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Discovery of periodic methanol masers associated with G323.46−0.08

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ABSTRACT

The 6.7 GHz methanol masers associated with G323.46−0.08 have undergone significant change since their discovery in 1992. After 2009 April, new features with a peak flux density of ∼500 Jy in the velocity channel $v = -68.35\,\mathrm{km\,s^{-1}}$, in the velocity range from −71 to $-68.5\,\mathrm{km\,s^{-1}}$ were detected. It is suggestive that it experienced an accretion event similar to that reported in S255-NIRS3 and NGC 6334I. Evidence of periodicity is found in all of the associated methanol masers with a period of ∼93.5 d. It is not possible to determine if this source was periodic before 2017. However, all the 6.7 GHz methanol masers are probably amplifying a common background periodic radio source.

Key words: masers – stars: formation – stars: protostars – ISM: individual objects: G323.46−0.08 – ISM: molecules – radio lines: ISM.

1 INTRODUCTION

The phenomenon of periodicity in Class II methanol masers was first presented by Goedhart, Gaylard & van der Walt (2003). Since then, the number detected has grown to 23 (Goedhart, Gaylard & van der Walt 2004; Goedhart et al. 2009; Araya et al. 2010; Szymczak et al. 2011; Fujisawa et al. 2014; Szymczak, Wolak & Bartkiewicz 2015; Maswanganye et al. 2015, 2016; Sanna et al. 2015; Szymczak et al. 2016; Sugiyama et al. 2017; Szymczak et al. 2018). Some have contemporaneous periodic 1665 and 1667 MHz OH (Goedhart et al. 2004; Green et al. 2012b), formaldehyde (Araya et al. 2010), and water (Szymczak et al. 2016) masers. There are four competing models to explain this periodicity: a pulsating proto-stellar object (Inayoshi et al. 2013; Sanna et al. 2015), periodic accretion (Araya et al. 2010), a rotating spiral shock (Parfenov & Sobolev 2014), or a colliding wind binary (CWB) star (and references therein van der Walt et al. 2016; van den Heever et al. 2019). A greater sample of periodic maser sources is required to better understand what is responsible for this phenomenon.

G323.46−0.08 is a massive star-forming region with a variety of associated maser species. Water masers were detected towards this source in 1981 (Caswell et al. 1989). Hydroxyl masers were first reported by Caswell & Haynes (1987). Cohen, Baart & Jonas (1988) independently detected 1665/7 MHz hydroxyl masers towards the bright far-infrared source IRAS15254−5621 associated with weak and extended 5 GHz radio continuum emission first reported by Haynes, Caswell & Simons (1978). Also weak, less than 20 Jy Class II methanol masers were also detected: 12.2 GHz masers in 1988 (Kemball, Gaylard & Nicolson 1988) and 6.7 GHz masers in 1992 (MacLeod, Gaylard & Nicolson 1992). The methanol maser association is indicative of massive star formation.

In this paper, we present the results of monitoring 6.7 GHz methanol masers associated with G323.46−0.08 using the Hartebeesthoek Radio Astronomy Observatory (HartRAO). We report that all the associated methanol masers are periodic in nature and some time lags are present. We also postulate that this source has undergone a flaring event similar to S255-NIRS3 (Caratti o Garatti et al. 2017) and NGC 6334I reported in Hunter et al. (2018) and MacLeod et al. (2018) and predict new regions of methanol maser activity will be found in G323.46−0.08.

2 OBSERVATIONS

The observations reported here were made using the 26 m telescope of Hartebeesthoek Radio Astronomy Observatory (HartRAO).[1] The 4.5 cm receiver is a dual, left (LCP) and right (RCP), circularly polarized, cryogenically cooled receiver. Each polarization was calibrated independently relative to Hydra A and 3C123, assuming

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[1]See http://www.hartrao.ac.za/spectra/ for further information.

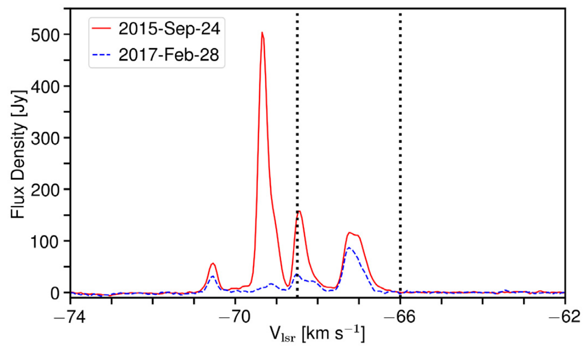

Figure 1. Selected spectra of the 6.7 GHz methanol masers associated with G323.46−0.08, observation taken on: 2015 September 24 (solid red line) and 2017 February 28. The vertical (dotted) lines, at −68.5 and $-66.0\,\mathrm{km\,s^{-1}}$, represent the velocity range in which 6.7 GHz methanol masers, with $S_{\rm peak}$ = 15.2 Jy, were previously reported by Green et al. (2012a).

