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Long-term and highly frequent monitor of 6.7 GHz methanol masers to statistically research periodic flux variations around high-mass protostars using the Hitachi 32-m

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Abstract. We initiated a long-term and highly frequent monitoring project toward 442 methanol masers at 6.7 GHz (Dec > -30 deg) using the Hitachi 32-m radio telescope in December 2012. The observations have been carried out daily, monitoring a spectrum of each source with intervals of 9–10 days. In September 2015, the number of the target sources and intervals were redesigned into 143 and 4–5 days, respectively. This monitoring provides us complete information on how many sources show periodic flux variations in high-mass star-forming regions, which have been detected in 20 sources with periods of 29.5–668 days so far (e.g., Goedhart *et al.* 2004). We have already obtained new detections of periodic flux variations in 31 methanol sources with periods of 22–409 days. These periodic flux variations must be a unique tool to investigate high-mass protostars themselves and their circumstellar structure on a very tiny spatial scale of 0.1–1 au.

Keywords. Stars: massive — stars: formation — masers.

1. Introduction

Periodic flux variability of the methanol masers was first discovered in G 009.62+00.19 E, and the periodic flux variability of the methanol masers has been detected in 20 sources so far (including quasi-periodic ones), with their periods from 29.5 to 668 days (e.g., Goedhart *et al.* 2004). Patterns of the variability have been classified into two categories: continuous, and intermittent with a quiescent phase. Such periodic flux variability was also observed in other masers, e.g., water in IRAS 22198+6336 (Szymczak *et al.* 2016), and the variations were synchronized with those of methanol masers in the same sources. The periodic variability, therefore, must be a common phenomenon at around high-mass (proto-)stars, but appears in limited conditions. Because of their short timescale, the periodic variability is potentially important in studying high-mass protostars (HMPSs) and their circumstellar structure on spatial scales of 0.1–1 au, which are estimated under the condition of Keplerian rotation. These area must be the most important to understand the evolutionary track of HMPSs through the mass accretion rates toward onto the stellar surface (Hosokawa & Omukai 2009), however it is impossible to spatially resolve such an area at the distance of HM star-forming regions even by using a future instrument as the extended ALMA (Atacama Large Millimeter/submillimeter Array).

Four models have been proposed for interpretations of the periodic flux variability, possibly caused by global variation on a central engine: a colliding-wind binary (van der Walt 2011), a stellar pulsation (Inayoshi *et al.* 2013), a circumbinary accretion disk (Araya *et al.* 2010), and a rotation of spiral shocks within a gap region in a circumbinary disk (Parfenov & Sobolev 2014). The first model is based on changes in the flux of seed photons, while the remaining three ones are based on changes in the temperature of dust grains at the masing regions.

In previous observations of the methanol masers, flux monitoring for statistically understanding the number of periodic sources was conducted toward only ∼200 sources (e.g., Goedhart *et al.* 2004; Szymczak *et al.* 2015), although all the methanol maser sample consists of more than 1,000 sources (e.g., Breen *et al.* 2015, and references therein).

2. Observations

We initiated a long-term, highly frequent, and unbiased monitoring project using the Hitachi 32-m radio telescope (Yonekura *et al.* 2016) on 30 December, 2012 toward a large sample of the 6.7-GHz methanol masers (442 sources) with declination > -30 deg. In order to cover a wide range of periods from shorter than one month to longer than one year, we designed the observations as follows: until August 2015, the observations were carried out daily, monitoring a spectrum of each of the 442 sources with intervals of 9–10 days. Since September 2015, the number of the target sources were reduced to 143. Sources with modulation index (the standard deviation divided by the averaged value of flux densities), larger that 0.3 were selected. The observations had been continued daily, achieving the intervals in each source of 4–5 days to complete the research for periodic sources with periods shorter than one month. The latter data, combined with the former ones, are used to search for periodic sources with periods longer than one year. For details on the backend setup used for the observations, see Sugiyama *et al.* (2017).

3. Results

By February 2017, we had detected many sources in which periodic flux variations would have been expected, such as G 036.70+00.09 in right-panel of Fig. 1. The 6.7 GHz methanol masers in G 036.70+00.09 presented a periodic variation with continuous pattern in multiple spectral features. To quantitatively evaluate periodicity, we adopted the Lomb-Scargle periodogram (Lomb 1976; Scargle 1982). This is the most reliable method to search for periodicity in flux variations of the methanol masers (Goedhart *et al.* 2014).

