DISCOVERY OF 6.035 GHz HYDROXYL MASER FLARES IN IRAS 18566+0408

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ABSTRACT

We report the discovery of 6.035 GHz hydroxyl (OH) maser flares toward the massive star-forming region IRAS 18566+0408 (G37.55+0.20), which is the only region known to show periodic formaldehyde (4.8 GHz H₂CO) and methanol (6.7 GHz CH₃OH) maser flares. The observations were conducted between 2008 October and 2010 January with the 305 m Arecibo Telescope in Puerto Rico. We detected two flare events, one in 2009 March and one in 2009 September to November. The OH maser flares are not simultaneous with the H₂CO flares, but may be correlated with CH₃OH flares from a component at corresponding velocities. A possible correlated variability of OH and CH₃OH masers in IRAS 18566+0408 is consistent with a common excitation mechanism (IR pumping) as predicted by theory.

Key words: H II regions – ISM: individual objects (IRAS18566+0408) – ISM: molecules – masers – radio lines: ISM – stars: formation

Online-only material: color figure, machine-readable table

1. INTRODUCTION

Maser lines from different molecular species, including water, hydroxyl, and methanol, are common observational phenomena associated with massive star-forming regions. The relation between different types of masers found around young stellar objects may yield important information about the evolutionary state of regions (e.g., Szymczak & Gérard 2004; Brenn et al. 2010). Moreover, excitation of different maser species may occur within overlapping ranges of physical conditions, thus, masers of different species originating from the same volume of gas can help narrow the physical conditions of specific regions (e.g., Edris et al. 2005; see also Fish 2007).

Masers from hydroxyl (OH) transitions are the prototypical example of astrophysical masers; indeed, astrophysical masers were first detected in OH (Weaver et al. 1963). The ground state lines at 1612, 1665, 1667, and 1720 MHz are the most commonly observed OH masers; however, masers from a number of exited states have also been detected (e.g., Baudry & Desmurs 2002). OH masers have been found in a variety of environments, from galactic star-forming regions (e.g., Argon et al. 2000; Fish et al. 2005) and supernova remnants (e.g., Brogan et al. 2000), to extragalactic environments (e.g., Darling & Giovanelli 2002; Baan et al. 1982). In the case of massive star-forming regions, many OH masers are found associated with compact H II regions (e.g., Fish et al. 2005), however a significant fraction of OH masers are also associated with earlier phases of massive star formation (e.g., Forster & Caswell 2000).

One maser line that is studied in massive star-forming regions corresponds to the F = 3− − 3+ hyperfine transition of the ²Π₁/₂ (J = 5/2) excited state of OH at a frequency of 6.035 GHz (Knowles et al. 1976). First detected by Yen et al. (1969) toward W3(OH), maser lines from this transition have been found associated with massive star formation in galactic and extragalactic environments (Caswell & Vaile 1995; Caswell 1995). The 6.035 GHz OH line shows a large flux density range in galactic maser sources, from more than 100 Jy to ~0.1 Jy (e.g., Baudry et al. 1997). The line widths are narrow; for example, most of the 6.035 GHz OH masers in the sample of Baudry et al. (1997) were more narrow than 0.35 km s⁻¹ (some were narrower than 0.18 km s⁻¹) with no correlation between line width and peak intensity. Many 6.035 GHz maser lines show a high fraction of circular polarization consistent with Zeeman pairs, allowing for the measurement of magnetic field strengths (e.g., Caswell & Vaile 1995; Caswell et al. 2009; Fish & Sjouwerman 2010). Most models agree that gas densities ≥ 10⁷ cm⁻³ are necessary to enable the population inversion (e.g., Baudry et al. 1997; Cragg et al. 2002).

The 6.035 GHz OH masers often exhibit variability on timescales of months to years. Nevertheless, some maser sources have shown relatively constant spectral profiles, in particular, the OH maser in W3(OH) showed almost no variability over two decades (Baudry et al. 1997).

