002 and ED046B. Cepheus A is a well-known, well-studied high-mass star-forming region located only 700 pc away, which hosts a cluster of young stellar objects. The brightest continuum source, HW2, is an HMYSO with a mass of $\sim 10\,M_\odot$ and bolometric luminosity of $2\times10^{4}\,L_\odot$. Our results, combined with previous VLBI observations, pinpoint flaring cloudlets near the presumed edge of a dust emission core. [1].

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1. Introduction

6.7 GHz class II methanol maser is the second strongest interstellar emission line (being surpassed only by 22 GHz water maser) and origins in the vicinity of high-mass young stellar objects (HMYSOs) [2]. There are currently more than 1300 class II CH_3OH maser sources detected in the Milky Way[1] [3]. Theoretical models suggest that 6.7 GHz emission originates in a gaseous environment with number densities lower than 10^9 cm $^{-3}$ and dust temperatures higher than 100 K [4, 5]. Evidence also shows that far-IR photons are essential in pumping class II CH_3OH masers. The 6.7 GHz line is a fairly good indicator of protostellar activity, as recent discoveries of giant bursts [6–8] have shown.

Cepheus A is a high-mass star-forming region located at a trigonometric distance of 700 pc [9]. This cluster's brightest continuum source is Cep A HW2 [10]. 6.7 GHz maser emission was detected towards Cepheus A numerous times with a similar spectral profile [11–18]; VLBI measurements pinpointed this emission within 1000 AU from the presumed position of the central protostar [19]. [13] detected anti-correlation between the red- and blue-shifted part of the 6.7 GHz spectrum, confirmed later by [20]. Proper motions of the 6.7 GHz cloudlets [17, 21] also suggest planar infall of the circumstellar matter around Cep A HW2, hinting at disc accretion as the best explanation for the formation of the Cep A HW2 system.

In this work, we present results of the of the 12-year-long single-dish monitoring of the 6.7 GHz masers in Cep A HW2 - part of this dataset was published previously in [20]. Additionally, we provide results of the two epochs of the VLBI imaging of the methanol masers. Our main result is detecting the periodic variability of the most red- and blue-shifted[2] parts of the 6.7 GHz spectrum.

2. Observations

2.1 Single dish

In this work, we used data acquired by the 32 m NCU radio telescope between June 2009 and November 2022. Some of this dataset (collected before March 2013) was published previously in [20]. Data was acquired with a standard cadence of 9 observations per month, and the typical system temperature ranged from 25 to 40K. The observations were taken in frequency switching mode with dual polarisation and a resulting spectral resolution of 0.09 km s^{-1}.

2.2 VLBI

We carried out EVN observations in June and October 2020 (project codes: RD002 and ED048B, respectively). Observations were taken in phase-referencing mode and correlated with two polarisation combinations: RR and LL. We used the 2007+777 as a fringe-finder in both projects, while phase reference sources were J2254+6209 and J2302+6405 for RD002 and ED048B projects, respectively. Target and phase-reference source scans were performed with a duration of 3 min 15 s and 1 min 45 s, respectively. The bandwidths were 2 and 4 MHz for experiments RD002

[1] https://maserdb.net

[2] With respect to the centroid velocity of the 6.7 GHz CH_3OH emission

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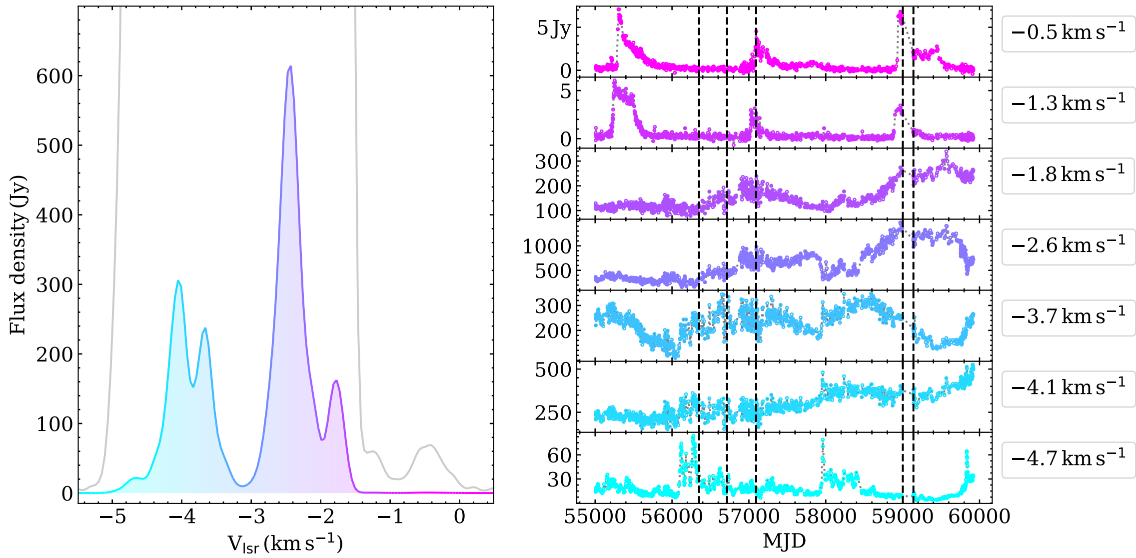