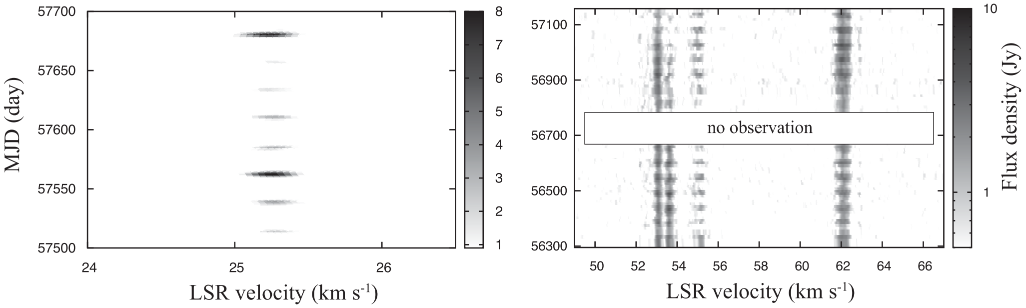

Figure 1. Dynamic spectrum of the 6.7 GHz methanol maser in periodic sources newly detected in our monitor. The horizontal and vertical axis is the local standard of rest velocity and the observation modified julian day, respectively. Gray color shows the flux density. (Left) G 014.23−00.50 with a period of 24 days. (Right) G 036.70+00.09 with a period of 53 days.

Here, we regard an oversampling factor of 4 and frequencies with false-alarm probability $\leqslant 10^{-4}$ as significant, as in Goedhart *et al.* (2014). Other two criteria to certify as a periodic source were set as follows: evaluated periods were accepted in the case of being detectable at least three periodic cycles during the entire observation period of ~1550 days, meaning detectable periods were shorter than ~520 days; the signal to noise ratio at the maximum timing was beyond 7.

As a result, we detected periodic flux variations in 42 sources, and for those 31 sources newly detected to host periodic variations, the periods of 22–409 days. Dynamic spectra as examples of the newly detected periodic sources, G 014.23−00.50 and G 036.70+00.09 with a period of 24 and 53 days (Sugiyama *et al.* 2017; Sugiyama *et al.* 2015), are shown in Fig. 1. These sources were classified into the pattern of periodic variability as intermittent and continuous, respectively.

These periodic sources are compiled with previous ones as histogram in terms of periods in Fig. 2. Left-panel in Fig. 2 shows the histogram classified into duration of monitor for the methanol masers: previous, our Hitachi but from September 2015, and Hitachi using all the data. On the other hand, right-panel in Fig. 2 is the same but classified into patterns of the periodic variability: continuous (sinusoidal), intermittent, and continuous but in a part of spectral features. This classification in terms of the pattern must be useful to distinguish which theoretical models are suitable to cause each periodic variation (van der Walt *et al.* 2016), such as the continuous pattern can be caused by the kappa mechanism in a stellar pulsation of HMPSs (Inayoshi *et al.* 2013).

On the basis of these data base for the periodic flux variations, we will verify a period-luminosity (P-L) relation, which is theoretically predicted in the stellar pulsation model. The P-L relation must be a unique tool to indirectly understand physical parameters, such as a mass, radius, and an accretion rate on the stellar surface, impossible to be reached by any observational instruments. In order to better constrain our results, we have initiated another related project of parallax measurements with VERA (VLBI Exploration of Radio Astrometry) for periodic sources, in which the source distance had not been measured by parallax. These measurements are necessary to precisely estimate the luminosity of sources causing periodic flux variations. We have also proceeded with the Hitachi 32-m monitor since June 2017 to complete periodic sources with periods up to two years, and the monitor will be finished by the beginning of 2019 yr.