A remarkable characteristic of 6.035 GHz OH masers is their association with 6.7 GHz CH₃OH masers. For example, Caswell (1997) reported interferometric observations of a sample of 30 massive star-forming regions and found multiple examples of groups of 6.035 GHz OH and 6.7 GHz CH₃OH masers coincident within ~1′′ (see also Etoka et al. 2005). The association between these two maser species is particularly interesting in the context of the discovery of periodic CH₃OH maser flares in massive star-forming regions (Goedhart et al. 2004, 2009; van der Walt et al. 2009; van der Walt et al. 2011; Szymczak et al. 2011). Among the periodic maser flare sources known, IRAS 18566+0408 (a massive star-forming region at a distance of 6.7 kpc) is unique because it exhibits periodic flares of 6.7 GHz CH₃OH and 6 cm H₂CO masers (Araya et al. 2010). Here, we present the results of monitoring observations of the 6.035 GHz OH maser in IRAS 18566+0408.
2. OBSERVATIONS AND DATA REDUCTION

The observations were conducted with the 305 m Arecibo Telescope\(^8\) in Puerto Rico between 2008 October and 2010 January. We monitored the 6.035 GHz main excited-state line of hydroxyl (OH; \(v_0 = 6035.0932\) MHz, \(^2\Pi_{3/2}, J = 5/2, F = 3 − 3\)\(^9\)) toward the young massive stellar object IRAS 18566+0408 (pointing position, R.A. = 18^h^59^m^00.988, decl. = +04°12′15.6″, J2000) for a total of 24 epochs. We used the WAPP spectrometer, two orthogonal linear polarization setup, nine level sampling, 3.125 MHz (155 km s\(^{-1}\)) bandwidth, and 2048 channels per polarization, resulting in a final channel separation of 1.53 kHz (0.076 km s\(^{-1}\)). We observed in position-switching (on-off) mode, with integration times of 1–5 minutes on-source per run. The reference (off) position was selected to cover the same hour-angle and declination as the on-source observations, with angular offsets of 2–6 minutes east from the R.A. of the source. The center bandpass LSR velocity was set to 85 km s\(^{-1}\). Data reduction was done in IDL using specialized reduction routines provided by the Arecibo Observatory. After checking for consistency, we averaged the polarizations and subtracted linear baselines. The spectra were imported to CLASS\(^10\) to measure line parameters and for further analysis.

The cryogenics system of the C-Band High receiver of the Arecibo Telescope was not always available, thus, the system temperatures ranged from \(\sim 30\) K (when the cryogenics were operational) to more than 200 K (when the cryogenics were turned off). This resulted in rms noise in the spectra of \(\sim 20\) mJy (with cryogenics) to more than 100 mJy (without cryogenics).

The calibrator B1857+129 was observed in every run for pointing and system checking (1 minute on-source observations). The pointing was better than 15″ (typically better than 10″). We measured a telescope beam size of \(\sim 44″\) (at 6.6 GHz), and a gain of \(\sim 6\) K Jy\(^{-1}\).

We also observed the 6.035 GHz OH maser source G34.26+0.15 (pointing position, R.A. = 18^h^53^m^18.5^s^, decl. = +01°14′59″, J2000; 40 km s\(^{-1}\) LSR central bandpass velocity) in most of the runs with the same spectral setup as the IRAS 18566+0408 observations. We observed G34.26+0.15 for system checking; in particular, as a positive control for detection of OH masers with the warm C-Band High receiver. We detected several OH masers in G34.26+0.15 (see Table 1). We also found weak (\(< 50\) mJy) broad (FWHM \(\gtrsim 10\) km s\(^{-1}\)) OH absorption in G34.26+0.15. The absorption line was almost undetectable in the unsmeared spectra, but after substantial smoothing (channel width of \(\sim 1\) km s\(^{-1}\)), we were able to detect the absorption in most runs. After averaging all data and smoothing to a channel width of 1.2 km s\(^{-1}\) (6 mJy rms), the line parameters of the absorption line were \(S_0 = -65\) mJy, \(V_{LSR} = 50\) km s\(^{-1}\), and FWHM = 18 km s\(^{-1}\). Absorption overlapping with maser lines of the 6.035 GHz transition has been detected toward other massive star-forming regions (e.g., Baudry et al. 1997).

