Variability monitoring of the hydroxyl maser emission in G12.889+0.489

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ABSTRACT
Through a series of observations with the Australia Telescope Compact Array we have monitored the variability of the ground-state hydroxyl maser emission from G12.889+0.489 in all four Stokes polarization products. These observations were motivated by the known periodicity in the associated 6.7-GHz methanol maser emission. A total of 27 epochs of observations were made over 16 months. No emission was seen from either the 1612- or 1720-MHz satellite line transitions (to a typical five sigma upper limit of 0.2 Jy). The peak flux densities of the 1665- and 1667-MHz emission were observed to vary at a level of ~20 per cent (with the exception of one epoch which dropped by ≤40 per cent). There was no distinct flaring activity at any epoch, but there was a weak indication of periodic variability, with a period and phase of minimum emission similar to that of methanol. There is no significant variation in the polarized properties of the hydroxyl, with Stokes $Q$ and $U$ flux densities varying in accord with the Stokes $I$ intensity (linear polarization, $P$, varying by ≤20 per cent) and the right and left circularly polarized components varying by ≤33 per cent at 1665 MHz and ≤38 per cent at 1667 MHz. These observations are the first monitoring observations of the hydroxyl maser emission from G12.889+0.489.

Key words: masers – stars: formation.

1 INTRODUCTION
A site of hydroxyl maser emission, G12.889+0.489, initially found in a search towards IRAS 18089−1732 (Cohen, Baart & Jonas 1988), was also found to be a prominent methanol maser at 6.7 GHz (Menten 1991). The variability of the methanol was identified by Caswell, Vaile & Ellingsen (1995) and led to the extensive monitoring of Goedhart, Gaylard & van der Walt (2004) and the discovery of periodicity (Goedhart et al. 2009). 6.7-GHz methanol masers exclusively trace the formation of high-mass stars and are hence closely studied to gain insight into the largely unknown processes of high-mass star formation. The discovery of periodicity in the methanol maser emission indicates a periodic variation in the inputs of the maser emission process which has significant implications for both the mechanism of maser emission and the nature of high-mass star formation, indicating periodic processes such as the interaction of winds from binary pre-main-sequence high-mass stars (e.g. van der Walt, Goedhart & Gaylard 2009).

Goedhart et al. (2009) found intensity variations in the methanol emission with a period of nearly 30 d that appeared stable, although variations from cycle to cycle in the peak amplitude of the flare were apparent. The flaring features peaked anywhere within an 11-d window, but the phase of the minima was stable. An amplitude variation with the same period is present in features at different velocities and at both 6.7- and 12.2-GHz transitions. Delays of up to six days were found between individual 6.7-GHz features and a one-day delay was found between the 12.2- and 6.7-GHz flares at the same velocities.

Hydroxyl observations since the discovery of the maser by Cohen et al. (1988) have included the positioning observations of Caswell (1998) and Argon, Reid & Menten (2000), and a detailed polarization study by Szymczak & Gérard (2009). Apparent variations in total intensity exceed 20 per cent, but intervals between observations were typically longer than one year and precise comparison is not possible with the significantly different instrumentation. Observations with the Parkes radio telescope (Caswell et al., in preparation) measured the hydroxyl emission in 2004 and 2005, finding peak flux densities of 8 Jy at 1665 MHz and 1.8 Jy at 1667 MHz. The Parkes spectra are in agreement at the two epochs to within 10 per cent and similar values were obtained by Szymczak & Gérard (2009) in observations made in 2003. Although the amplitudes have shown some variation, the velocities of the features are consistent over all previous observations.

The majority (~80 per cent) of hydroxyl masers in regions of high-mass star formation have associated methanol maser emission (Caswell 1998), with many sites exhibiting a close spatial coincidence, implying a common masing gas and pumping source. Models of maser pumping suggest that both species are pumped by infrared emission from dust surrounding the high-mass pre-main-sequence object (e.g. Moore, Cohen & Mountain 1988; Cragg, Sobolev & Godfrey 2005; Gray 2007). Hence, there...
Table 1. Details of observations. ‘–’ mark observations where data were unusable. The first observation, denoted by ‘imaging’, was a synthesis imaging observation as discussed in the text.

