High-cadence 6.7 GHz methanol maser monitoring observations by Hitachi 32-m radio telescope to detect the signs of the accretion burst

yoshinori.yonekura.sci@vc.ibaraki.ac.jp
Yoshinori Yonekura, Yoshihiro Tanabe, and Ren Moriizumi (Ibaraki University)

Almost all **6.7 GHz methanol masers are known to be associated with high-mass protostellar objects**. After the discovery of this maser in 1991 (Menten91), **more than 1000 objects** associated with this maser are detected. Because this maser is pumped by the radiation from the central star, the flux density of this maser was thought to be somewhat stable. In 2003, the periodic flux variability for this maser sources G9.62+0.20E is reported (Goedhart+03). Until now, **29 maser sources with periodic flux variability have been found** (Olech+19, Proven adzri+19, Olech+22, Tanabe+23). Five mechanisms for the flux variability is suggested: colliding wind binary (van der Walt+09, 11), spiral shock (Parfenov+14), periodic accretion of material from the circumbinary disc (Araya+10), an eclipsing binary (Maswanganye+15), and pulsation of the central star (Inayashi+13, Sanne+15). Aside from the periodic flux variability, **non-periodic sudden flux rises** with the factor of 10-1000 were detected for 4 maser sources (S255IR-IRS3 [Fujisawa+15], NGC 6334 I-MM1 [MacLeod+18], G358.93-0.03 [Sugiyama+19], G24.33+0.14 [Wolak+19]). These sudden flux rises were confirmed to be the results of the **accretion burst** from the observational results of the brightening of the central sources in NIR/FIR/(Sub-)mm (Caratti o Garatti+17, Hunter+17, Stechlum+21, Hirota+22).

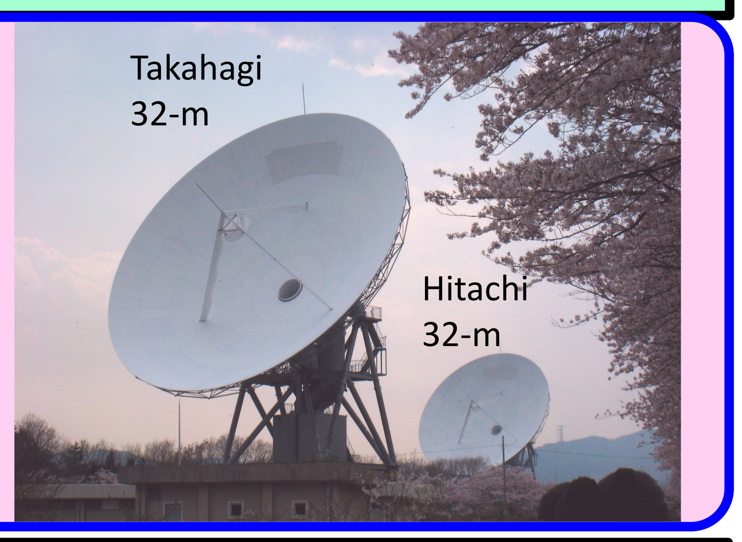
We started high-cadence monitoring observations of 6.7 GHz methanol masers **from Dec. 2012 using Hitachi 32-m radio telescope** (Yonekura+16). Observations have been conducted basically every day. On average, 13 hours of observations have been made per day, amounting to **4000-5000 hours per year**. The cadence varies by sources: **one observation in 1-50 days**. We have **newly identified ~20 sources with periodic flux variability** in addition to already known 29 sources. We have also **detected 5 sources with sudden flux rises in 2019-2022**, including G358.93-0.03 which was confirmed to be associated with the accretion burst.

Hitachi 32-m and Takahagi 32-m radio telescopes, at Ibaraki station, Mizusawa VLBI Observatory, NAOJ

- ∗ Former satellite communication antennas used by KDDI at 4 and 6 GHz, decommisioned at 2007.
- ∗ Upgraded to radio telescopes at 6.7, 8.4, and 22 GHz, cooled receiver equipped (Yonekura+16).
- ∗ Observations:
  - — VLBI imaging observations (EAVN: East-Asian VLBI Network, JVN: Japanese VLBI Network) 200-300 hours / yr
  - — VLBI observations (with small numbers of baseline(s)) for the detection study (Yamaguchi [Yamaguchi 32m, 34m] and Ibaraki [Hitachi 32m, Takahagi 32m]) 200-300 hours/yr
  - — Single-dish observations at 6.7 GHz: up to 8000 hours × 2 antennas can be used for our own science!