The upper panel of Figure 1 shows a typical spectrum of the 6.035 GHz OH maser in G34.26+0.15, obtained on 2008 November 18. None of the maser components detected in G34.26+0.15 showed clear variability (see Table 1). As an example, the light curves of the two brightest components are shown in the lower panel of Figure 1. For both velocity components, \(\chi^2\) fits (with weighting for the uncertainty of each point) show that the individual data points are consistent within 3σ of the linear fits. In other words, we did not detect significant short-term variability (flares) in any of the G34.26+0.15 maser components.

As part of our monitoring program, we also observed the OH transitions at 6.016 GHz, 6.030 GHz, and 6.049 GHz with the same spectral configuration of the 6.035 GHz observations. No lines were detected toward IRAS 18566+0408 at the same rms levels of the 6.035 GHz data (see Table 2).

3. RESULTS

We detected 6.035 GHz OH maser emission in IRAS 18566+0408 in 4 out of 24 observational epochs. This is the first detection of 6.035 GHz OH maser emission in IRAS 18566+0408. We list in Table 2 the rms of each run and the line parameters of the detections. The maser at 85.8 km s\(^{-1}\) was detected at all four epochs. At the first of the four epochs (2009 March 11), a second maser was detected at 89.0 km s\(^{-1}\). The flux densities of the 85.8 km s\(^{-1}\) maser in the two orthogonally linear polarizations were consistent within 2.6σ in all runs, whereas the 89.0 km s\(^{-1}\) maser showed consistent flux density between the two polarizations within 3.6σ. There could be some linearly polarized emission at \(\lesssim 3\)σ levels; our data are not suitable for a more precise determination.\(^11\) The telescope was not configured to record all four Stokes parameters; hence, it is not possible to extract information about the degree of circular polarization from the data.

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\(^9\) JPL spectra line catalog (Pickett et al. 1998) accessed through the database for astronomical spectroscopy (http://spectraloague.net).

\(^10\) CLASS is part of the GILDAS software package developed by IRAM.

\(^11\) There are examples of sources with significant 6.035 GHz OH linear polarization (e.g., Knowles et al. 1976).
Figure 1. System checking observations of G34.26+0.15. The upper panel shows the 6.035 GHz OH spectrum from the 2008 November 18 observations (0.15 km s\(^{-1}\) channel width). As an example, the light curves of the two brightest maser components are shown in the lower panel. The dashed lines are linear fits of the components in the form \(S_\nu(t) = a(t - JD_{2,454,754.40}) + b\), where \(a = 0.15 \pm 0.07 \text{ mJy day}^{-1}\) and \(b = 413 \pm 16 \text{ mJy}\) for the 58.3 km s\(^{-1}\) line, and \(a = 0.00 \pm 0.05 \text{ mJy day}^{-1}\) and \(b = 341 \pm 11 \text{ mJy}\) for the 60.9 km s\(^{-1}\) line. The length of the error bars is three times the rms noise of the respective spectrum. Data points with large error bars correspond to observations conducted with no cryogenics.

Figure 2 shows the spectra obtained on 2009 March 11 (detection of two lines), 2009 August 15 (non-detection), and 2009 November 7 (detection of a single line). It is clear from the figure that the flux density of the maser varies with time; specifically, we detected two flare events. We found no significant change in line width or peak velocity of the 85.8 km s\(^{-1}\) maser.