| Epoch | Gregorian Date | Modified Julian Date | Array config. | Integration time (min) | 1612 (mJy) | 1665 (mJy) | 1667 (mJy) | 1720 (mJy) |
|-------|----------------|----------------------|---------------|------------------------|------------|------------|------------|------------|
|       |                |                      |               |                        |            |            |            |            |
| imaging | 2010-05-20    | 553 36.5             | 6C            | 32                     | 57         | 64         | 49         | 64         |
| 1     | 2010-05-24    | 553 40.5             | 6C            | 40                     | 44         | 59         | 49         | 56         |
| 2     | 2010-06-03    | 553 63.5             | 6C            | 40                     | 34         | 35         | 42         | 41         |
| 3     | 2010-06-07    | 553 67.5             | 6C            | 40                     | 69         | 42         | 39         | 58         |
| 4     | 2010-06-10    | 553 70.5             | 6C            | 40                     | 32         | 41         | 34         | 39         |
| 5     | 2010-06-14    | 553 74.5             | 6C            | 40                     | 34         | 34         | 34         | 44         |
| 6     | 2010-06-18    | 553 78.5             | 6C            | 70                     | 29         | 32         | 33         | 41         |
| 7     | 2010-06-27    | 553 87.5             | 6C            | 60                     | 38         | 40         | 49         | 42         |
| 8     | 2010-06-29    | 553 89.5             | 6C            | 40                     | 50         | 51         | 57         | 65         |
| 9     | 2010-07-02    | 553 92.5             | 6C            | 40                     | –          | 55         | 49         | –          |
| 10    | 2010-07-04    | 553 94.5             | 6C            | 40                     | 45         | 46         | 53         | 51         |
| 11    | 2010-07-08    | 553 98.5             | 1.5D          | 45                     | 40         | 62         | 62         | 45         |
| 12    | 2010-07-15    | 554 05.5             | EW352         | 40                     | 200        | 137        | 141        | 259        |
| 13    | 2010-07-18    | 554 08.5             | EW352         | 40                     | 184        | 219        | 131        | 254        |
| 14    | 2010-07-21    | 554 11.5             | EW352         | 45                     | 113        | 90         | 91         | 102        |
| 15    | 2010-07-27    | 554 17.5             | H168          | 80                     | 52         | 53         | 57         | 57         |
| 16    | 2010-07-29    | 554 19.5             | H168          | 45                     | 56         | 61         | –          | 68         |
| 17    | 2010-08-01    | 554 22.5             | H168          | 40                     | 82         | 90         | 91         | 96         |
| 18    | 2010-08-05    | 554 26.5             | H168          | 72                     | 46         | 66         | 55         | –          |
| 19    | 2011-08-26    | 558 12.5             | 6B            | 40                     | 33         | 37         | 36         | 36         |
| 20    | 2011-08-27    | 558 13.5             | 6B            | 40                     | 42         | 37         | 36         | 38         |
| 21    | 2011-08-29    | 558 15.5             | 6B            | 40                     | 34         | 39         | 39         | 35         |
| 22    | 2011-08-30    | 558 16.5             | 6B            | 40                     | 37         | 41         | 35         | 35         |
| 23    | 2011-08-31    | 558 17.5             | 6B            | 40                     | 33         | 35         | 37         | 35         |
| 24    | 2011-09-01    | 558 18.5             | 6B            | 40                     | 48         | 39         | 34         | 36         |
| 25    | 2011-09-02    | 558 19.5             | 6B            | 40                     | 43         | 38         | 43         | 39         |
| 26    | 2011-09-03    | 558 20.5             | 6B            | 40                     | 31         | 37         | 34         | 35         |

is an expectation that any variability in emission of one species will correlate with variability in the other. Early evidence for hydroxyl maser variability (e.g. Robinson, Goss & Manchester 1970) was followed by several more focused variability studies (e.g. Sullivan & Kerstholt 1976; Clegg & Cordes 1991), but these showed no clear periodicity of hydroxyl masers in star-forming regions. More recent investigations of possible common flaring behaviour between the methanol and the ground-state hydroxyl masers have been inconclusive (e.g. MacLeod & Gaylard 1996), but correlated variability of excited-state hydroxyl with methanol (Al-Marzouk et al. 2012) and formaldehyde with methanol (Araya et al. 2010) has been found recently. With methanol emission from G12.889+0.489 established to be periodic in nature, we were motivated to initiate monitoring observations of the associated hydroxyl emission.