Figure 1: Results of the single-dish monitoring. *Left*: the coloured line presents the average single-dish spectrum of the 6.7 GHz CH_3OH transition for the period between 2009 and 2022; the grey line shows the same data but magnified 100 times to make the red-shifted features at −0.5 and −1.3 km s^{-1} visible; *right*: the light curves of two flaring and five persistent features. The dashed vertical lines indicate epochs of the EVN observations.

and ED048B, respectively. We used two correlator passes; one with 128 channels to improve the sensitivity of calibrator maps and the second with high spectral sampling (2048 channels). This combination resulted in spectral resolutions of 0.045 and 0.09 km s^{-1}, respectively. Public data from EVN [17, 19] and JVN [21] archives were also used.

3. Results

3.1 Red-shifted flaring emission

Our single-dish monitoring revealed the appearance of the features at LSR velocities −0.5 and −1.3 km s^{-1} three times: in 2010, 2015, and 2020, indicating at least 5-year-long quasi-periodic behaviour with characteristic profile: sharp rise followed by a much more gradual decrease in flux density. Flare parameters derived from single-dish data are presented in Table 1, and their light curves are also illustrated in Fig. 1. The appearance of this emission was the main reason for the conduction of the EVN maser observations towards Cep A HW2 in projects RD002 and ED048B - low amplitude emission was pinpointed near the edge of the dust disc (Fig. 2), reported previously in [1]. A comparison of the new data with archival observations reveals that the red-shifted emission was also detected in 2015 [17] and 2006 [21], which is consistent with our ephemeris. There is also a noticeable lag between flare onsets of the −0.5 and −1.3 km s^{-1} features that tend to decrease from cycle to cycle. These observed phenomena allowed us to rule out most of the periodic emission scenarios that could result in the sharp-rise slow-decay pattern: colliding wind binary [24], which cannot reproduce delays between the onset of the −0.5 and −1.3 km s^{-1} flares, pulsation instability [25] (a period of ∼5 years requires about 40 $M_\odot$ protostar, which is much more

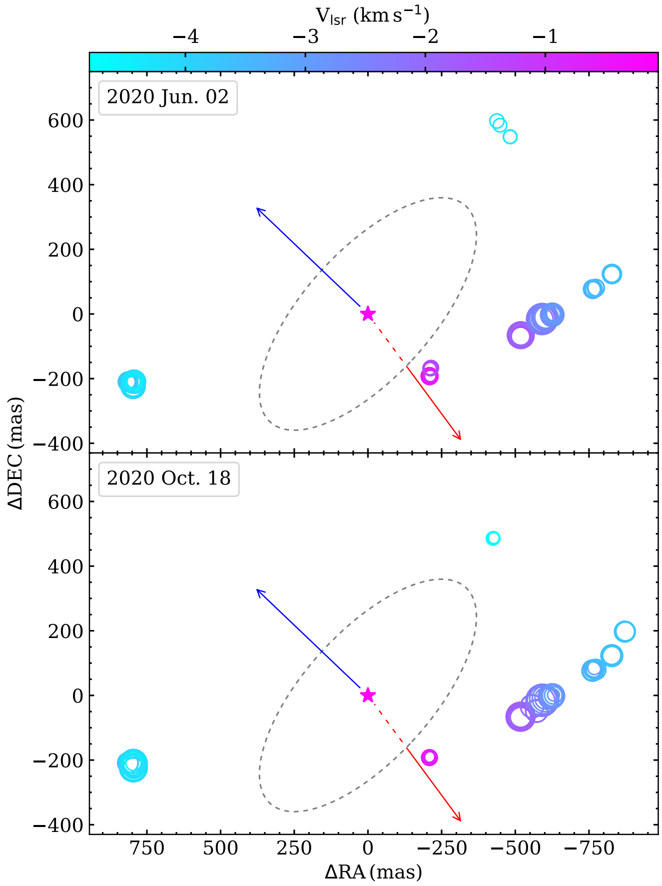

Figure 2: Spatial distribution of the 6.7 GHz methanol maser spots in Cep A HW2 for the experiments RD002 (*top*) and ED048B (*bottom*). The circle size is scaled as the logarithm of the peak brightness; its colour corresponds to the local standard of rest velocity scale shown in the wedge. The magenta star marks the Cep A HW2 position reported in [22]: α(J2000)=22$^{\rm h}$56$^{\rm m}$17.9816$^{\rm s}$, δ(J2000)=62°01′49.572″. The ellipse denotes the dust disc emission at 0.9 mm [1], and the arrows mark the elongated knot directions at the base of the jet detected at 7.5 mm [23].

than previous estimations for Cep A HW2 [1, 17]), and spiral shocks generated by an OB binary [26] (requires almost exact edge-on configuration to reproduce light curves, and it cannot produce observed delays).

