Long-term with short-intervals monitor of 6.7 GHz CH$_3$OH masers using Hitachi 32-m radio telescope to statistically research the periodic flux variability around high-mass protostars

K Sugiyama$^{1,2,*}$, Y Yonekura$^3$, K Motogi$^4$, Y Saito$^5$, M Momose$^5$, M Honma$^1$, T Hirota$^1$, M Uchiyama$^6$, K E I Tanaka$^{7,8}$, B H Kramer$^{9,2}$, K Asanok$^2$, P Jaroenjittichai$^2$ and K Fujisawa$^{10}$

$^1$Mizusawa VLBI Observatory, National Astronomical Observatory of Japan (NAOJ), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
$^2$National Astronomical Research Institute of Thailand (NARIT), 260 Moo 4, T. Donkaew, A. Maerim, Chiang Mai, 50180, Thailand
$^3$Center for Astronomy, Ibaraki University, 2-1-1 Bunkyo, Mito, Ibaraki 310-8512, Japan
$^4$Graduate School of Sciences and Technology for Innovation, Yamaguchi University, 1677-1 Yoshida, Yamaguchi, Yamaguchi 753-8512, Japan
$^5$College of Science, Ibaraki University, 2-1-1 Bunkyo, Mito, Ibaraki 310-8512, Japan
$^6$Advanced Technology Center, NAOJ, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
$^7$Department of Earth and Space Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
$^8$ALMA project, NAOJ, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
$^9$Max Planck Institute for Radio Astronomy, Auf dem Hügel 69, 53121-Bonn, Germany
$^{10}$The Research Institute for Time Studies, Yamaguchi University, 1677-1 Yoshida, Yamaguchi, Yamaguchi 753-8511, Japan

*E-mail address: koichiro@narit.or.th and koichiro.sugiyama@nao.ac.jp

Abstract. We initiated a long-term with short-intervals monitoring project toward 442 CH$_3$OH masers at 6.7 GHz (Dec > -30 deg) using Hitachi 32-m radio telescope of Japan in Dec 2012. Our observations have been carried out daily, monitoring a spectrum of each source with intervals of 9-10 days. In Sep 2015, the number of the targets sources and intervals were redesigned into 143 and 4-5 days to detect periodic variations with periods shorter than 30 days. We have so far obtained new detections of periodic flux variations in 31 CH$_3$OH sources with periods of 22-409 days. These periodic flux variability with timescale between a few months and a few years must be a unique tool to study high-mass protostars themselves and their circumstellar structures on a tiny spatial scale of 0.1-1 au (~1.5 x 10$^7$-8 km). We will also present the future prospect via monitoring of OH and H$_2$O masers in these periodic sources using 40-m Thai National Radio Telescope that is under construction by NARIT.
1. Introduction
High-mass stars (8 times heavier than the solar mass) play a key role in the evolution of the Universe because they provide heavy elements and UV radiation, and contribute the formation of the next generation stars via outflows/jets, expansion of ionized regions, and supernova explosions. How to form and evolve the high-mass stars is one of important issues in Astronomy. The CH$_3$OH maser (Microwave Amplification by Stimulated Emission of Radiation) at 6.7 GHz is one of the brightest radio emissions in interstellar sources, and mostly associated with high-mass star-forming regions [1]. This maser, thus, is an exclusive observational probe to study high-mass stars. The CH$_3$OH maser has presented characteristic flux variations, and one of them is periodic flux variability. The periodic variability of the CH$_3$OH masers was first discovered in G 009.62+00.19 E [2], and the periodic flux variability had been detected in 12 sources as of Dec 2012, with their periods from 29.5 to 668 days [3]. Patterns of the variability have been classified into mainly two categories: continuous such as sinusoidal curve, and intermittent with a quiescent phase. Such periodic flux variability was also observed in H$_2$CO/OH/H$_2$O masers [4-6], and the variations were synchronized with those of CH$_3$OH masers in the same source. The periodic variability, thus, might be a common phenomenon at around high-mass (proto-)stars, but probably appears in a limited condition and/or a certain duration at evolutionary phase. Because of their short timescale, the periodic variability is potentially unique probe to study high-mass protostars (HMPSs) themselves and their circumstellar structure on tiny spatial scales of 0.1-1 au (~1.5 x 10$^{-7}$-8 km), which are estimated under the condition of Keplerian rotation. Although these regions must be the most important to understand the evolutionary track of HMPSs through the mass accretion rates toward onto the stellar surface [7], it is impossible to spatially resolve such a tiny region at the distance of HM star-forming regions even by using future instruments such as the extended ALMA (Atacama Large Millimeter/submillimeter Array).

Four models have been proposed to interpret the periodic variability: colliding-wind binary (CWB) [8], stellar pulsation [9], circumbinary accretion disk [4], and rotation of spiral shocks within a gap region in a circumbinary disk [10]. The first model is based on changes in the flux of seed photons, while the other ones are based on changes in the temperature of dust grains at the masering regions.

In previous observations of the CH$_3$OH masers, flux monitoring for statistically understanding the number of periodic sources was conducted toward only ~200 sources [3,11], although all the CH$_3$OH maser sample consists of more than 1,000 sources ([12] and references therein).

2. Observations
We initiated a long-term, short-intervals, and unbiased monitoring project using Hitachi 32-m radio telescope of Japan [13] on Dec 30, 2012 toward a large sample of the CH$_3$OH masers at 6.7 GHz (442 sources) selected with a simple criterion of declination higher than -30 deg. In order to cover a wide range of periods from a month to a few years, we designed the observations as follows: until Aug 2015 observations were carried out daily, monitoring a spectrum of each source with intervals of 9-10 days. Since Sep 2015, target sources were reduced to 143 selected with a criterion of modulation index (the standard deviation over the averaged value of flux densities) if it was larger than 0.3. 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 are also used with the former ones to search for periods longer than one year. For the backend setup in details, see the reference [14].

