Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Detection of the longest periodic variability in 6.7 GHz methanol masers with iMet

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Abstract. Long-term monitoring observations of the 6.7 GHz methanol masers by Hitachi 32-m operated by Ibaraki University, which are named as "the Ibaraki 6.7 GHz Methanol Maser Monitor (iMet)", have revealed that the periods of the flux variability of 6.7 GHz methanol masers in the five high-mass star-forming regions G05.900−0.430, G06.795−0.257, G10.472+0.027, G12.209−0.102 and G13.657−0.599 are over 1000 days. These periods are approximately twice the longest known period of 6.7 GHz methanol masers of 668 days for G196.45−1.68. The facts that the flux variation patterns show symmetric sine curves and that the luminosity of the central protostar and periods of maser flux variation are consistent with the expected period-luminosity (PL) relation suggest that the mechanism of maser flux variability of G05.900−0.430, G10.472+0.027 and G12.209−0.102 can be explained by protostellar pulsation instability. From the period-luminosity relation, central stars of these three sources are expected to be very high-mass protostars with a mass of $\sim$40 $M_{\odot}$ and a mass accretion rate of $\sim 2\times10^{-2}$ $M_{\odot}\mathrm{yr}^{-1}$. On the other hand, G06.795−0.257 and G13.657−0.599 have luminosities that are an order of magnitude smaller than that expected from PL relation, and the variation patterns are intermittent, suggesting a variation mechanism of these sources originated from binary system.

Keywords. ISM: masers, stars: formation, stars: massive

1. Introduction

The Class II methanol maser is a well established tracer of high-mass star-forming regions (HMSFRs) and several astronomical masers have presented their characteristic periodic flux variations. Goedhart et al. (2003) first discovered a periodic flux variation of 243.3 d in the 6.7 GHz methanol masers associated with HMSFR G9.62+0.20E. By 2020, 28 periodic methanol maser sources have been reported (Tanabe *et al.* 2023 and references therein). Their periods range from 23.9 d (for G14.23−0.50 reported by Sugiyama et al. 2017) to 668 d (for G196.45−1.68 reported by Goedhart et al. 2004). Several explanations of mechanism for these maser periodicity have been proposed; colliding wind binary (CWB) system (van der Walt 2011), protostellar pulsation (Inayoshi et al. 2013), spiral shock in a circumbinary system (Parfenov & Sobolev 2014), periodic accretion in a circumbinary system (Araya et al. 2010), and eclipsing binary system (Maswanganye et al. 2015). These models can explain the maser flux variations of some sources well, however, there is no clear consensus on the general mechanism of maser periodicity. In this paper, we present the new discovery of periodicity in 6.7 GHz methanol maser source in five HMSFRs, and discuss the mechanism of their flux variability.

2. Observation

Monitoring observations of the 6.7 GHz methanol maser were made with the Hitachi 32m telescope of Ibaraki station, a branch of the Mizusawa VLBI Observatory of

Table 1. List of sources.

Source	R.A. (J2000)	Dec. (J2000)
G05.900−0.430	18 00 40.86	−24 04 20.80
G06.795−0.257	18 01 57.75	−23 12 34.90
G10.472+0.027	18 08 38.20	−19 51 50.10
G12.209−0.102	18 12 40.24	−18 24 47.50
G13.657−0.599	18 17 24.26	−17 22 12.50

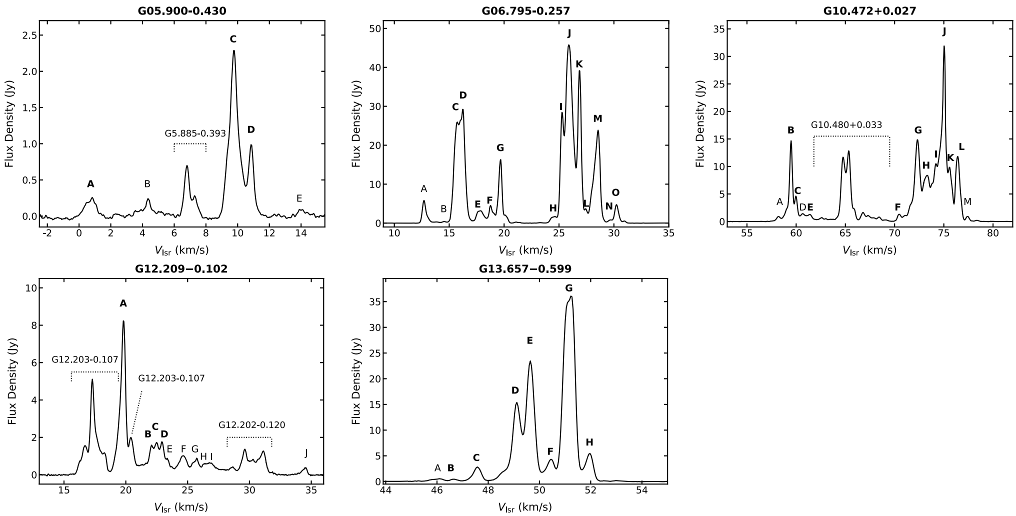

Figure 1. Averaged spectra of the 6.7 GHz methanol maser associated with five sources. Labels indicate each velocity feature and for features in bold, the periodicity is detected in this paper.

the National Astronomical Observatories Japan (NAOJ), operated jointly by Ibaraki University and NAOJ (Yonekura et al. 2016). The data presented in this paper are as a part of the Ibaraki 6.7 GHz Methanol Maser Monitor (iMet) program†.