3.2 Anti-correlation between chosen spectral features

Anti-correlation between the blue- and red-shifted part of the 6.7 GHz spectrum of the Cep A HW2 was reported initially in [13] and confirmed by later observations in [20]. Extending the latter dataset allows for a closer examination of this phenomenon - correlation coefficients (Tab. 2) show that correlation is weakly pronounced when the whole dataset is considered. When only periods of activity of the −4.7 km s^{-1} feature are taken into account (2012, 2017, 2022), the anti-correlation between −2.6 and −4.7 km s^{-1} spectral components becomes strongly pronounced - see Fig. 3. The recovered distance between −2.6 and −4.7 cloudlets is about 850 AU [17] and the

Table 1: Flare parameters of the −1.3 and −0.5 km s^{-1} features.

V_{lsr} (km s^{-1})	t_{start} (MJD)	t_{peak} (MJD)	t_{end} (MJD)	F_{peak} (Jy)
2010 Flare				
−1.3	55222	55255	55609	6.0
−0.5	55283	55307	55679	7.6
2015 Flare				
−1.3	57018	57025	57117	2.7
−0.5	57070	57095	57297	3.3
2020 Flare				
−1.3	58888	58953	59104	3.5
−0.5	58929	58966	59512	7.0

Table 2: Pearson correlation coefficients of the 6.7 GHz spectral features in Cep A HW2 for the whole monitoring period. Coefficients marked with bold font denote significant correlation.

Feature (km s^{-1})	−1.8	−2.6	−3.7	−4.1
−2.6	**0.87**			
−3.7	0.26	0.28		
−4.1	0.47	0.59	0.60	
−4.7	−0.32	−0.43	0.32	0.24

measured delay between dips of the former and peaks of the latter is about 8 days, which stays within an order of magnitude with light-crossing time. Considering also the nearly edge-on configuration of the system ($i = 64°$ [17]), we propose the radiative connection scenario, described in [27], as the viable explanation of this phenomenon.

3.3 Proper motions

Following procedures similar to those described in [17], we can combine the results of the EVN archival observations (project code: ES071C) and the new VLBI dataset to derive proper motions of one of the flaring cloudlets (−0.5 km s^{-1}). We estimated the proper motion of the cloudlet to be $\mathrm{V_{RA}} = -2.06 \pm 0.12$ km s^{-1} and $\mathrm{V_{DEC}} = 2.91 \pm 0.17$ km s^{-1}. Using angles provided by [17], we can present the proper motion vectors in a face-on view of the Cep A HW2 system (Fig. 4). Comparison of the infall and orbital velocities of the flaring and nearby cloudlets [17] shows that orbital motion is rather sub-Keplerian and measured infall velocity decreases for the cloudlets closer to the dust disc (Fig. 5).

4. Conclusions

The main result of this work is the detection of quasi-periodic flares of the red-shifted 6.7 GHz emission. Flares occur every ∼1800 days and last about a few hundred days. In addition, we found

