QUASI-PERIODIC FORMALDEHYDE MASER FLARES IN THE MASSIVE PROTOSTELLAR OBJECT IRAS 18566+0408

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ABSTRACT

We report results of an extensive observational campaign of the 6 cm formaldehyde maser in the young massive stellar object IRAS 18566+0408 (G37.55+0.20) conducted from 2002 to 2009. Using the Arecibo Telescope, the Very Large Array, and the Green Bank Telescope, we discovered quasi-periodic formaldehyde flares (P ≈ 237 days). Based on Arecibo observations, we also discovered correlated variability between formaldehyde (H2CO) and methanol (CH3OH) masers. The H2CO and CH3OH masers are not spatially coincident, as demonstrated by different line velocities and high angular resolution MERLIN observations. The flares could be caused by variations in the infrared radiation field, possibly modulated by periodic accretion onto a young binary system.

Key words: ISM: individual objects (IRAS 18566+0408) – ISM: molecules – masers – radio lines: general

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

1. INTRODUCTION

IRAS 18566+0408 (G37.55+0.20) is a massive star-forming region located at a kinematic distance of 6.7 kpc (Araya et al. 2004). The region is visible in Spitzer GLIMPSE infrared data (Benjamin et al. 2003) and shows an outflow that has been detected in CO, SiO, and the 4.5 μm IRAC band (Araya et al. 2007c; Beuther et al. 2002; Zhang et al. 2007). At smaller scales, Very Large Array (VLA, NRAO) observations reveal a radio continuum source, possibly an ionized jet (Araya et al. 2007c). The bolometric luminosity of the object is approximately 10^5 L☉ (equivalent to an O8 zero-age main-sequence (ZAMS) star; Zhang et al. 2007; Sridharan et al. 2002).

IRAS 18566+0408 harbors one of the few known 6 cm formaldehyde (H2CO) masers in the Galaxy (Araya et al. 2008). The H2CO maser in IRAS 18566+0408 showed a strong flare in 2002 (Araya et al. 2007b). Here, we report results of a monitoring program of the H2CO maser intended to investigate the nature of the flare.

2. OBSERVATIONS

2.1. Arecibo Observations

Using the 305 m Arecibo Telescope, we monitored the 6 cm H2CO maser (J_k,k = 1_1→0_0, ν_o = 4829.6594 MHz) in IRAS 18566+0408. The pointing position was R.A. = 18°59′09″.98, decl. = 04°12′15″.6 (J2000; Araya et al. 2005). The monitoring program had three intervals: 2006 May to 2007 April, 2008 January to 2008 May, and 2008 October to 2009 November. A total of 48 runs were conducted (Figure 1; see Table 1, online version).

We observed 5 minutes on-source integration per scan with typically one or two scans per run in a position switching mode. Observations prior to 2008 June were conducted with the Interim autocorrelator, dual linear polarization, 1.56 MHz bandwidth, and 2048 channels (0.047 km s^-1 per channel). The data reduction was done using the CLASS program. The WAPP spectrometer was used since 2008 October, with 3.125 MHz bandwidth and 2048 channels (0.095 km s^-1 channel width). The calibration of the WAPP data was done in IDL using Arecibo-IDL routines. The data were smoothed to a channel width of 0.19 km s^-1. We observed B1857+129 in most of the runs to check the pointing and measure the telescope gain. The pointing error was less than 12″ in general, and the gain varied between 5 and 9 Jy per channel. The system temperature was typically 26 K. The Arecibo half-power beamwidth (HPBW) is ≈1′ at 4860 MHz. We detected no significant variability of the linewidth or the peak velocity of the maser.