the flux scale of Ott et al. (1994). The point source sensitivity (PSS) employed to convert the measured temperatures is PSS(LCP) = $5.58\,\mathrm{Jy\,K^{-1}}$ and PSS(RCP) = $4.49\,\mathrm{Jy\,K^{-1}}$. Observations were recorded with a 1024-channel (per polarization), 1.0 MHz bandwidth spectrometer. Frequency switching was employed as was half-power beamwidth pointing correction observations for all epochs of observation. The total velocity extent of each observation is $22.5\,\mathrm{km\,s^{-1}}$ and resolution is $0.044\,\mathrm{km\,s^{-1}}$. The observing frequency is 6668.518 MHz and this is corrected for the Local Standard of Rest (LSR) velocity $v_{\rm LSR} = -67.2\,\mathrm{km\,s^{-1}}$. Each epoch of observation comprises two six-min observations achieving a sensitivity of ∼0.1 K or ∼0.8 Jy per polarization.

In an effort to identify and study new variable sources, 97 bright methanol masers were selected from the Methanol Multi-Beam (MMB) survey (Green et al. 2009, 2010, 2012a; Caswell et al. 2010, 2011) and re-observed in 2015; the results will be published in the PhD dissertation of Mr. E. Proven-Adzri. Only one of these sources, G323.46−0.08, was included in the methanol maser monitoring programme at HartRAO; it was the brightest maser observed in the sample with the greatest amount of variation. The initial observation of G323.46−0.08 was taken on 2015 September 24. Monitoring observations commenced on 2017 February 28 and were made every 10−15 d. However, the cadence of observations varied depending on the availability of the telescope, and the weather conditions. At times, observations were done daily, but there are also observations separated by weeks. The coordinates that the telescope pointed to were R.A. = $15^{\rm h}\,29^{\rm m}\,19\overset{\rm s}{.}3$ and Dec. = $-56^\circ\,31'\,22\overset{''}{.}8$ (J2000). Pointing accuracy of these observations was about 20″.

3 RESULTS

In Fig. 1, we present spectra of the initial 6.7 GHz methanol maser observation for G323.46−0.08 in 2015 and the first in the monitoring programme in 2017. Maser emission is detected in the velocity range $v = -70.9$ to $-68.5\,\mathrm{km\,s^{-1}}$ where all emission at $v \le -68.5\,\mathrm{km\,s^{-1}}$ is new; maser emission has only been previously reported in the velocity extent $v = -68.5$ to $-66.0\,\mathrm{km\,s^{-1}}$, see Green et al. (2012a). We report the strongest maser emission in the velocity channel $v = -69.35\,\mathrm{km\,s^{-1}}$ was 504 Jy on 2015 September 24 and decreased by a decay factor of 53 to 9.3 Jy in 2017 February 28. During the course of our observations, ∼1200 d, the peak amplitude in this channel has decayed by a factor of ∼200. All velocity components have much stronger emission than previously reported; 6.7 GHz methanol maser emission though may have declined since 2015.The strongest 6.7 GHz methanol emission after 2015 is found in the channel $v \sim -67.11\,\mathrm{km\,s^{-1}}$.

To investigate the temporal behaviour of the associated 6.7 GHz methanol masers, we first plot the dynamic spectra in Fig. 2 (a). Quasi-periodic variability appears to be present in every velocity channel between $v = -70.93$ and $-65.97\,\mathrm{km\,s^{-1}}$ and where $S_{6.7} >$ 3 Jy. We present the time-series plots for selected velocity channels in Fig. 2(b) and find that at the time of writing, we report eight flares have occurred, enumerated in the plot. The flares reach no quiescent phase before the next flare begins for the first six, thereafter they may. We estimate the period, ∼94 ± 3 d from the temporal differences between each peak in these velocity channels and presented in Table 1. Using the Lomb−Scargle periodogram method (Scargle 1982), we estimate the period for each velocity channel and include in the same table. The average period for all channels is 93.5 ± 2.0 d calculated from the latter method.

The maximum flux density in each of the velocity channels shown in Fig. 2 were strongest during flare 2, then decreased until flare 6. Emission in $v = -67.11\,\mathrm{km\,s^{-1}}$ appear to reach common maxima (∼70 Jy) and minima (∼40 Jy) in flares 7 and 8.