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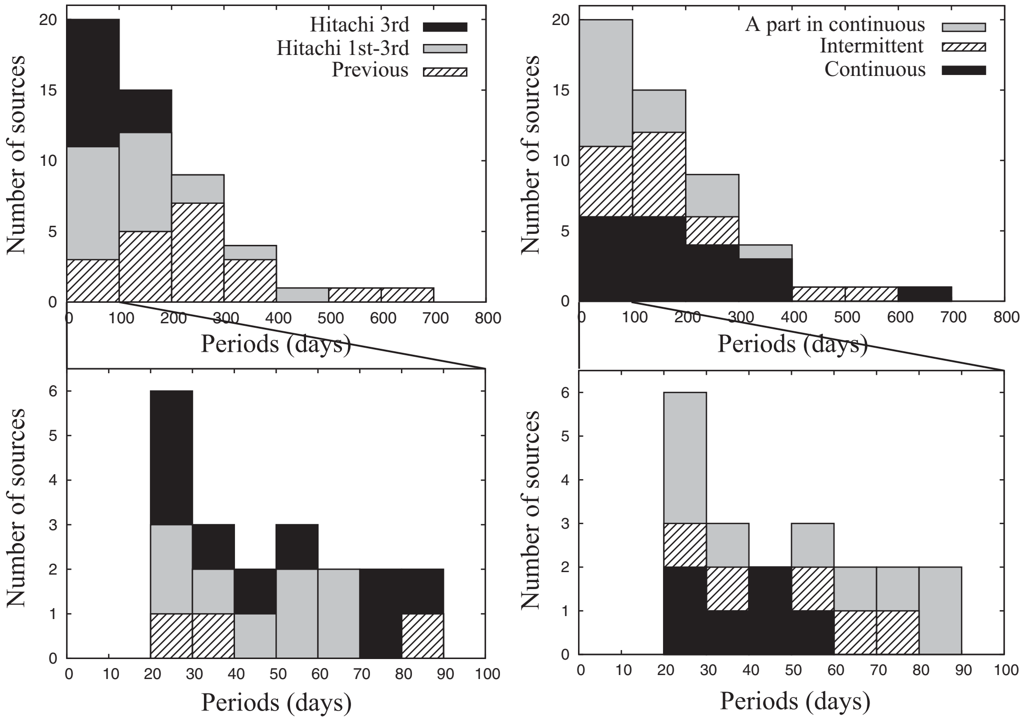

Figure 2. Histogram compiling all the periodic sources in terms of periods. (Left) Classified into duration of monitor for the methanol masers: previous, our Hitachi but from September 2015, and Hitachi using all the data shown by shaded, gray, and black boxes, respectively. The lower-panel is close-up to periods up to 100 days. (Right) Classified into patterns of the periodic variability: continuous (sinusoidal), intermittent, and continuous but in a part of spectral features shown by black, shaded, and gray boxes, respectively.

References

Araya, E. D., Hofner, P., Goss, W. M., *et al.* 2010, *ApJL*, 717, L133

Breen, S. L., Fuller, G. A., Caswell, J. L., *et al.* 2015, *MNRAS*, 450, 4109

Goedhart, S., Gaylard, M. J., & van der Walt, D. J. 2004, *MNRAS*, 355, 553

Goedhart, S., Maswanganye, J. P., Gaylard, M. J., & van der Walt, D. J. 2014, *MNRAS*, 437, 1808

Hosokawa, T. & Omukai, K. 2009, *ApJ*, 691, 823

Inayoshi, K., Sugiyama, K., Hosokawa, T., Motogi, K., & Tanaka, K. E. I. 2013, *ApJL*, 769, L20

Lomb, N. R. 1976, *Ap&SS*, 39, 447

Parfenov, S. Y. & Sobolev, A. M. 2014, *MNRAS*, 444, 620

Scargle, J. D. 1982, *ApJ*, 263, 835

Sugiyama, K., Yonekura, Y., Motogi, K., *et al.* 2015, *PKAS*, 30, 129

Sugiyama, K., Nagase, K., Yonekura, Y., *et al.* 2017, *PASJ*, 69, 59

Szymczak, M., Wolak, P., & Bartkiewicz, A. 2015, *MNRAS*, 448, 2284

Szymczak, M., Olech, M., Wolak, P., Bartkiewicz, A., & Gawroński, M. 2016, *MNRAS*, 459, L56

van der Walt, D. J. 2011, *AJ*, 141, 152

van der Walt, D. J., Maswanganye, J. P., Etoka, S., Goedhart, S., & van den Heever, S. P. 2016, *A&A*, 588, A47

Yonekura, Y., Saito, Y., Sugiyama, K., *et al.* 2016, *PASJ*, 68, 74