3. Results
To quantitatively evaluate periodicity, we adopted the Lomb-Scargle periodogram [15]. Furthermore, other two criteria were set as follows: (1) periodicity is continued at least three periodic cycles, and (2) the signal to noise ratio at the maximum timing is larger than or equal to 7.

As a result, we detected periodic flux variations in 42 sources, and for 31 of 42 sources newly detected to host periodic variations with the periods of 22-409 days. For instance, G 014.23-00.50 and G 036.70+00.09 presented their periods of 24 and 53 days with intermittent and continuous pattern, respectively, as shown in figure 1 [14,16].
Figure 1. Dynamic spectra of the 6.7 GHz CH$_3$OH masers in periodic sources newly detected in our monitor. The horizontal and vertical axis is the observation date in modified Julian day and the local standard of rest velocity, respectively. Gray color shows the flux density in the unit of Jy ($=10^{-26}$ Wm$^{-2}$ Hz$^{-1}$) in logarithmic scale, which is brighter than 3 sigma (rms noise level). (Left) G 014.23-00.50 with a period of 24 days. (Right) G 036.70 + 00.09 with a period of 53 days.

These periodic sources are compiled with previous ones that obtained by other authors using other telescopes as histogram in terms of periods in figure 2. Left-panel in figure 2 shows the histogram classified into duration and cadence of monitor for the CH$_3$OH masers, while right-panel is the same but classified into patterns of the periodic variability. This classification in terms of the pattern must be useful to distinguish which theoretical models are suitable to cause each periodic variation, e.g. the continuous pattern can be caused by the kappa mechanism in a stellar pulsation of HMPSs [9] on the basis of the database, 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 onto 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.

Furthermore, 40-m Thai National Radio Telescope (TNRT40-m) that is under construction by NARIT is expected to strongly contribute for completing the study of understanding the evolutionary track of HMPSs via the periodic flux variability of masers. As mentioned in section 1, the periodicity of CH$_3$OH masers has been synchronized to H$_2$CO/OH/H$_2$O masers in some sources. This synchronization will be usable to make it clear whether the periodic source with the intermittent pattern is explained by CWB or stellar pulsation on the basis of the difference of pumping mechanisms, those are radiative for OH/CH$_3$OH(6.7 GHz) and collisional for H$_2$CO/H$_2$O, respectively. For instance, CWB is providing a weak shock at every proximity point in binary system, which causes changes in the flux of seed photons for masers, and possibly pumps H$_2$O masers. If we can detect synchronization between radiative CH$_3$OH and collisional H$_2$O masers in the same source, it will be good evidence to interpret their periodicity by CWB. Otherwise, it will be able to be interpreted by the stellar pulsation. At commissioning phase of TNRT40-m, L- and K-bands receivers that enable us to observe OH and H$_2$O masers will be installed and thus we will initiate these follow-up monitor observations toward the Hitachi database for 6.7 GHz CH$_3$OH masers showing periodic flux variability to complete the project.

4. Conclusion
We have detected 42 sources showing periodic flux variations quantitatively evaluated via Lomb-Scargle periodogram, and for 31 of 42 sources have been newly detected with the periods of 22-409
days. These sources will be a good target for TNRT40-m from the beginning of commissioning phase via follow-up observing OH and H$_2$O masers to research synchronization with CH$_3$OH maser.

Figure 2. Histogram compiling all the periodic sources in terms of periods. (Left) Classified into duration of monitor for the CH$_3$OH masers: previous monitor by other authors, our Hitachi using all the data (labeled as “1st-3rd”), and Hitachi but from Sep 2015 (“3rd”) 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, intermittent, and continuous but in a part of spectral features shown by black, shaded, and gray boxes, respectively.

References
[1] Minier V, Ellingsen S P, Norris R P and Booth R S 2003 Astron. Astrophys. 403 1095
[2] Goedhart S, Gaylard M J and van der Walt D J 2003 Mon. Not. R. Astron. Soc. 339 L33
[3] Goedhart S, Gaylard M J and van der Walt D J 2004 Mon. Not. R. Astron. Soc. 355 553
[4] Araya E D, Hofner P, Goss W M, Kurtz S, Richards A M S, Linz H, Olmi L and Sewilo M 2010 Astrophy. J. Lett. 717(2) L133
[5] Green J A, Caswell J L, Voronkov M A and McClure-Griffiths N M 2012 Mon. Not. R. Astron. Soc. 425 1504
[6] Szymczak M, Olech M, Wolak P, Bartkiewicz A and Gawroński M 2016 Mon. Not. R. Astron. Soc. 459 L56
[7] Hosokawa T and Omukai K 2009 Astron. J. 691 823
[8] van der Walt D J 2011 Astron. J. 141 152
[9] Inayoshi K, Sugiyama K, Hosokawa T, Motogi K and Tanaka K E I 2013 Astrophy. J. Lett. 769(2) L20
[10] Parfenov S Y and Sobolev A M 2014 Mon. Not. R. Astron. Soc. 444 620
[11] Szymczak M, Wolak P and Bartkiewicz A 2015 Mon. Not. R. Astron. Soc. 448 2284
[12] Breen S L et al 2015 Mon. Not. R. Astron. Soc. 450(4) 4109
[13] Yonekura Y et al 2016 Publ. Astron. Soc. Jpn. 68(5) 74
[14] Sugiyama K et al 2017 Publ. Astron. Soc. Jpn. 69 59
[15] Scargle J D 1982 Astrophys. J. 263 835
[16] Sugiyama K et al 2015 Publ. Korean Astron. Soc. 30 129