We note in Fig. 2 that the flaring in some velocity channels appears to precede or follow others, e.g. time lags. In the early flares, Flares 1−3, flaring in the velocity channel $v = -68.43\,\mathrm{km\,s^{-1}}$ leads all others; the largest is ∼12 ± 8 d with $v = -69.35\,\mathrm{km\,s^{-1}}$. However, we also note that the onset of each flare in each channel effectively began on the same day. Each of the flares underwent slower decline than onset phases. The average ratio of the flare decay to onset time varies from 1.0 to 1.8 for the selected velocity channels and the average ratio for all flares is 1.5 ± 0.2, see Table 1. The weakening of the emission in the channels, −69.35 and $-68.82\,\mathrm{km\,s^{-1}}$, made it difficult to analyse the ongoing flaring maser emission activity.

4 DISCUSSION

4.1 An event similar to S255-NIRS3 or NGC 6334I(N)?

Masers were instrumental as a diagnostic tool in the study of accretion events in two sources. Caratti o Garatti et al. (2017) reported that S255-NIRS3 underwent a significant accretion event via near-infrared observations. This event was accompanied by 6.7 GHz methanol maser flaring (Fujisawa et al. 2015; Szymczak et al. 2018) which increased by a factor of 10 over five months. Similarly, MacLeod et al. (2018) reported a significant flaring event towards NGC 6334I in its associated methanol, hydroxyl, and water maser transitions. Several different maser transitions of OH, H_2O, and CH_3OH were detected in a similar velocity range suggesting they were co-spatial and in a new region of maser activity (MacLeod et al. 2018). This was confirmed by Hunter et al. (2018) who reported new regions of excited OH and methanol masers some coincident. The masers took 8.5 months to reach a peak and several transitions continued masing for years after (MacLeod et al. 2018). Hunter et al. (2017b) proposed that the explosive event reported in NGC 6334I was the result of a major accretion event. Is the flaring of the methanol masers in G323.46−0.08 the result of another accretion event?

It is important to first note that the maser features present in G323.46−0.08 prior to 2009 April were sufficiently weak such that they would not be discernible from new much brighter maser features in the present single-dish spectra and were not monitored. We can only say that the originally detected, and present, methanol