The 6.7 GHz CH3OH line (L_i = 51→60 A^+, ν_o = 6668.5192 MHz) was also observed with integration time on-source between 1 and 2 minutes. The same Interim and WAPP configurations described above were used for the CH3OH observations. The spectra were smoothed to a channel width of 0.07 km s^-1 (see Figure 2). The Arecibo HPBW is ≈0′′72 at 6600 MHz. A detailed description of all CH3OH observations

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13 The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.
14 CLASS is part of the GILDAS software package developed by IRAM.
2.2. VLA Observations

We used the VLA to observe the 6 cm H$_2$CO maser in IRAS 18566+0408 at seven epochs after 2006 (see Table 1, online version). The pointing positions were R.A. = $18^h59^m10^s.10$, decl. = $04^\circ12^\prime12^\prime\prime.0$ (J2000) for the A and B array observations, and R.A. = $18^h59^m10^s.00$, decl. = $04^\circ12^\prime25^\prime\prime.0$ (J2000) for the C array observations. The seven observations, together with the two previous VLA observations from the literature (Araya et al. 2007), are shown in Figure 1. We used a 2IF mode with a bandwidth of 1.56 MHz (97 km s$^{-1}$) and 255 channels (6.104 kHz, 0.38 km s$^{-1}$ channel width). We observed 3C286 and 3C48 as flux density calibrators, with assumed flux densities of 7.52 Jy and 8.192 Jy (0.094 km s$^{-1}$ channel width), and dual circular polarization. The system temperature was ≃ 20 K in all runs. After checking for radio frequency interference and consistency between the two circular polarizations, the data were averaged and smoothed to a channel width of 0.38 km s$^{-1}$. All data reduction was done with the NRAO software package AIPS following standard spectral-line procedures. The H$_2$CO maser positions measured with the VLA (A configuration) in 2003 and 2007 agree within 50 mas.

2.3. GBT Observations

The Green Bank Telescope (GBT) was used on five dates in 2008 to observe the H$_2$CO maser (see Table 1, online version). The GBT H$_2$CO flux density measurements from 2008, together with prior the GBT observations from the literature (Araya et al. 2007b), are shown in Figure 1.

The quasar J1851+005 was observed for pointing and focus adjustments. The pointing corrections were less than 8$''$. The observations of 2008 April 7 and 15 were done in a standard position switching mode with integration time on-source between 5 and 10 minutes. The observations in 2008 May and October were conducted in a frequency switching mode with integration time on-source between 10 and 30 minutes. We used the GBT spectrometer, with a bandwidth of 12.5 MHz (775 km s$^{-1}$), 8192 channels (0.094 km s$^{-1}$ channel width), and dual circular polarization. The system temperature was ≃ 20 K in all runs. After checking for radio frequency interference and consistency between the two circular polarizations, the data were averaged and smoothed to a channel width of 0.38 km s$^{-1}$. All data reduction was done in IDL using the GTBIDL procedures.15

2.4. MERLIN Observations

High angular resolution observations of the 6.7 GHz CH$_3$OH masers in IRAS 18566+0408 were conducted with Multi-Element Radio Linked Interferometer Network (MERLIN)16 on 2008 April 3, 4, and 20 to determine the location of the CH$_3$OH masers with respect to the H$_2$CO maser. The pointing position was R.A. = $18^h59^m09^s.98$, decl. = $04^\circ12^\prime15^\prime\prime.6$ (J2000). The CH$_3$OH masers were observed with a bandwidth of 0.5 MHz and 255 channels (1.96 kHz, 0.088 km s$^{-1}$ channel width). Each observing run lasted approximately 10 hr. The quasar 1904+013 was observed as a complex gain calibrator with a broadband (13 MHz) during approximately 2 minutes for every ≃ 7 minutes observation of the CH$_3$OH masers. We observed 3C84 in the narrow (0.5 MHz) and wide (13 MHz) setups to determine the solutions needed to transfer the phase calibration.

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15 http://gbtidl.nrao.edu/
16 MERLIN is a National Facility operated by the University of Manchester at Jodrell Bank Observatory on behalf of STFC.