Monitoring observations began on 2013 Jan. The cadence of observations is once per every ∼10 d from the start of the monitoring observations to 2015 Aug., and once per every ∼5 d from 2015 Sep. to the present. Observations after 2014 May were made at about the same azimuth and elevation angle to minimize intensity variations due to systematic telescope pointing errors. The half-power beam width of the telescope is $\sim 4.6'$ with the pointing accuracy better than $\sim 30''$ (Yonekura et al. 2016). The coordinates of target sources adopted in our observations are summarized in Table 1. The reference for these coordinates is Green et al. (2010). Observations are made by using a position-switching method. The OFF position is set to ΔR.A. = + 60′ from the target source. The integration time per observation is 5 minutes for both the ON and OFF positions. After averaging over 3 channels, the 1-sigma root-mean-squares noise level is approximately 0.3 Jy and the velocity resolution is 0.13 km s^{-1}.

3. Result

The averaged spectra integrated all scans of each source are presented in Figure 1. We detected several velocity features in each source and in Figure 1, features shown in bold, the periodicity is detected in this paper. The periodicity was estimated by employing the

† http://vlbi.sci.ibaraki.ac.jp/iMet/

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Table 2. Detected periodicity and protostellar parameter.

Source	v_{lsr} (km s^{-1})	P (d)	Luminosity* $\log(L/L_\odot)$	Distance (kpc)	Distance† ref
G05.900−0.430	9.77	1265 (266)	4.8	5.9	A
G06.795−0.257	19.68	1002 (120)	4.0	3.0	A
G10.472+0.027	59.48	1652 (346)	5.7	8.6	B
G12.209−0.102	22.97	1280 (239)	5.5	13.4	A
G13.657−0.599	49.12	1258 (213)	4.4	4.5	A

*Urquhart et al. (2018). †A; Reid et al. (2016) estimated the shapes of the spiral arm by the Bayesian approach. B; Sannna et al. (2014) estimated by trigonometric parallax.

Lomb-Scargle (LS) periodogram method (Lomb 1976 and Scagle 1982). The LS method can give us false detection of a period, and thus we adopted the false alarm probability functions which is probability of judging the value corresponding to noise as a signal. In this paper, if the peak value of the power spectrum is larger than the 0.01% false alarm level, we decided the obtained period is reliable. The error of periods obtained by the LS method are estimated as the half width of half maximum (HWHM) of each peak in the periodogram.

In this paper, we present the time series and LS periodogram for one velocity feature which has the period with the largest LS power in each source. The results of periodic analysis are summarized in Table 2 and Figure 2. For all the sources, the detected periods are over 1000 days. Harmonic peaks are seen in the periodogram for G06.795−0.257 and G13.657−0.599. The flux variation pattern is classified into two types: continuous (G05.900−0.430, G10.472+0.027, and G12.209−0.102) and intermittent (G06.795−0.257 and G13.657−0.599).

4. Discussion

Inayoshi et al. (2013) proposed that the high-mass protostars with large mass accretion with rates of $\dot{M}_* \gtrsim 10^{-3}$ $M_\odot$ yr^{-1} become pulsationally unstable. This instability is caused by the κ mechanism in the He^+ layer. The luminosity of the protostars varies periodically and as the temperature of the surrounding material rises to and falls from a temperature suitable for maser pumping, resulting in that the maser fluxes increase and decrease. In this model, the flux variation pattern of the associated maser is expected to be continuous, thus the protostellar pulsation instability model may well describe the variation in G05.900−0.430, G10.472+0.027, and 12.209+0.102. Inayoshi et al. (2013) also derived the period-luminosity (PL) relation

$$\log \frac{L}{L_\odot} = 4.62 + 0.98 \log \frac{P}{100 \text{ days}}, \tag{1}$$

where L is luminosity of the protostar and P is period expected from the maser variation.

Figure 3 plots the estimated periods versus protostellar luminosity for each source. The solid line represents the PL relation given by equation (1). In figure 3, the central protostar luminosity and periods of maser flux variation are roughly consistent with the expected PL relation suggest that the mechanism of maser flux variability of G05.900−0.430, G10.472+0.027 and G12.209−0.102 can be explained by protostellar pulsation instability. If the pulsationally unstable model is applied for these sources, the protostellar mass and mass accretion rate for these three sources estimated from the detected period using the equations (2) and (4) in Inayoshi et al. (2013) are $M_* \sim 4 \times 10$ $M_\odot$ and $\dot{M}_* \sim 2 \times 10^{-2}$ $M_\odot$ yr^{-1}, respectively.

