Mid-infrared and Maser Flux Variability Correlation in Massive Young Stellar Object G036.70+0.09

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Abstract

We present the discovery of the simultaneous flux variation of a massive young stellar object (MYSO) G036.70 +0.09 (G036.70) both in the maser emission and mid-infrared (MIR; $\lambda = 3$–5 $\mu$m) bands. Using the ALLWISE and NEOWISE archival databases that cover a long time span of approximately 10 yr with a cadence of 6 months, we confirm that G036.70 indicates a stochastic year-long MIR variability with no signs of a WISE band color change of W1 (3.4 $\mu$m) – W2 (4.6 $\mu$m). Cross-matching the MIR data set with the high-cadence 6.7 GHz class II methanol maser flux using the Hitachi 32 m radio telescope that discovered its periodicity in the methanol maser of 53.0–53.2 days, we also determine the flux correlations between the two bands at different timescales, year-long and day-long, both of which have never been reported in MYSOs, except when they are in the accretion burst phase. The results of our study support the scenario that a class II methanol maser is pumped up by infrared emission from accreting disks of MYSOs. We also discuss the possible origins of MIR and maser variability. To explain the two observed phenomena, a stochastic year-long MIR variability with no signs of significant color change and maser-MIR variability correlation or a change in mass accretion rate and line-of-sight extinction because of the nonaxisymmetric dust density distribution in a rotating accretion disk are possible origins. Observations through spectroscopic monitoring of accretion-related emission lines are essential for determining the origin of the observed variability in G036.70.

Unified Astronomy Thesaurus concepts: Variable stars (1761); Time domain astronomy (2109); Young stellar objects (1834); Massive stars (732); Infrared astronomy (786); Circumstellar masers (240)

1. Introduction

Massive stars play a significant role in star formation activities and metal enrichment in galaxies and, hence, in the evolution of galaxies (e.g., Zinnecker & Yorke 2007; Tan et al. 2014, and references therein) as well as in the growth of supermassive black holes in the universe (e.g., Thompson et al. 2005; Inayoshi & Haiman 2016; Ichikawa & Inayoshi 2017). However, owing to observational difficulties, detailed views of the youngest phase of massive stars, massive young stellar objects (MYSOs), have yet to be resolved.

Variability studies are a promising means to investigate distant and compact objects such as mass-accreting MYSOs and their disks and/or outflows. For lower-mass YSOs, owing to the small extinction of dust with $A_V < 10$ (Ménard & Bertout 1999), observations in both the optical and near-infrared (NIR; $\lambda < 3$ $\mu$m) bands have been well conducted over the last 50 yr. Such optical and NIR variability studies involving the emission lines and continuum of lower-mass YSOs have revealed the physics of star formation and pre-main-sequence stellar evolution, such as the existence of rotating cool/hot spots (Bouvier & Bertout 1989), infalling/rotating dusty objects (Cody et al. 2014), and drastic mass-accretion rate variation (Audard et al. 2014). However, for MYSOs, such optical or NIR systematic variability surveys were not reported until recently, due to huge extinction toward MYSOs and hence difficulty of optical and NIR observations.

Recently, high-amplitude ($\Delta K_s > 1$ mag) year-scale variability in MYSOs was reported for the first time in the $K_s$ band using Vista Variables in Via Lactea (VVV) survey data (Kumar et al. 2016). Following this study, lower-amplitude variables, approaching $\Delta K_s > 0.15$ mag, were detected in 190 out of 718 MYSO candidates in the same VVV survey data (Teixeira et al. 2018). This discovery motivates authors to search for variability at longer wavelengths. Considering that MYSOs are heavily obscured by their surrounding gas and dust, searching for variability in the mid-IR (MIR; $\lambda > 3$ $\mu$m) is more suitable owing to its relative insensitivity toward dust extinction. Uchiyama & Ichikawa (2019) recently reported $\sim 1$ yr scale MIR variable MYSOs by using the combined ALLWISE and NEOWISE data, which cover an observation period of $\sim 10$ yr with a cadence of 6 months (Wright et al. 2010; Mainzer et al. 2011, 2014). Radio bands also provide significant information mostly from nonthermal emissions for certain MYSOs. These are observed as masers, which often indicate periodic and/or nonperiodic flux variations in the radio bands. Some masers are classified as strongly related to MYSOs (e.g., Minier et al. 2003; Breen et al. 2013; Motogi et al. 2016). In particular, certain class II methanol masers are
considered to be associated with accreting disks of MYSOs (e.g., Sugiyama et al. 2014; Motogi et al. 2017; Sanna et al. 2017) with a typical size of several hundred AU (Tan et al. 2014), pumped up by thermal radiation in the MIR (Cragg et al. 2005). The origins of periodic maser activity have been widely discussed in the previous decade, such as the periodic accretion of circumbinary material in binary system (Araya et al. 2010), a colliding wind binary (van der Walt et al. 2009; van der Walt 2011), stellar pulsation of an accreting MYSO (Inayoshi et al. 2013), rotation of spiral shocks in the gaps of circumbinary disks (Parfenov & Sobolev 2014), and a low-mass YSO blocking ultraviolet radiation from a high-mass star in an eclipsing binary system (Maswanganye et al. 2015). Recently, flux correlation of a 6.7 GHz methanol maser with infrared emission has been reported in a drastically variable burst MYSO (Caratti o Garatti et al. 2017; Uchiyama et al. 2020; Stecklm et al. 2021). For periodic variability, such a correlation is reported in the intermediate-mass YSO G107.298+5.639 (Olech et al. 2020). However, a study of the variability correlations in the IR and masers in MYSOs associated with a periodic 6.7 GHz maser as well as the IR color variability during the methanol maser flux variation is still lacking.