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**Table 1**

| Date       | $S_v$ (mJy) | rms (mJy) | Telescope |
|------------|-------------|-----------|-----------|
| 2002 Jul 27| 28.5        | 1.3       | Arecibo   |
| 2002 Sep 18| 38.3        | 3.2       | VLA-CnB   |
| 2002 Nov 9 | 118         | 10        | GBT       |
| 2002 Nov 15| 146.2       | 8.2       | GBT       |
| 2002 Dec 16| 28.3        | 1.2       | Arecibo   |
| 2003 Sep 5 | 38.4        | 5.0       | VLA-A     |
| 2003 Oct 12| 22.1        | 2.2       | Arecibo   |
| 2004 Oct 16| 23.9        | 3.6       | GBT       |
| 2005 Jul 17| 36.9        | 7.7       | GBT       |
| 2006 May 25| 18.4        | 2.2       | Arecibo   |

Notes. Data prior 2006 is from Araya et al. (2004, 2005, 2007a, 2007b). The synthesized beams of our VLA observations in A, B, and C configurations were approximately 0.75, 1.7, and 5", respectively.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Together with results from an ongoing monitoring program will be reported in the future.

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**Figure 1.** Light curve of the H$_2$CO maser flux density in IRAS 18566+0408. Data obtained with Arecibo, VLA, and GBT are shown with different symbols. Measurements before 2006 are from Araya et al. (2007b). The dotted line is an extrapolation of the 2006–2007 Arecibo observations assuming an exponential decay of the flux density and a slow decrease of the flare period (see Section 3). The solid lines are the functions $S_v(t) = A_1 e^{-t/t_{dec}} + A_2 e^{-t/t_{dec}^2}$, where $t_{dec} = 2,454,084$ JD (the date of the 2006 December flare peak), and $A_1$ is 85 and 9.0 for the upper and lower curves, respectively.

(A color version of this figure is available in the online journal.)
3. RESULTS

We detected five new flare events and discovered periodicity (see Figure 1); IRAS 18566+0408 is the only (quasi)periodic H$_2$CO maser system known. The flares have a periodicity of $\sim 237$ days, a duration (at half-maximum) of $\sim 30$ days, and an order of magnitude increase in flux density. The peak flare intensity and maser intensity during the quiescent state show a monotonic decay (Figure 1). Possible causes of the decay include changes in maser pumping and gas motions affecting beaming.

The flares are not strictly periodic. The period derived from the 2006 December and 2008 November flares is $238 \pm 4$ days, and the period derived from the 2006 December and 2008 March flares is $234 \pm 1$ days. The flare of 2009 August was well sampled during the rising part of the flare, but we do not have a good determination of its peak. Assuming that the measurement of 2009 August 15 corresponds to the maximum of the flare, the period would be $244 \pm 4$ days. If the 2002 flares were part of a periodic cycle of outbursts, then the period would be $248 \pm 5$ days (the uncertainties are 3$\sigma$ errors from autocorrelation analysis). Most of the recent flares have a shorter period than the one estimated from the data prior to 2007.

The combined effect of (quasi)periodic flares, monotonic flux density decay, and tendency toward decreasing period as a function of time is exemplified by the dotted line in Figure 1. The dotted line was generated as follows: (1) the light curve from 2006 May to 2007 January was used as a template; (2) the template was extrapolated assuming an exponential decrease in the interval between consecutive flare peaks ($\tau = 237 \times 2^{-j/62}$ days, where $j=1$ for the interval between the 2006 December and 2007 August flares, $j=2$ for the interval between the 2007 August and 2008 March flares, etc.) and an exponential decay in the maser flux density ($S_\nu \propto 2^{-t - t_{\text{ref}}/878}$ mJy, where $t_{\text{ref}}$ is the Julian Date of the 2006 December flare peak). This simple extrapolation (representative fit) based on the 2006–2007 observations roughly reproduces the peak date and variability profile of the flares, as well as the flux density measurements between 2003 and 2005. The flare of 2009 August shows that the period is neither constant nor strictly monotonically decreasing. Nevertheless, the occurrence of the flares has been regular enough to successfully predict the approximate date of the 2008 and 2009 flares to schedule observations. Indeed, the MERLIN observations were scheduled to coincide with the predicted flare of 2008 April (Figure 2).