2 OBSERVATIONS

Observations were made with the Australia Telescope Compact Array (ATCA), commencing with a full synthesis image on 2010 May 20 consisting of four cuts of 10 min spread over eight hours. This was followed by 26 epochs over 1.5 yr with typical integration times of 40 min on source. These observations were divided into two groups: the first with one to two observations per week for ∼10 weeks, the second with one observation approximately every 24 h for seven days. Observations were centred at 1612.2310 MHz, 1665.4018, 1667.3590 MHz and 1720.5300 MHz, corrected for the motion of the local standard of rest. The ATCA calibrator 1830−210 was used for phase calibration for the first group of observations and the ATCA calibrator 1829−207 for the second group (with positional uncertainties of <0.15 and <0.01 arcsec, respectively). Both groups used the primary ATCA flux density calibrator PKS 1934−638, with flux densities bootstrapped to this (with a resultant systematic uncertainty of <2 per cent). All observations were made with the new Compact Array Broadband Backend (Wilson et al. 2011), adopting the CFB 1M-0.5k mode (2048 channels over 1 MHz giving 0.5-kHz channel spacings), obtaining all four polarization products. The velocity channel separations were 0.091, 0.088, 0.088 and 0.085 km s⁻¹ for the 1612-, 1665-, 1667- and 1720-MHz transitions, respectively. The full listing of the observations and noise levels is given in Table 1. Antenna 4 was not used for epochs 7 to 18 due to the upgrade of the low-frequency (1–3 GHz) receiver. Observations were made within the local sidereal time range 14:30 to 22:00 h and predominantly in the 6-km array configurations (6B and 6C), but eight epochs were observed with compact configurations (see Table 1 for details). There were no systematic variations in flux density for the observations with the short baseline (compact) array configurations compared with the long baseline (6-km) configurations. The data were reduced and processed with the MIRIAD software package using standard techniques (Sault & Killeen 2004). Following the positioning observation, spectral profiles were obtained with the task UVSPEC and a time series of Gaussian fits determined through fitting a Gaussian in the spectral domain with χ² minimization for each epoch.
3 RESULTS

The position of the strongest emission at 1665 and 1667 MHz from the initial (full synthesis imaging) observation was found to be RA(J2000) $18^h 11^m 51.45$ and Dec.(J2000) $-17^\circ 31' 29.7''$ with a positional error of $\leq 0.4$ arcsec. This is coincident (to within the errors) with an earlier ATCA measurement (Caswell 1998) and with a Very Large Array measurement at 1665 MHz (Argon et al. 2000). Position estimates of the strongest methanol features at 6.7 and 12.2 GHz (Caswell 2009; Xu et al. 2011) are $18^h 11^m 51.40$, $-17^\circ 31' 29.6''$ and $18^h 11^m 51.396$, $-17^\circ 31' 29.91''$, respectively, a nominal offset from the hydroxyl of 0.7 arcsec $\pm 0.6$ arcsec. At an astrometric distance of 2.3 $\pm 0.1$ kpc (Xu et al. 2011), this small angular offset would correspond to a physical offset of 1500 au ($\sim 10$ light days). We found that the peak flux densities of the main features in both the 1665- and 1667-MHz transitions showed variability, but by less than 20 $\pm$ 3 per cent from the maximum peak flux density with the exception of one epoch in the 1665-MHz transition and one epoch in the 1667-MHz transition, where emission dropped by 31 $\pm$ 3 and 38 $\pm$ 3 per cent, respectively. The averaged spectra and extrema for the ground-state transitions are given in Fig. 1. The average spectrum is the combination of the median value at each spectral channel taken from the values of all epochs of observations. Similarly the extrema are the highest and lowest values for a spectral channel across all epochs, excluding the furthest outliers (to avoid bias by any extreme noise fluctuations). The Gaussian fits used to construct the time series had errors of 0.01 km s$^{-1}$ for both of the 1665-MHz features (found to be centred at 33.01 and 35.26 km s$^{-1}$) and $<0.01$, 0.02, 0.02 and 0.03 km s$^{-1}$ for the four (weaker) 1667-MHz features (at 33.46, 32.82, 34.79 and 31.53 km s$^{-1}$, respectively). Any variation in the fitted peak velocity was within the errors and no systematic shift in the peak velocity of features was found. There was also no consistent shift in velocity for the epochs which had minima in the flux density. The time series for the main features at each frequency are shown in Figs 2 and 3. No emission was detected from the satellite line transitions at any of the epochs (to $\sim 0.2$ Jy $\sigma$ limit). Additionally, for the last eight epochs the excited-state transitions at 6030 and 6035 MHz were observed, but also did not have any detected emission (to $\sim 0.2$ Jy $5\sigma$ limit).