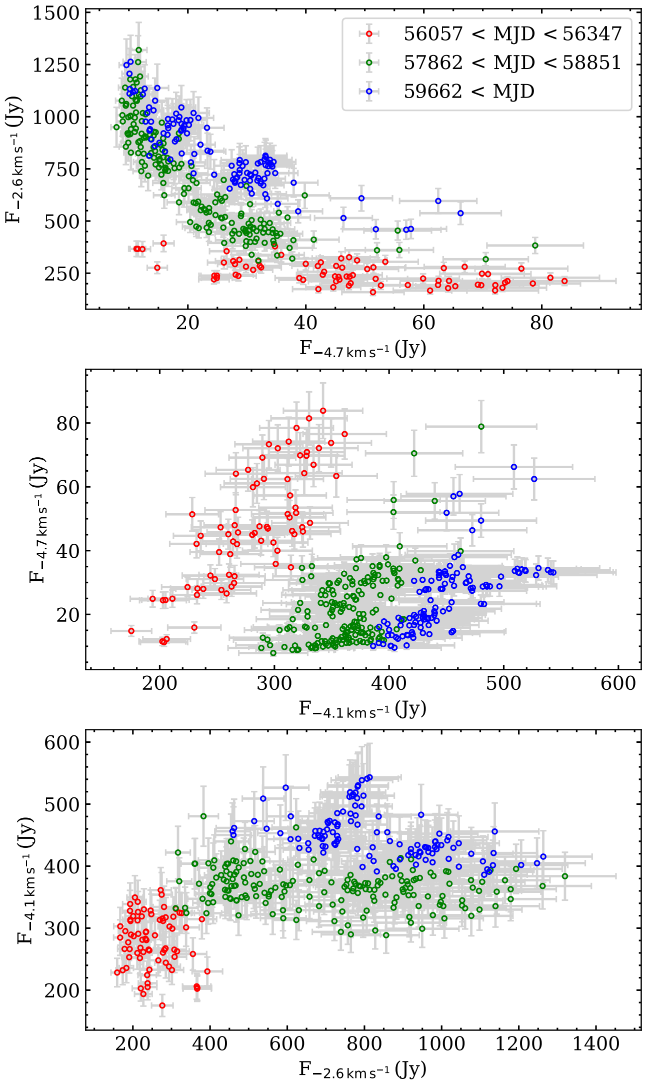

Figure 3: Comparison of the peak flux densities of the selected spectral features. Data presented in this graph cover the periods of activity of the $-4.7\,\mathrm{km\,s^{-1}}$ spectral feature (we provide exact periods on the legend in the top-right corner of the figure). Pearson correlation coefficients are −0.76, −0.07, and 0.49 for the top, mid and bottom graphs, respectively.

that also the most blue-shifted ($V_{lsr} = -4.7\,\mathrm{km\,s^{-1}}$) emission undergoes flaring events every five years, and its emission is anti-correlated with the strongest ($V_{lsr} = -2.6\,\mathrm{km\,s^{-1}}$) feature. The latter phenomenon is a signpost of the radiative connection between −4.7 and $-2.6\,\mathrm{km\,s^{-1}}$ cloudlets. Our observations also confirm the sub-Keplerian nature of the circumstellar molecular disc. Based on our ephemeris, the following expected events are flares of the −0.5 and $-1.3\,\mathrm{km\,s^{-1}}$ features (first quarter of 2025) and the burst of the $-4.7\,\mathrm{km\,s^{-1}}$ feature, anti-correlated with $-2.6\,\mathrm{km\,s^{-1}}$ feature (last quarter of 2027).

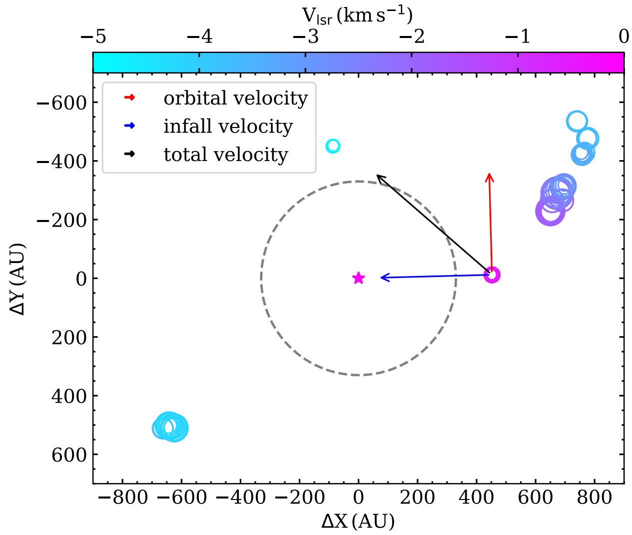

Figure 4: Face-on view of the Cep A HW2 system derived using inclination angle $i = 64°$ and position angle PA = 134°. The presented data is the same as at the bottom of Fig. 2.

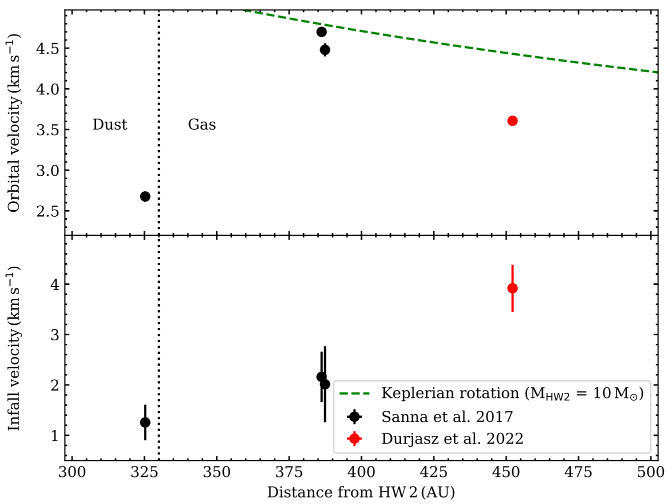

Figure 5: Orbital and infall velocities of the 6.7 GHz cloudlets, observed in [17] (black) and [28] (red) with Keplerian rotation curve superimposed. The dotted vertical line marks the boundary between dust and gas disc.

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