➔ dedicated to **long-term highly-cadence monitoring observations** of 6.7 GHz methanol masers

Fig. 1. Hitachi 32-m and Takahagi 32-m antennas.



Time variation of 6.7 GHz methanol masers

- 29 sources are known to show periodic variability (as of 2023)
- only ~ 2--3 % of the total number of 6.7 GHz methanol maser [≥ 1,000]
- period: 14–1260 days (sinusoidal, intermittent).

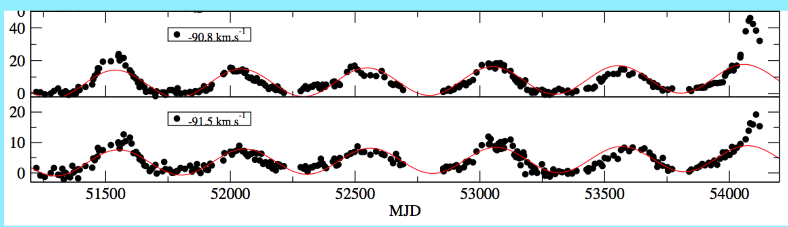


Fig. 2a. Time variation of the 6.7 GHz methanol maser in G 331.13-00.24 shows "continuous" pattern (Goedhart+07).

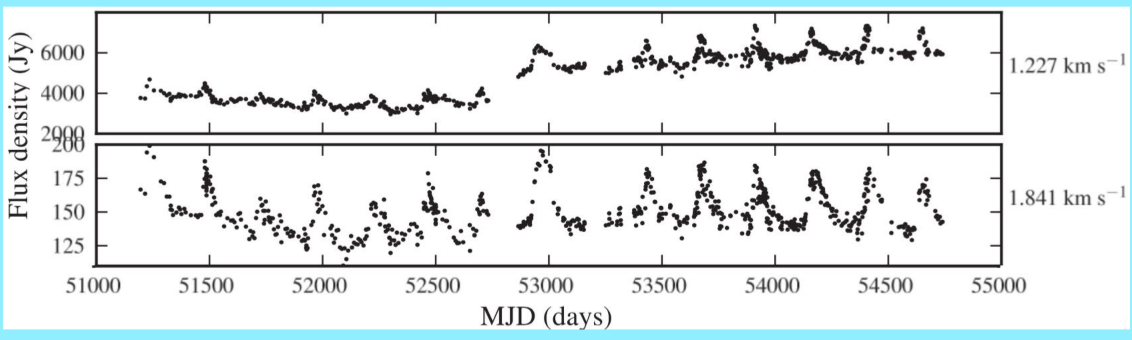


Fig. 2b. Time variation of the 6.7 GHz methanol maser in G 009.62+00.20 E shows Intermittent pattern (Goedhart+14).

Possible mechanisms

- Colliding wind binary (van der Walt+09, 11)
- Stellar pulsation instability (Inayoshi+13, Sanna+15)
  - — P-L relation is suggested
- Spiral shock heating in a circum-binary disk (Parfenov & Sobolev 14)
- periodic accretion of material from the circumbinary disc (Araya+10)
- a very young low-mass companion blocking the ultraviolet radiation from the high-mass star in an eclipsing binary (Maswanganye+15)