We also monitored the 6.7 GHz CH$_3$OH transition with Arecibo. The 6.7 GHz CH$_3$OH spectrum shows a group of

![Figure 2. Spectra of the H$_2$CO and CH$_3$OH masers obtained with the Arecibo Telescope on 2006 December 14 (insets). We show the Arecibo Telescope light curves from 2006 May to 2009 November of the H$_2$CO (top panel) and of three CH$_3$OH maser components (middle and bottom panels). The H$_2$CO absorption at 85 km s$^{-1}$ originates from the extended molecular cloud where the massive (proto)star is located. The dates of the MERLIN observations (Figure 3) are marked with vertical lines.](image-url)
nine maser components spread between 78 and 88 km s\(^{-1}\).

Figure 2 shows the H\(_2\)CO and CH\(_3\)OH spectra obtained on 2006 December 14, and the light curve of the H\(_2\)CO maser and three CH\(_3\)OH maser components. We discovered that the CH\(_3\)OH maser component at 87.8 km s\(^{-1}\) (hereafter component 9) shows flares that are similar to the H\(_2\)CO maser flares. Specifically, the peaks of all CH\(_3\)OH (component 9) were simultaneous (within 10 days) to the peaks of the H\(_2\)CO flares. IRAS 18566+0408 is thus the first system where the periodic behavior of the flares could be caused by a variety of astrophysical processes; chief among these are stellar pulsations and binary-induced variability. Some types of pulsating variable stars have periods of hundreds of days (e.g., Eyer & Mowlavi 2008). Nevertheless, the light curves of Figure 2 show that the periodic variability of the other CH\(_3\)OH masers in Section 4, but an in-depth discussion of the variability of all CH\(_3\)OH masers is beyond the scope of this work.

4. DISCUSSION

The velocities of the CH\(_3\)OH maser component 9 and the H\(_2\)CO maser (Figure 2, insets) differ by 8.3 km s\(^{-1}\), and the masers are separated by ~2000 AU (12 light days, 0'32') in projection (Figure 3). Given that the two masers showed simultaneous flares, the origin of the masers is not located in either one of the maser regions, otherwise one component would have always flared before the other. The different variability behavior of the different CH\(_3\)OH components shows that the flares are not caused by a homogeneous and large-scale change in the background radio continuum, e.g., in the flare of 2006, the CH\(_3\)OH component 3 did not show a flare even though it is located in-between the H\(_2\)CO and CH\(_3\)OH masers that showed a flare (compare the position of the masers shown in Figure 3 with the light curves of Figure 2). We therefore find unlikely that the flares are caused by a change in the background radio continuum.

It is also unlikely that the flares are triggered by a propagating sound/density wave or shock front. For example, assuming that the CH\(_3\)OH component 9 and H\(_2\)CO masers are located at the same distance from the source that triggers the variability (explaining simultaneous flares), the minimum distance between the driving source and the masers is ~1000 AU (i.e., masers and driving source located in the plane of the sky; see Figure 3). This minimum distance implies that the travel time of a 10 km s\(^{-1}\) wave from its origin to the maser regions is ≥500 yr, which is far greater than the time scale of the flares (i.e., ~30 days flare duration, ~237 days periodicity). Faster (J-)shocks (100 km s\(^{-1}\) and greater) are unlikely because the molecules would dissociate with the passing of a single shock front (e.g., Hollenbach & McKee 1989; Garay et al. 2002), instead of showing periodic variability. The absence of significant changes in the line peak velocity and linewidth, as well as the smooth decay of the maser emission during the quiescent phase, argues against the J-shock hypothesis.

In contrast, a radiative origin of the flares appears more likely. If the two maser regions are in the plane of the sky with the source of pumping radiation between them (assumed hereafter to be the massive protostar or its surroundings), then the radiation front would take only about six days to reach the maser regions. This travel time provides a better match to the time scales of the flares. In addition, changes in maser gain due to variability of the radiation field are consistent with the excitation mechanism of the Class II CH\(_3\)OH masers (i.e., infrared pumping; Cragg et al. 2005).