4. DISCUSSION

We show in the upper panel of Figure 3 the light curve of the 6.035 GHz OH maser component at 85.8 km s\(^{-1}\), including the four detections and all 3\(\sigma\) upper limits. We detected two flare events: the first a single epoch detection in 2009 March and the second a series of three detections from 2009 September through 2009 November. Given the null detections before and after each of these flares obtained when the cryogenics were operational (low rms), we can restrict the two events to a maximum duration of approximately eight and five months, respectively.

As mentioned in the introduction, IRAS 18566+0408 is the only region known to exhibit quasi-periodic 6 cm H\(_2\)CO and 6.7 GHz CH\(_3\)OH flares. In the lower three panels of Figure 3 we show the light curves of two 6.7 GHz CH\(_3\)OH maser components and the light curve of the 6 cm H\(_2\)CO maser (data from Araya et al. 2010; E. D. Araya et al. in preparation). While the 87.8 km s\(^{-1}\) CH\(_3\)OH maser component shows very similar flares to those of the H\(_2\)CO maser, the flares of the CH\(_3\)OH maser component at 86.4 km s\(^{-1}\) are not as well defined, and the flares may have a delay of 1–3 months with respect to H\(_2\)CO. We note that in addition to the two (weak) flare events of the 86.4 km s\(^{-1}\) CH\(_3\)OH maser shown in Figure 3, two other flare events of this velocity component have been detected (Araya et al. 2010). Thus, there is evidence that the 86.4 km s\(^{-1}\) CH\(_3\)OH maser shows quasi-periodic flares, although not as clearly defined or as regular as the H\(_2\)CO and 87.8 km s\(^{-1}\) CH\(_3\)OH maser lines.

As seen in Figure 3, the 85.8 km s\(^{-1}\) OH maser reported in this work has a similar variability behavior to the 86.4 km s\(^{-1}\) CH\(_3\)OH maser. Thus, the light curves of the two CH\(_3\)OH masers associate the 86.4 km s\(^{-1}\) maser with the OH, and the 87.8 km s\(^{-1}\) maser with the H\(_2\)CO. The velocity difference between the two methanol masers is quite small (1.4 km s\(^{-1}\)) but they are found at opposite ends of the CH\(_3\)OH maser arc imaged by Araya et al. (2010), with a projected separation of \(\sim 6000\) AU along the arc.

Given the similar variability profiles and LSR velocities, both OH and 86.4 km s\(^{-1}\) CH\(_3\)OH masers could originate from the same volume of gas. Based on the data reported here, we cannot reliably measure the time delay between the peak of the OH and H\(_2\)CO flares, but we can rule out simultaneous flares (see Figure 3). Our data are consistent with a delay of 1–3 months between the OH and H\(_2\)CO flares just as observed between the H\(_2\)CO and 86.4 km s\(^{-1}\) CH\(_3\)OH maser. Interferometric observations and a longer monitoring program are needed to confirm the association between the 86.4 km s\(^{-1}\) CH\(_3\)OH and 85.8 km s\(^{-1}\) OH masers.
Figure 2. Detection of 6.035 GHz OH maser flares in IRAS 18566+0408. The first panel shows the two maser components detected on 2009 March 11. No maser was detected on 2009 August 15 (middle panel), and a single maser was detected on 2009 November 7. The cryogenics were operational in all three epochs shown in the figure.