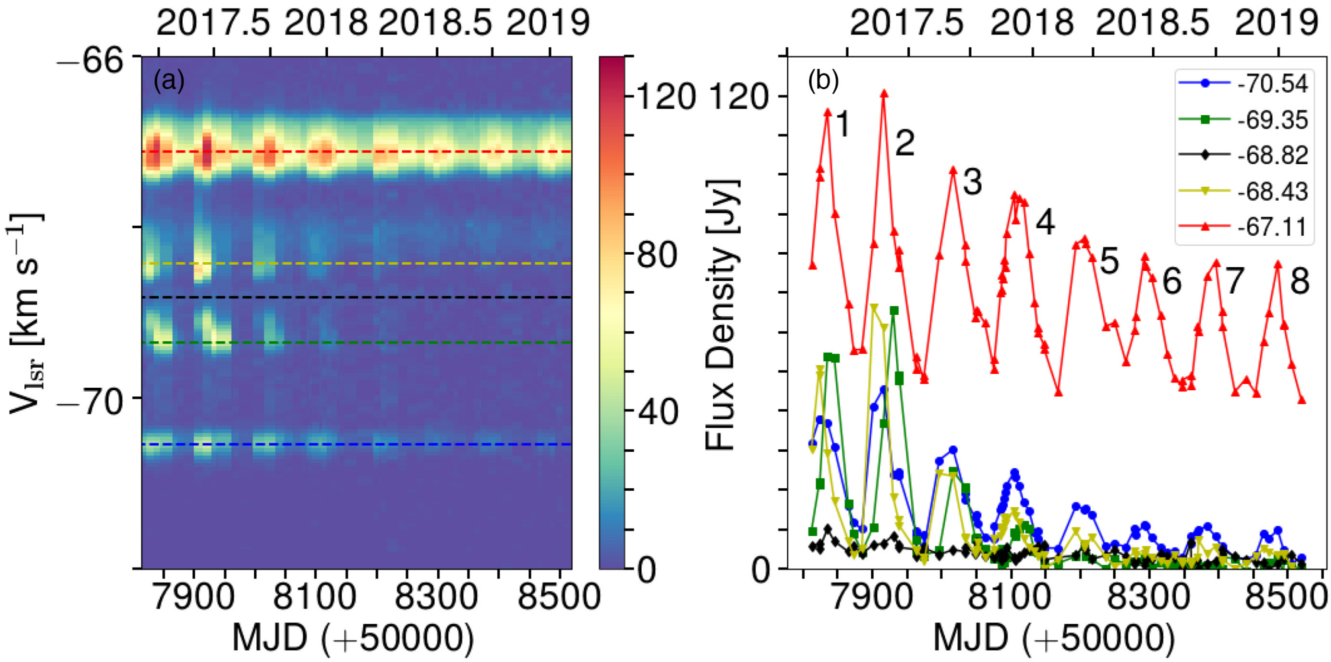

Figure 2. Results of 6.7 GHz methanol monitoring observations of G323.46−0.08: (a) dynamic spectral plot and (b) time-series plots of various velocity channels: −67.11 km s^{-1} (red upright triangles),−68.43 km s^{-1} (yellow upside down triangles), −68.82 km s^{-1} (black diamonds), −69.35 km s^{-1} (green squares), −70.54 km s^{-1} (blue circles). The individual flares are enumerated 1−8.

Table 1. Information of individual 6.7 GHz methanol maser velocity channels. Average peak-to-peak time difference, and standard deviation in parentheses, for each velocity channel is presented. The period for each velocity channel is determined using a Lomb−Scargle periodigram method and standard deviation of all five values is used as the error and shown in parentheses.

Velocity Channel (km s^{-1})	Period Peak-to-peak (days)	Period Lomb−Scargle (days)	Ratio of decay to onset
−70.54	94(6)	92.9	1.6
−69.35	93(10)	90.3	1.1
−68.82	96(12)	95.7	1.4
−68.43	96(14)	94.7	1.5
−67.11	93(8)	92.9	1.8
Average	94(3)	93.5(2.0)	1.5(0.2)

masers are found within ∼ 20″ of each other. They were weak, <20 Jy, and showed little variability (Caswell et al. 1995a,b). The average flux density since discovery in 1991 (MacLeod et al. 1992) until the last reported observation in 2011 (Green, Caswell & McClure-Griffiths 2015) is $S_{6.7} = 17.5 \pm 2.5$ Jy.

G323.46−0.08 was observed several times at 6.7 GHz since it was discovered in 1991 October 01 when it was reported as a single maser at $\upsilon = -67$ km s^{-1} with $S_{6.7}$(Peak) $= 16 \pm 3$ Jy (MacLeod et al. 1992). Single-dish observations in 1994 May (Caswell 1997) and 2009 April (Green et al. 2012a) reported maximum flux densities less than 20 Jy in a velocity range $-68.5 \le \upsilon \le -66.0$ km s^{-1} and $\upsilon_{peak} = -67.0$ km s^{-1}. Ground-state 1665/7 MHz OH maser emission is reported by Caswell & Haynes (1987) in $\upsilon = -72$ to -64.5 km s^{-1}. Likewise, Caswell (1997) found a similar velocity range for 6030/5 MHz excited OH masers. The entire velocity range of the methanol maser emission shown in Fig. 1 falls within the range spanned by the associated hydroxyl masers.

Interferometric observations were made in 1994 May (Caswell 1997) and August (Walsh et al. 1998), and 2011 September (Green et al. 2015). Green et al. (2015) stated they found four regions of maser emission: two with excited OH masers only, one with both excited OH and methanol masers, and one with methanol only. The velocity range of the new methanol emission is similar to that of the excited OH masers, $\upsilon \le -69.5$ km s^{-1}, in an area with no previously detected methanol maser emission and ∼0.″7 north of the nearest known methanol maser region.

4.2 Temporal behaviour

The average temporal behaviour of the periodic flares from the selected velocity channels is similar to that reported for G9.62 + 0.20 by Goedhart et al. (2004) in that the flares rise more quickly than they decay. However, it is more like G12.89 + 0.49 (Goedhart et al. 2004) or G339.99−0.43 (Maswanganye et al. 2016) both of which also have no quiescent phase and evidence for periodic flaring is seen across their entire 6.7 GHz velocity extents. It was also reported that the 6.7 GHz methanol masers of G12.89 + 0.49 underwent a strong flaring event (Goedhart et al. 2009). The shorter flare cycle, 93.5 d as compared to 244 d for G9.62 + 0.20, can explain the lack of a quiescent phase at least while the flares are quite strong. In the case of G323.46−0.08, as the flares weakened, a quiescent phase has appeared.

It is not clear which model best describes the cause of the periodicity in this source. van der Walt, Goedhart & Gaylard (2009) suggest that the decay of the maser flare might be due to the recombination of an H II region. The recombining ionized gas resulting in maser emission decay may not have sufficient time to relax to the non-flaring state before the next flare commences. In the later flares seen in Fig. 2 they have weakened and may fully recombine entering a brief quiescent phase strengthening the argument in favour of the CWB model.