On the other hand, the sources which has a variable pattern with intermittent (G06.795−0.257 and G13.657−0.599) show an order of magnitude smaller than those luminosity expected from PL relation. Thus a variation mechanism of these sources may

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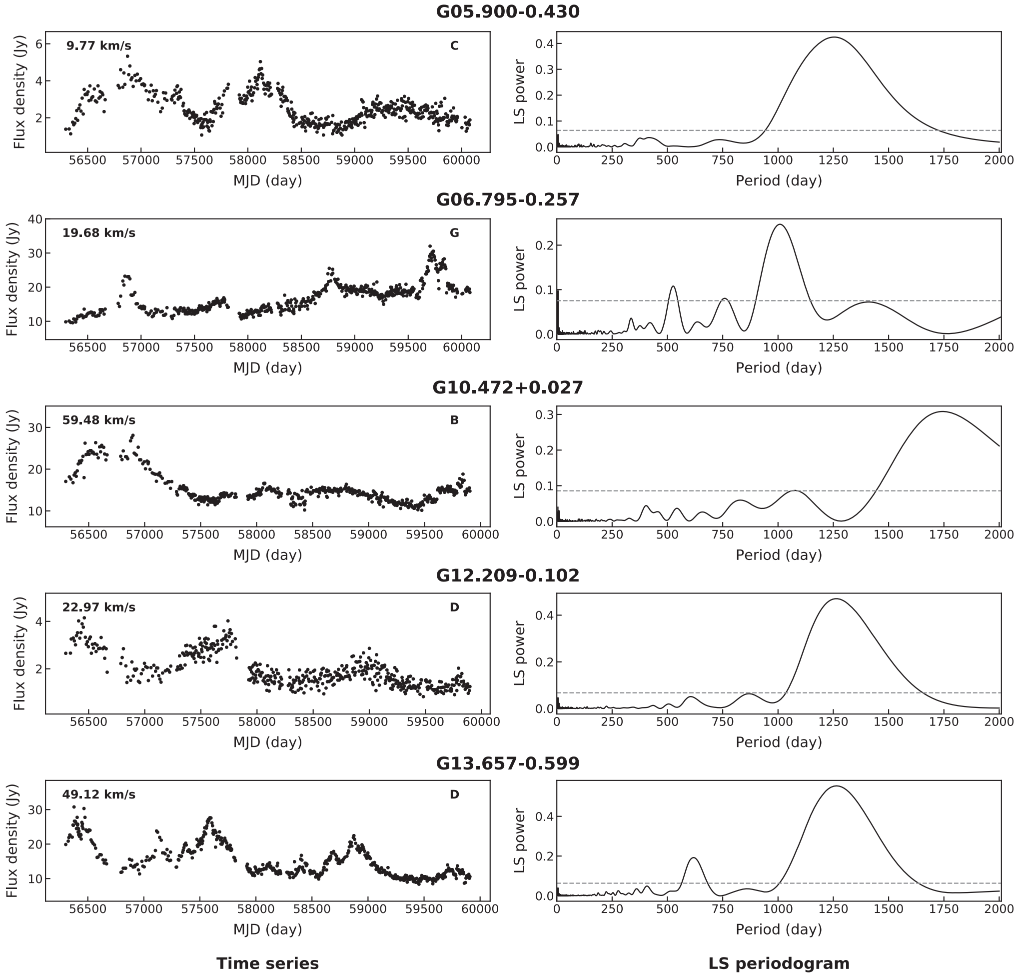

Figure 2. Time series and results of periodic analysis for each source. The first column show the time series of flux density of each velocity feature. We excluded the data points whose flux densities are less than 3 σ. The second column show the LS power spectra plots. The dotted lines in second column represent the 0.01% false alarm probability levels. In left panels for each source, labels of alphabet represent velocity features shown in Figure 1.

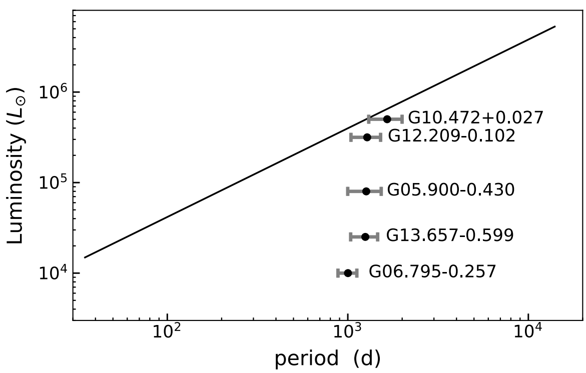

Figure 3. Protostellar luminosity versus estimated maser periods. The solid line represents the PL relation given by Inayoshi et al. (2013). According to Urquhart et al. (2018), the total uncertainty of luminosity due to measurement error and SED fitting is ∼100%, which does not include uncertainty of distance of sources.

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from binary system. VLBI observations with high spatial resolution will lead to a better understanding of the nature of these sources.

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