Table 2
Line Parameters of the 6.035 GHz OH Masers in IRAS 18566+0408

| Observation Date | rms (mJy) | $S_0$ (mJy) | $V_{LSR}$ (km s$^{-1}$) | Width (km s$^{-1}$) | $\int S_0 \, dv$ (mJy km s$^{-1}$) |
|------------------|-----------|-------------|-------------------------|--------------------|--------------------------------|
| 2008 Oct 14      | 9.0       | ...         | ...                     | ...                | ...                            |
| 2008 Oct 23      | 26        | ...         | ...                     | ...                | ...                            |
| 2008 Nov 2       | 25        | ...         | ...                     | ...                | ...                            |
| 2008 Nov 6       | 21        | ...         | ...                     | ...                | ...                            |
| 2008 Nov 10      | 22        | ...         | ...                     | ...                | ...                            |
| 2008 Nov 14      | 22        | ...         | ...                     | ...                | ...                            |
| 2008 Nov 18      | 25        | ...         | ...                     | ...                | ...                            |
| 2008 Nov 22      | 24        | ...         | ...                     | ...                | ...                            |
| 2008 Dec 2       | 22        | ...         | ...                     | ...                | ...                            |
| 2008 Dec 9       | 25        | ...         | ...                     | ...                | ...                            |
| 2009 Jan 10      | 91        | ...         | ...                     | ...                | ...                            |
| 2009 Mar 11      | 17        | 158         | 85.85 (0.01)           | 0.29 (0.04)        | 48.7 (4.8)                     |
|                   |           |             | 106                     | 0.20 (0.06)        | 23.0 (5.2)                     |
| 2009 Apr 14      | 139       | ...         | ...                     | ...                | ...                            |
| 2009 May 15      | 137       | ...         | ...                     | ...                | ...                            |
| 2009 Jun 12      | 86        | ...         | ...                     | ...                | ...                            |
| 2009 Jun 27      | 113       | ...         | ...                     | ...                | ...                            |
| 2009 Jul 3       | 91        | ...         | ...                     | ...                | ...                            |
| 2009 Jul 9       | 261       | ...         | ...                     | ...                | ...                            |
| 2009 Jul 16      | 160       | ...         | ...                     | ...                | ...                            |
| 2009 Aug 15      | 20        | ...         | ...                     | ...                | ...                            |
| 2009 Sep 30      | 22        | 251         | 85.82 (0.01)           | 0.30 (0.02)        | 80.7 (5.0)                     |
| 2009 Nov 7       | 23        | 158         | 85.86 (0.01)           | 0.24 (0.04)        | 40.9 (5.0)                     |
| 2009 Nov 29      | 27        | 134         | 85.82 (0.02)           | 0.23 (0.05)        | 32.2 (5.4)                     |
| 2010 Jan 7       | 19        | ...         | ...                     | ...                | ...                            |

Note. 1σ statistical errors from the fit are shown in parentheses.

High angular resolution observations have shown an association between 6.035 GHz OH and 6.7 GHz CH$_3$OH masers. For example, Caswell (1997) found that both maser species often show emission at similar velocities and coexist in elongated structures with projected sizes of ~2000 to 6000 AU. The discovery of 6.035 GHz OH flares and possible correlated variability with 6.7 GHz masers brings a new (time-dependent) aspect to the relation between these maser species.

The physical mechanism causing the periodic flares of CH$_3$OH masers detected in a number of sources (e.g., Goedhart et al. 2004) is still unclear. However, van der Walt (2011; see also van der Walt et al. 2009) reproduced remarkably well the flare profiles observed toward G9.62+0.20E with a colliding wind binary (CWB) model, in which the flares are caused by a change in the background radio continuum modulated by the orbital parameters of a young massive binary. Based only on the detection of 6.035 GHz OH flares reported here, we cannot address whether the CWB model is applicable in the case of IRAS 18566+0408. Nevertheless, as discussed by Araya et al. (2010), the H$_2$CO and CH$_3$OH maser flares in IRAS 18566+0408 are likely caused by a change in the maser gains and not by a change in the background continuum. In this scenario, the maser gains are modulated by some periodic phenomenon external to the maser regions (possibilities include periodic accretion events onto a central protobinary system). If the CH$_3$OH flares are caused by a change in the maser gain, then correlated variability with OH masers would indicate a similar excitation mechanism for 6.035 GHz OH and 6.7 GHz CH$_3$OH masers. Indeed, theoretical models have shown that the excitation mechanism of class II CH$_3$OH masers is infrared pumping.
Figure 3. Light curve of 6.035 GHz hydroxyl, 6.7 GHz methanol, and 4.8 GHz formaldehyde masers in IRAS 18566+0408. The error bars are three times the rms noise; three times the rms is also shown as upper limits for the non-detections (triangles). The upper limit of the 2009 July 9 observations (which is outside of the axis range) is 0.8 Jy. The upper panel shows the light curve of the OH maser component at the velocity 85.8 km s\(^{-1}\). The bottom panels show two 6.7 GHz CH\(_3\)OH and the 6 cm H\(_2\)CO maser light curves from Araya et al. (2010). 