The repeating nature of the temporal profile of each flare in each velocity channel suggests that the cause of the variability is external to the masing region (van der Walt et al. 2009). Most maser features associated with G9.62 + 0.20 are non-flaring and all reside within 1300 AU of each other at a distance of 5.2 kpc (Sanna et al. 2015); the flaring features are supposedly superimposed on a hyper-compact H II region. However, Caswell (1997) found that the 6.7 GHz methanol (MMB) masers associated with G323.46−0.08 are superimposed on a background compact H II region (Caswell 1997). It is not clear that the masers reported in Caswell (1997) are the periodically flaring masers reported here. In the CWB model by van den Heever et al. (2019), the methanol masers must be superimposed on the edge of the H II region where the ionization front is expanding and contracting behind (along the line-of-sight) and across the maser spot causing the maser to flare. It is possible that new regions of methanol maser activity are now present along the edge of expanding/contracting ionization front, e.g. new masing regions were reported for NGC 6334I after an accretion event was detected (Hunter et al. 2017a). However, the new masers of NGC 6334I were reported at a significantly different velocity extent than previously detected masers (MacLeod et al. 2018). Conversely, if the masing regions identified in Caswell (1997) include the periodically flaring masers, then our argument in favour of the CWB model is weakened. Also, a compact H II region represents a later epoch of massive star formation. This would imply that there is a periodic maser phase at a later epoch in the massive star formation process or that the phase is longer-lived. It is also possible that a major accretion event has made the protostar unstable and pulsate thereby causing the maser periodicity (Inayoshi et al. 2013); no significant variability was found historically (Caswell et al. 1995a,b). No geometry is required for the pulsating star model to explain why all of the methanol components are varying. The fact that all the maser emission is periodic, shows a developing quiescent phase, and is superimposed on a compact H II region will be important in determining what theoretical model might best explain this periodicity. New interferometric observations may resolve this issue at least for the periodically flaring masers associated with G323.46−0.08.

The average time lag between the peaks reached in the velocity channels $v = -68.43$ and $v = -69.35\,\mathrm{km\,s^{-1}}$, $\sim 12 \pm 8$ d, might be the result of the light travel time between regions experiencing flaring. However, each of the eight flares began at about the same time for each velocity channel. These maser features may simply reside in regions with different physical conditions reacting differently to the background variation of seed photons. In the later flares where the peak flux densities are significantly reduced, see flares 5 to 8 in Fig. 2, no obvious time lags are detected.

Like S255-NIRS3 and NGC 6334I, methanol masers associated with G323.46−0.08 have experienced a significant brightening between 2011 and 2015. Also, it is possible a new region of methanol maser activity has formed in G323.46−0.08, perhaps to the north where the brightest excited OH maser is located, with $v_{\mathrm{peak}} = -70.5\,\mathrm{km\,s^{-1}}$ (Green et al. 2015) or anywhere along the north–south arc of masers. Interferometric observations are required to determine where the new methanol maser emission is occurring. If the methanol masers are in the vicinity of excited OH masers, then perhaps periodicity is present in these excited OH masers; single-dish monitoring is required to test this possibility.

5 SUMMARY AND FUTURE WORK

We report here the discovery of new 6.7 GHz methanol maser emission associated with G323.46−0.08 for $v \leq -68.5\,\mathrm{km\,s^{-1}}$. Monitoring of this source lead us to also report periodic 6.7 GHz methanol masers associated with this massive star-forming region. In all velocity channels where 6.7 GHz methanol maser emission is present each exhibit periodic variations. We determine the periodicity of these masers is 93.5 ± 2.0 d. We propose a common background variable source drives this periodicity.

We suggest that G323.46−0.08 may have experienced a similar event to that reported in S255-NIRS3 and NGC 6334I; all velocity channels experienced a significant increase in emission after 2009 April. The strongest emission in the velocity channel $v = -68.35\,\mathrm{km\,s^{-1}}$ reported as $\sim$500 Jy in 2015 declined by a factor of $\sim$50 in the intervening 17 months before monitoring began. We predict new region(s) of 6.7 GHz methanol maser activity will be detected associated with G323.46−0.08 but we are unable to definitively state whether they will be regions associated with those originally reported. We have begun monitoring the associated 1.665 and 6.035 GHz OH masers, 12.2 GHz methanol masers, and 22.2 GHz water masers associated with G323.46−0.08 and will continue to monitor the 6.7 GHz masers. We propose that interferometric observations will be made to help us better characterize this new unique periodic methanol maser.

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