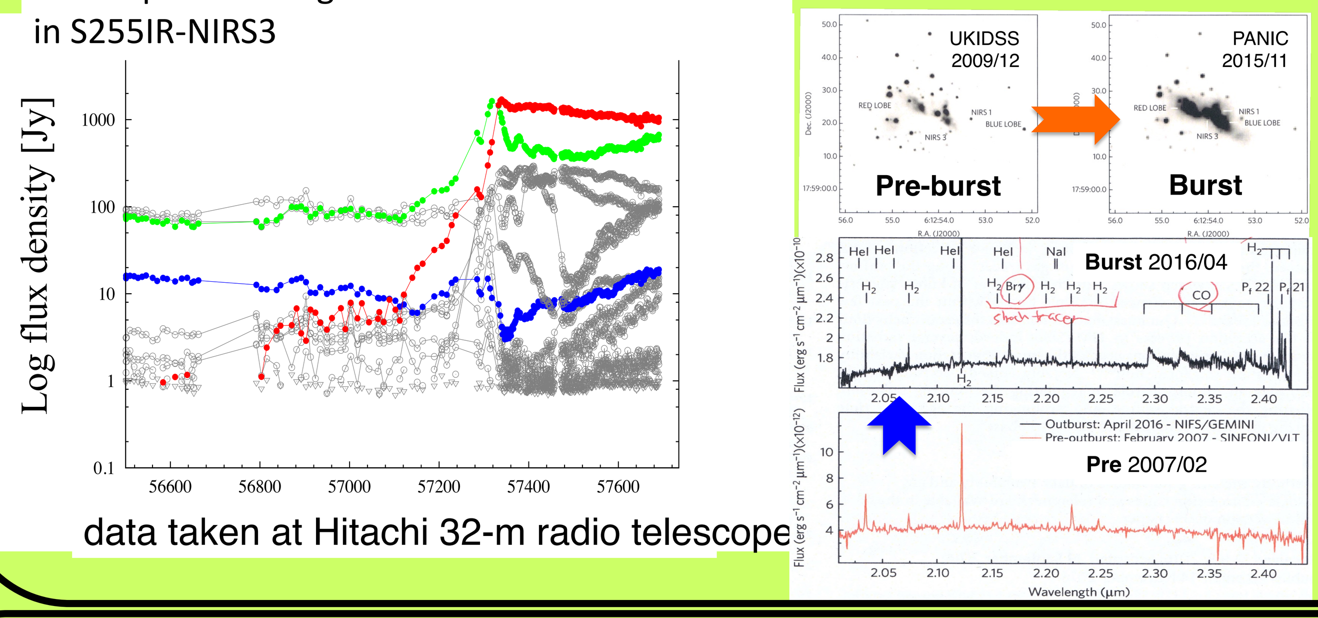
(Episodic) Accretion bursts in SFRs @ High-mass stars

1st example: discovery by monitoring observations of 6.7 GHz methanol maser using Yamaguchi 32-m (Fujisawa+ 15)

2nd example: same as 1st example but by South-African 26-m radio telescope (MacLeod+18)

1st sample: Bursting flux rises of CH3OH masers in S255IR-NIRS3

Verified in NIR-band with PANIC (Caratti o Garatti+ 17)



Extreme bursts are detected also in NIR

- ΔH ~3.5 mag, ΔK ~2.5 mag
- M dot ~ 5 x 10-3 Msun/yr

Imaging / Spectroscopy with VLT / GEMINI

- expansion to NE-SW
- H2 / Bry and CO band-heads are also detected
- tracing release/heating phenomenon orignated from accretion on the disk

Fig. 3. (left) Time variation of the 6.7 GHz methanol maser in S255IR-NIR3 taken at Hitachi 32-m. (right) NIR images and spectra taken before and after the burst.

2nd sample: via multi-masers in NGC 6334I-MM1 (MacLeod+ 18)

Simultaneous burst at (sub-)mm dust (Hunter+ 17)

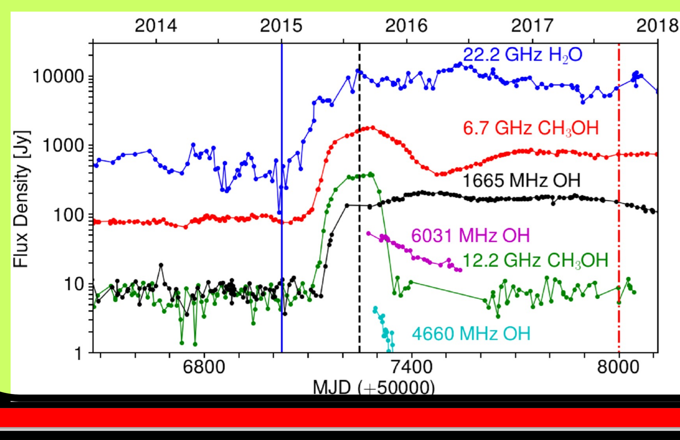
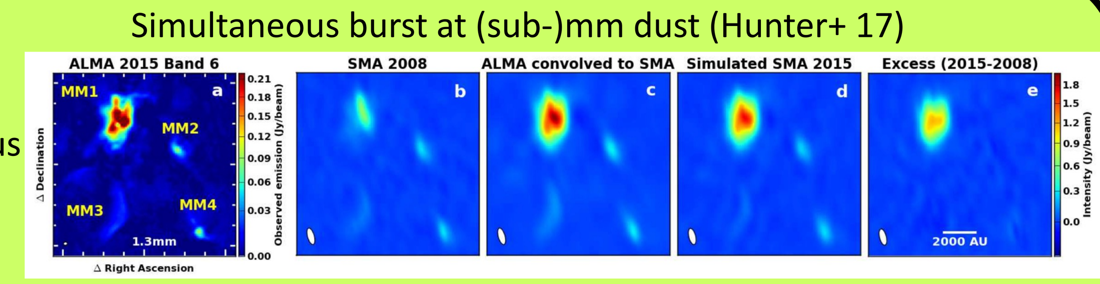