(e.g., Cragg et al. 2005), and that the population inversion of 6.035 GHz OH masers is also predominantly due to infrared radiation (Gray 2001; see also Pihlström et al. 2008; Baudry et al. 1997).\(^{12}\)

The possibility that the maser flares are caused by gain variability due to changes in the infrared radiation field can qualitatively explain some of the differences between the various light curves. For example, a 70 day delay of the OH flare following the H\(_2\)CO flare could result from the time required for pumping photons to propagate between the H\(_2\)CO and the OH maser regions. A 70 lt-day distance corresponds to 12,000 AU, which is of the same order as the 6000 AU projected size of the CH\(_3\)OH maser arc reported by Araya et al. (2010).

If the 87.8 km s\(^{-1}\) CH\(_3\)OH and the H\(_2\)CO maser regions are closer to the central source of infrared field variability, then an exponential amplification of a change in the infrared pumping rate would result in a clear flare signature. On the contrary, maser regions located at greater distances would show a less clear flare signature due to geometrical dilution of the variable radiation field, optical depth effects, and a greater relative contribution of other sources of pumping photons. It is worth mentioning that the models of Cragg et al. (2002) predict that the 6035 MHz OH masers appear in zones of high density and high OH column density, but relatively low gas temperature. In fact, at kinematic temperatures > 70 K, the line would eventually be quenched. This suggests that H\(_2\)CO masers may occur in warmer gas closer to the central energy source than the excited OH masers. However, the exact circumstances will become clear only after interferometric mapping of the OH maser and the dense molecular gas is conducted.

Interferometric observations are also required to investigate the relation between the masers discussed here and ground state OH emission in the region, which has been detected with single-dish telescopes (Szymczak & Gérard 2004). For example, Edris et al. (2007) mapped the 1665 and 1667 MHz masers in this source using the NRAO Green Bank Telescope (GBT; \(8^\prime\) beam size). Although the LSR velocities of the OH ground state masers are similar to the CH\(_3\)OH, H\(_2\)CO, and 6.035 GHz OH masers, the positions of the ground state OH masers obtained with the GBT do not correspond to the H\(_2\)CO maser position within the quoted errors (Edris et al. 2007).

5. SUMMARY

Using the 305 m Arecibo Telescope in Puerto Rico, we detected two flare events of the 6.035 GHz OH maser toward the massive star-forming region IRAS 18566+0408. This region is the only known source of periodic H\(_2\)CO and CH\(_3\)OH maser flares. Despite poor sampling of the OH light curve during the flares, our observations clearly show that the peaks of the OH flares were not simultaneous with the H\(_2\)CO peaks, but rather had delays of approximately a month or more. In contrast, the peaks of the OH flares appear to be correlated with a 6.7 GHz CH\(_3\)OH maser at corresponding LSR velocity. Our results strengthen the association between 6.035 GHz OH and 6.7 GHz CH\(_3\)OH masers found in previous observational work and are consistent with a similar inversion mechanism of

\(^{12}\) However, collisional excitation may also have a prominent role as indicated by Cragg et al. (2002).
these maser species (radiative excitation). The delay between the H$_2$CO and OH flares might be caused by the difference in arrival times of pumping photons between the two maser regions. Consequently, interferometric observations will be the next natural step in order to pinpoint the exact location of the OH masers. A more extended monitoring program is also needed to confirm the association between the OH and CH$_3$OH masers.

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