A Lomb–Scargle periodogram (following the algorithm of Press & Rybicki 1989) was used to search for any periodicity in each of the six features shown in the time series, with results displayed in Fig. 4. At low significance there is a suggestion of a 0.03 to 0.04 cycles d$^{-1}$ peak which would correspond to a period of 25 to 30 d, coincident with the period of the 6.7-GHz methanol maser. It is most noticeable in the 33.0 and 35.3 km s$^{-1}$ peak features of the 1665-MHz transition which have power peaks at 0.034 cycles d$^{-1}$ (29.4 d). This power peak was not affected by excluding the two highest flux density epochs from the periodogram. In contrast, after exclusion of the two lowest flux density epochs, the power peak was less evident for the 33 km s$^{-1}$ feature and absent for the other features. This implies, comparable to the methanol, that the suggested periodicity is predominantly in the minima of the emission.

The features in the 1665-MHz Stokes I spectrum at 31.6, 33.0 and 34.0 km s$^{-1}$ were found on average to be 91 , 55 and 70 per cent linearly polarized, respectively. The features in the 1667-MHz Stokes I spectrum at 31.5, 32.9, 33.4 and 34.8 km s$^{-1}$ were found on average to be 84 , 72 , 23 and 2 per cent linearly polarized, respectively. The averaged and extreme spectra of the linear polarization are shown in Fig. 5. The right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP) features, derived from RHCP $= (I + V)/2$ and LHCP $= (I - V)/2$, are shown in Fig. 6. Spectra from Argon et al. (2000) taken in 1993 January, limited to 1665 MHz, and only RHCP and LHCP, show the same features as our spectra but typically at half the intensity. Archival unpublished data from Parkes confirm the lower intensity near that epoch (1993 July). The Argon et al. Very Large Array (VLA) data suggest that some spectral features are spatial blends of several nearby components (although not well resolved by the VLA beam), but the separations of all major features in the velocity range 32 to 36 km s$^{-1}$ are less than 0.15 arcsec.

In our monitoring sessions, of all the circularly polarized features, the RHCP features were found to vary by up to 33 $\pm$ 3 per cent from the maximum and the LHCP features by up to 38 $\pm$ 3 per cent from the maximum. Our measurement of the feature found at 31.6 km s$^{-1}$ in both the 1665- and 1667-MHz transitions is of particular note. It is an outlying feature both in velocity and spatially. The 1665-MHz emission has an offset position of RA(J2000) $18^h 11^m 51.53$ and Dec.(J2000) $-17^\circ 31' 27.3''$ [the 1667 MHz RA(J2000) $18^h 11^m 51.54$ and Dec.(J2000) $-17^\circ 31' 28.6''$]. Both transitions have high fractional linear polarization. The polarization position angle of this feature at 1665 MHz varies between 6 $^\circ$ and 16 $^\circ$ with a median angle of 12 $^\circ$. The averaged spectrum has a

![Figure 1. Range in flux density variation in Stokes I for G12.889+0.489 at each ground-state hydroxyl transition. The solid line is the averaged spectrum, constructed from the median value from all epochs for each spectral channel. The two dashed lines show the net extreme values (having excluded the most extreme noise-biased values).](https://academic.oup.com/mnras/article-abstract/425/2/1504/1196955)
position angle of $12^\circ$. The position angle of this feature at 1667 MHz varies between $0^\circ$ and $10^\circ$ with a median angle of $5^\circ$. The averaged spectrum has a position angle of $5^\circ$. The error in the position angle due to noise is estimated to be $5^\circ$.

4 DISCUSSION

As stated in the introduction, the methanol maser counterpart of G12.889+0.489 has quasi-periodic flaring at both 6.7 and 12.2 GHz (Goedhart et al. 2009). There are time delays between the two frequencies and the flaring period occurs anywhere within an 11-d window, but minima are regular (with a period of 29.5 d). This periodic variability was ascribed by the authors as likely being due to variation in the radio continuum emission (the seed photons for the maser emission) or to variation in the infrared emission (pumping the maser). We note that, extrapolating from the work of Goedhart et al. (2009), our range of epochs should have included flaring activity and minima (three minima should occur in the first session of observations and the second session should be wholly between two adjacent minima). Goedhart et al. show that the methanol exhibits flux density variations of 60 to 70 per cent. With the exception of one epoch, the hydroxyl emission we measure varies by only 20 per cent. The current data have no strong indication of periodicity, but do suggest at low significance variation with a comparable period to the methanol, with the minimum at MJD 553 79 nominally agreeing with the extrapolated minima epoch of the methanol. Further observing epochs will be required to make firm conclusions on the periodicity of variation.