Fig. 4. (left) Time variation of the various masers in NGC6334I-MM1. (right) (sub-)mm dust continuum images taken before and after the burst.



- burst is detected in 0.87 and 1.3 mm dust continuum with SMA/ALMA between 2008 and 2015
- ~4 times in flux density within 7 years => ~70 times in Luminosity

Observations

Target selection

(1) Compilation of the "master catalog"

(a) Compilation catalog at 2009
- — Xu+09

(b) Parkes (methanol multibeam [MMB] survey)
- — Caswell+10: 183 sources (345 < L < 6, |B| ≤ 2)
- — Green+10: 119 sources (6 < L < 20, |B| ≤ 2)
- — Green+12: 207 sources (186 < L < 330, |B| ≤ 2)

(c) Arecibo Methanol Maser Galactic Plane Survey (AMGPS)
- — Pandian+07: 86 sources (35 < L < 54)
- — Pandian+11: position measurements of 82 sources (MERLIN, EVLA)

(2) selection
- sources with Decl. ≥ -30 deg.

→ 442 sources are selected for the monitoring observations at Ibaraki

Observations

Telescope: Hitachi 32-m
Integration time = 5 min.
Bandwidth = 8 MHz (centered on 6668 MHz [the rest freq. is 6,668.5192 MHz])
Velocity coverage ~ 360 km/s (not centered at Vlsr = 0 km/s)
Velocity resolution ~ 0.044 km/s (8 MHz is divided into 8192 ch)
Tsys* ~ 25 K (zenith) — 40 K (EL = 15 deg)
Trms (typical) ~ 0.3 Jy

Cadence

Period
1: 2012/Dec./30 — 2014/Jan./10
2: 2014/May/07 — 2015/Aug./24
3: 2015/Sep./18 — 2017/Mar./07
4: 2017/Jun./14 — now

[1 & 2]
- 442 sources are divided into 9 groups (1,2,...,9)
- each group is observed once per ~9 days

[3]
- 154 sources showing variability are selected from the results of period 1 and 2.
- 154 sources are divided into 4 groups (A,B,C,D)
- each group is observed once per ~4 days

[4]
hybrid of (1&2) & 3
sequence = [1ABCD2ABCD3ABCD...8ABCD9ABCE]

Results:

We have **newly identified ~20 sources with periodic flux variability** in addition to already known 29 sources. Here we show some examples of the time variation of the flux density.