Given that the CH\(_3\)OH and H\(_2\)CO masers show correlated variability, the excitation mechanism of the two maser species must be similar. The excitation mechanism of the H\(_2\)CO masers has been a controversial topic (Araya et al. 2006, 2007c; Hoffman et al. 2003); our discovery of the correlated H\(_2\)CO and CH\(_3\)OH masers shows that the excitation mechanism of the H\(_2\)CO masers is probably infrared pumping.

At the observed misalignment between an ionized jet, a Spitzer IRAC 4.5 \(\mu\)m excess, and an SiO outflow could be caused by
precession due to a binary system (Araya et al. 2007; Zhang et al. 2007).

Recently, van der Walt et al. (2009) proposed that the CH$_3$OH flares in G9.62+0.20E (which have a periodicity very similar to the H$_2$CO and CH$_3$OH flares in IRAS 18566+0408) are modulated by variability from a colliding wind binary, responsible for a change in the background radio continuum and/or pumping radiation. Even though such a colliding wind model reproduces the variability of the CH$_3$OH maser flares in G9.62+0.20E, we consider the model unlikely in the case of IRAS 18566+0408. The H$_2$CO flares are not strictly periodic (Figure 1), thus, an additional, stochastic mechanism is implicated. Minor local turbulence could superimpose irregularities on the response to a periodical cause but does not explain the combination of decay and irregularity.

Here, we propose an alternative scenario for the maser flares in IRAS 18566+0408: periodic accretion of circumbinary disk material. This process has been predicted and has observational evidence in the case of some young, low-mass binaries (Artymowicz & Lubow 1996; Jensen et al. 2007; Günther & Kley 2002; Mundt et al. 2010). In this scenario, material from the circumbinary disk is accreted onto the protostars or accretion disks, heating the dust and increasing the infrared radiation field, resulting in higher microwave amplification due to greater maser gain. For example, the smoothed particle hydrodynamics simulations by Artymowicz & Lubow (1996) show that a binary system with mass ratio 0.79 and eccentricity $e = 0.5$ will experience bursts of accretion onto the binary components with a dimensionless time dependence that is quite similar to the H$_2$CO light curve. In a binary with mass ratio $\sim 0.8$ (e.g., a 20 and 16 $M_\odot$ binary) and $e = 0.5$, a periodicity of $\sim 240$ days is expected if the semimajor axis of the most massive component is $\sim 1.1$ AU. The short flare events traced by H$_2$CO and CH$_3$OH masers in IRAS 18566+0408 (this work) and CH$_3$OH masers in G9.62+0.20E (Goedhart et al. 2004) could be caused by an orbital configuration similar to the one discussed above. Less flare-like (more undulated and/or aperiodic) variability seen in other CH$_3$OH maser sources (Goedhart et al. 2004) would be expected from binary systems with lower eccentricities (see Artymowicz & Lubow 1996). That is, the model of Artymowicz & Lubow (1996) could explain not only the time scale for the periodicity, but also the duration of the flaring events, depending essentially on the eccentricity of the binary system. Thus, periodic maser flares could trace the properties of young massive binaries that are actively accreting. Moreover, accretion of circumbinary material may cause mass equalization in massive binaries. For example, in the model of Artymowicz & Lubow (1996), the lower mass component of the binary is the one with a higher accretion rate (see however Günther & Kley 2002).

5. SUMMARY

We detected the first (quasi)periodic H$_2$CO maser flare system. The maser is coincident with a massive protostellar candidate (IRAS 18566+0408). The periodicity of the flares is approximately 237 days. We also detected the 6.7 GHz CH$_3$OH flares that are correlated to the H$_2$CO outbursts. Regardless of whether the H$_2$CO maser flares reported in this work unveil tight massive binaries still undergoing accretion or some other process, our discovery shows that short time-scale changes (weeks to months) in physical conditions surrounding massive protostars are not random, but that underlying (semi)harmonic mechanisms are at work during the process of massive star formation.

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