The polarization properties we observe are comparable to the work of Szymczak & Gérard (2009), who measured the full polarization properties at 1665 and 1667 MHz with all four Stokes parameters with the Nancay telescope in 2003. They found linear polarization of 87.3 and 76.7 per cent in two 1665-MHz features at 31.59 (the kinematic and spatial outlier mentioned previously) and 32.76 km s$^{-1}$, respectively, and both features had low circular polarization at the epoch of the observations (14.6 and 8.9 per cent, respectively). If the persistently strong features, 1665-MHz RHCP at 35.3 km s$^{-1}$ and the 1665-MHz LHCP at 33.1 km s$^{-1}$, are a Zeeman pair, the implied magnetic field strength is +3.7 mG. This is corroborated with the 1667-MHz emission where the brightest RHCP at 34.8 km s$^{-1}$ and the brightest LHCP feature at 33.4 km s$^{-1}$ also give an implied magnetic field strength of +3.7 mG.

A qualitative explanation for some of the methanol maser sources with long periods (e.g. 9.62$^{+0.20}_{-0.10}$ and 188.95$^{+0.89}_{-0.78}$) is that of a colliding wind binary system (van der Walt et al. 2009; van der Walt 2011), a system which could periodically alter either the seed flux or pumping mechanism of the maser emission (although for the example sources in the work of van der Walt et al. the seed flux is more likely in view of their long periods). The hydrogen winds of the binary pre-main-sequence stars either heat the circumstellar dust or cause additional ionization of hydrogen surrounding the forming high mass star. In the case of G12.889+0.489, an upper limit to continuum emission of 1 mJy has been established (Walsh et al. 1998), but if there is a very weak region of ionized hydrogen providing the seed photons, the possible offset location of the hydroxyl relative to the methanol (by $\sim1500$ au) may place the hydroxyl sufficiently far away so as to be minimally affected, explaining the lower prominence of periodicity in the hydroxyl emission. On the other hand, the optical depth at the lower frequency of the hydroxyl emission could be such that the seed radiation does not respond as
**Figure 3.** Time series for the two brightest features at 1665 MHz and the four brightest features at 1667 MHz in Stokes $I$ for the second group of observations, spanning 8 d. Errors are the combination of the rms noise and the errors in the Gaussian fit in the spectral domain. The solid grey vertical line shows an epoch of the extrapolated minima of methanol emission from Goedhart et al. (2009).

An aspect of this model is that we may expect to see rotation of polarization angle of features with the passing of shocks associated with the colliding winds (and the flares of maser emission). As mentioned in Section 3 we have one feature at $31.6 \text{ km s}^{-1}$ with high linear polarization, but this does not show significant variation in polarization angle (variation is within the noise).

An alternative theory to account for periodicity in masers has been put forward by Araya et al. (2010). This was proposed to explain the periodicity in formaldehyde and methanol maser emission in IRAS 18566+0408 through circumbinary disc accretion. In this model the accreting material heats the dust, increasing the photons pumping the maser. In this variety of model, an offset location could also be sufficient to diminish the effect on the hydroxyl emission.

An important aspect of G12.889+0.489 is the shortness of the periodicity (29.5 d), which any model for the system must account for. Additionally, the suggestion that the minima of hydroxyl emission may coincide with the minima of the methanol implies that the periodicity may arise from a quenching or suppression mechanism, rather than flaring. Continued monitoring of this maser source across the various maser transitions is required to provide further insight.

**5 SUMMARY**

We have obtained the first monitoring observations of G12.889+0.489 with the ATCA, finding variability at the level of 20 per cent on time-scales of days. Despite no distinct flaring characteristics, the hydroxyl variability showed possible periodicity similar to that of methanol, with the minimum of emission at the same phase. It will require a full programme of sensitive daily monitoring of G12.889+0.489 at the ground-state hydroxyl transitions to fully test the apparent periodic behaviour in the variability, and thus assess whether the mechanism causing periodicity in the methanol maser counterpart is shared with the hydroxyl.
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