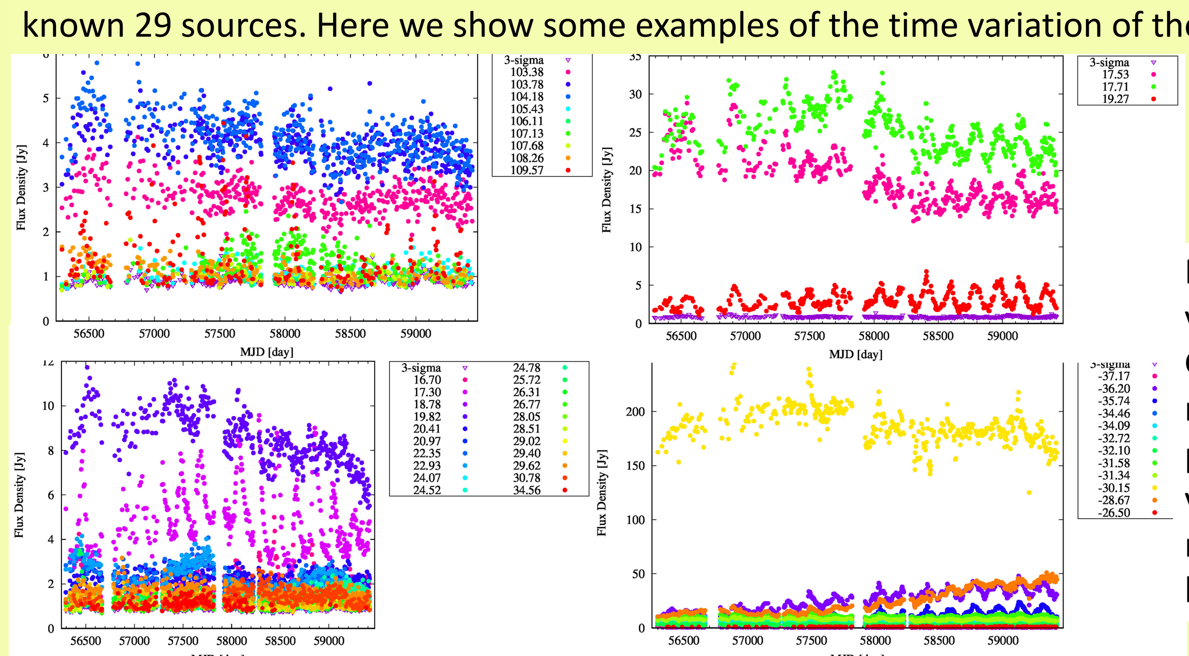


Fig. 5. Time variation of 6.7 GHz methanol masers whose periodic flux variation are newly identified by us.

Results: 3rd sample: Bursting flux rise of 6.7 GHz methanol maser toward G358.931-0.030

Monitoring observations at Ibaraki

Because the variation of the flux density of this source before 2019 was **not significant**, we had been observing the source once per ~50 days.

- The last obs. before the detection of the burst @ 2018/Oct./31(DOY=304) 06:09 UT
- Obs. at 2019/Jan./14, 01:14 UT => detection of the burst
- Jan./17 and later: daily observations
- Jan./18 informed Maser Monitoring Organization "M2O"
- Jan./29 submitted to Astronomer's Telegram Sugiyama+19 (ATel, 12446)

The flux density reached ~1000 Jy in March/2019, and then decreased. The current flux density is ~10 Jy, nearly the same as that before the burst.

Observational results by Hitachi 32-m is available at http://vlbi.sci.ibaraki.ac.jp/iMet/G358.9-00-190114/

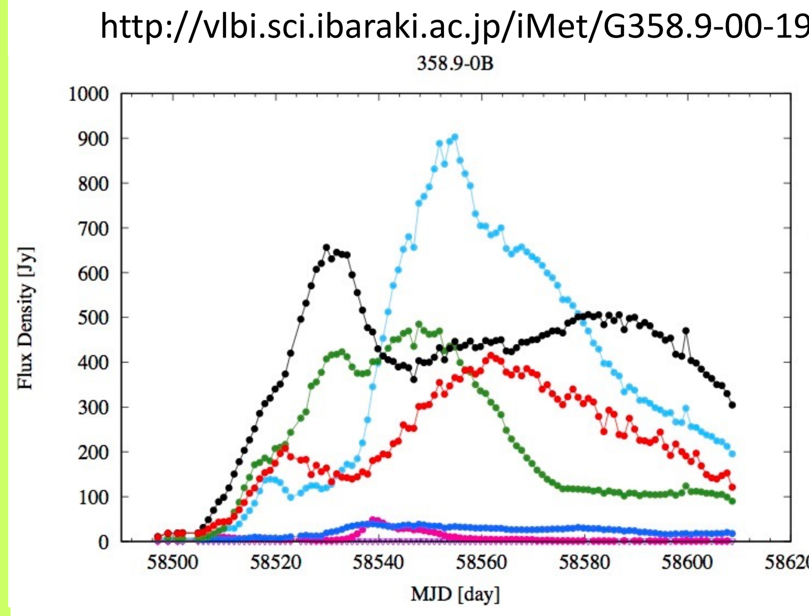


Fig. 6. Time variation of the 6.7 GHz methanol maser in G358.931-0.030 taken at Hitachi 32-m.

follow-up observations

Thanks to the establishment of "**M2O**" in 2017, **immediate multi-wavelength observations** (such as single-dish observations of methanol and other masers, VLBI imaging of methanol and other masers, cm and mm dust continuum observation, optical and infrared observations) are made worldwide [see Fig. 7 (taken from Burns+22)]. Followings are examples of early results (many more papers have been published !)]

- MacLeod et al. (2019) : Single-dish monitoring observations by 26-m radio telescope in South Africa. **4 new transitions are detected. 2 of the 4 is the first detection from the celestial objects.**
- Breen et al. (2019) : Observations by MOPRA and ATCA. **6 transitions between 6-8, 20-46 GHz are the first detections from the clestial objects. 3 of 6 is vt =1 torsionally-excited.**
- Brogan et al. (2019) : Multi-epoch observations by SMA and ALMA. **14 new transition** are detected **between 199-361 GHz**. Most of the transitions are vt =1 torsionally-excited. one is the vt = 2 transition and the first detection from the clestial objects.
- Stecklum et al. (2021) : Infrared observations by **SOFIA confirmed an accretion burst**.
- Detection of the **propagation of the "heat-wave"** by multi-epoch VLBI imaging observations (Burns+20)

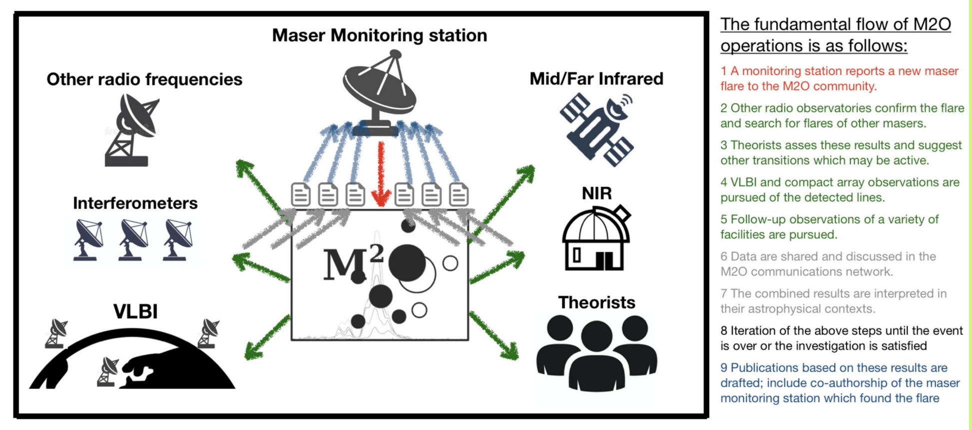


Fig. 7. Flow-chart of M2O.

Rest Freq	Transition	E_L(K)	Comments	Ref.
6,181.128(21)	$17(-2) \rightarrow 18(-3)\ E\ (v_t{=}1)$	718	new maser (B)	4
6,668.5192(8)	$5(1) \rightarrow 6(0)\ A^+$	49		1
7,682.232(50)	$12(4) \rightarrow 13(3)\ A^-$	261	new maser (B)	3
7,830.864(50)	$12(4) \rightarrow 13(3)\ A^+$	261	new maser (B)	3
12,178.597(4)	$2(0) \rightarrow 3(-1)\ E$	20	new detection(M)	1
12,229	$16(5) \rightarrow 17(4)\ E$	451	new maser(M)	2
19,967.3961(2)	$2(1) \rightarrow 3(0)\ E$	27		1
20,347	$17(6) \rightarrow 18(5)\ E$	533	new maser(M)	2
20,970.651(50)	$10(1) \rightarrow 11(2)\ A^+\ (v_t{=}1)$	451	new maser (B)	3
23,121.0242(5)	$9(2) \rightarrow 10(1)\ A^+$	141	new detection (*) (M)	1

new maser: first detection from celestial objects
new detection: new detection from G358.931-000.030
B: Breen et al. (2019), G: MacLeod et al. (2019), *: 4th object that shows this maser
Refs.: 1. Muller et al. (2004), 2: https://spec.jpl.nasa.gov/, 3: Tsunekawa et al. (1995), 4: Pickett et al. (1998)

Table. 1. Detected lines in cm wavelength (compiled from Breen+19 and MacLeod+19)

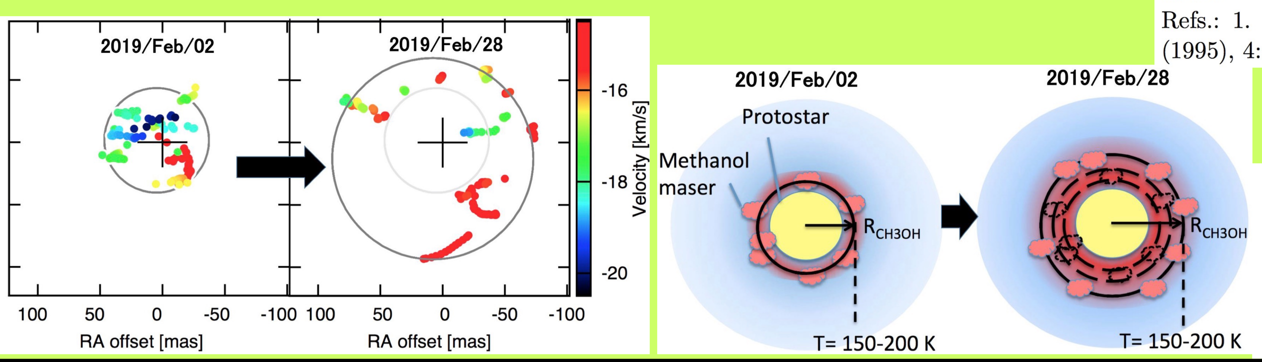


Fig. 8. (left) Results of VLBI observations at 2019/Feb./02 and Feb./28 (Burns+20). (right) Models of the temperature distribution of the disk and the position of 6.7 GHz methanol maser sources.

Results: Other 4 flux rise detected by Hitachi 32-m in 2019-2022

detected on 2020/Feb./10 | Detected on 2020/Feb./28 | Detected on 2020/Jul./13 | Detected on 2022/Oct./01

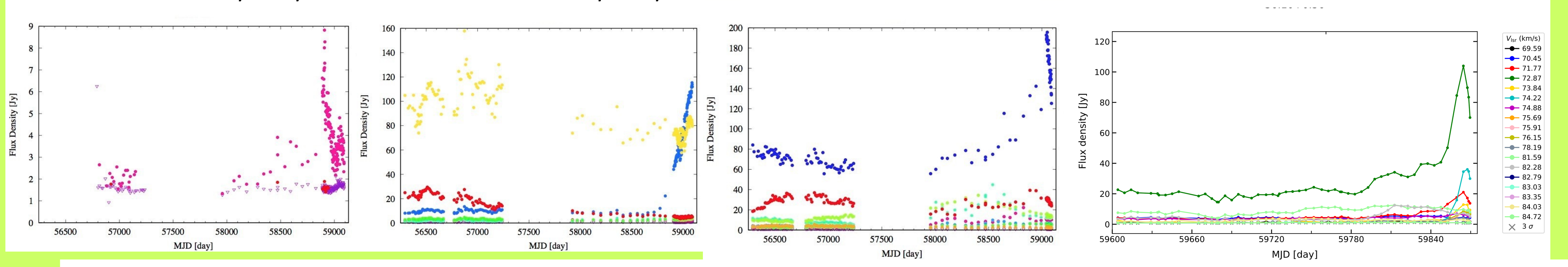


Fig. 9. Time variations of four 6.7 GHz methanol maser sources which show sudden flux rise in 2019-2022 detected by Hitachi 32-m.

All the data are available at iMet (Ibaraki 6.7 GHz class II methanol maser database) web at **http://vlbi.sci.ibaraki.ac.jp/iMet/**

Acknowledgement: This work is partially supported by the Inter-university collaborative project "Japanese VLBI Network (JVN)" of NAOJ. This study benefited from financial support from the Japan Society for the Promotion of Science (JSPS) KAKENHI program (21H01120 and 21H00032).