In this study, we investigate the variability and the flux variability correlations of the MIR and 6.7 GHz methanol maser emissions for MYSO G036.70+0.09 (hereafter referred to as G036.70; the absolute coordinate from Bartkiewicz et al. 2009 and Pandian et al. 2011 in J2000.0 is R.A.=18:57:59.123, decl.=+03:24:06.12); this methanol maser has a periodic flux variability with a period of ~53 days (Sugiyama et al. 2015, 2019). We use methanol maser data that were observed in a long-term and high-cadence monitoring program conducted using the Hitachi 32 m radio telescope (Yonekura et al. 2016; Sugiyama et al. 2019) and WISE archival MIR data, particularly at bands 1 (W1; 3.4 μm) and 2 (W2; 4.6 μm).

2. Archival Data

2.1. Cross-matching with WISE

We obtained the MIR counterparts of G036.70 through positional matching with WISE data to generate the MIR (3–5 μm) light curve. We collected multi-epoch photometry data from the ALLWISE (for all four bands; Wright et al. 2010) and the most recent NEOWISE (only for W1 and W2; Mainzer et al. 2011, 2014) 2020 data release that covers observations between 2013 December 13 (MJD 56639) and 2019 December 13 (MJD 58830). WISE has a 90-minute orbit and conducts ~12 observations of a source over ~1 day period. It visits a specified location every six months.

In this study, we conducted a cross-matching procedure in the same manner as Uchiyama & Ichikawa (2019). We summarize the key steps here. We applied a cross-matching radius of 2″ based on the positional accuracy using the 2MASS catalog (e.g., see Ichikawa et al. 2012, 2017, 2019). These initial data points comprised 179 multi-epoch photometric data points.

We then applied additional parameters to obtain reliable photometric data. We used a profile-fitting magnitude w2/2mpro with reliable photometric qualities, such as a signal-to-noise ratio higher than 10.0 (gb_qual = A) and the best image quality (qi_fact > 0.5). We further selected photometric data that were not affected by artificial source contamination, the South Atlantic Anomaly, or moonlight, qual_frame > 0.0, saa_sep > 5.0, and moon_masked = 0, as well as the contamination flag as cc_flags = 0, which are known to be unaffected by known artifacts. MYSOs are often very bright, reaching the saturation limit at ~8 and 7 mag in W1 and W2 bands. To avoid unreliable photometric data like this, we selected photometric points with fewer than 5% (w1/2_sat < 0.05) saturated pixels and then removed the data with failed background sky fitting and a poor point-spread function (PSF) profile fitting, flagged as w1/2_sky = NaN and w1/2_rchi2 ≤ 150. This selection process finally retained 116 and 160 photometric data points for G036.70 in the W1 and W2 bands, respectively, as depicted in Figure 1.

2.2. 6.7 GHz Methanol Maser Data

To compare with WISE archival data, we used a part of the 6.7 GHz methanol maser monitoring data that were observed by the Hitachi 32 m radio telescope (Sugiyama et al. 2015; Yonekura et al. 2016; Sugiyama et al. 2019). The velocity

Figure 1. Left: MIR light curves of G036.70 in the WISE W1 (blue; top panel) and W2 (red; bottom panel) data. The single selected exposures are presented with the error values. Right: Light curves of G036.70 in 6.7 GHz methanol maser data. Each color represents each main velocity component of the 6.7 GHz methanol maser. The faint lines represent the original data, and the thick lines represent the 50-day-binning data to observe the year-scale variability. The thick blue line represents the positional matching with WISE data to generate the MIR light curve. We collected multi-epoch photometry data from the ALLWISE (for all four bands; Wright et al. 2010) and the most recent NEOWISE (only for W1 and W2; Mainzer et al. 2011, 2014) 2020 data release that covers observations between 2013 December 13 (MJD 56639) and 2019 December 13 (MJD 58830). WISE has a 90-minute orbit and conducts ~12 observations of a source over ~1 day period. It visits a specified location every six months.

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coverage of the data is $\sim 360 \text{ km s}^{-1}$, with a velocity resolution of $\sim 0.044 \text{ km s}^{-1}$. The typical root mean square (RMS) noise level (1σ) was $\sim 0.3 \text{ Jy}$. The traditional chopper-wheel method (Ulich & Haas 1976) was used for the absolute flux calibration, yielding a typical 1σ error of 7%. The flux decrease due to the pointing error is estimated to be as much as $\sim 3\%$, which can be calculated from the beam size at 6.7 GHz of $\sim 4.6$ and the typical pointing error of $< 30\'$. Thus, in total, the error of the observed flux density is estimated to be $< 10\%$. Between 2012 December and 2015 August, monitoring observations in intervals of 10 days were conducted. More intense monitoring (September until now. Here, we use the observation data

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3. Results

3.1. Overview of Light Curves in the MIR and 6.7 GHz Maser Emission

Figure 1 presents the light curves of WISE MIR bands (left panel; W1/W2 in the top/bottom) and the 6.7 GHz maser emission (right panel). In the right panel, the thick lines represent the 50-day-binning radio data to observe the year-scale variability for easy comparison with WISE MIR data. Both the MIR and radio wavelengths indicate a year-scale variability. The magnitudes of the flux variation span 0.4 mag both in the W1 and W2 bands, whereas radio observations indicate a flux magnification of as much as $\sim 4$ times (see the purple and yellow lines). The radio light curves also indicate shorter timescale variabilities, which are prominent as several spike features in the right panel of Figure 1. In contrast, the MIR indicates only the stochastic flux variation in the averaged WISE data, although it does not have a time resolution of less than a half year, and periodic variability shorter than this period cannot be detected in these data.

3.2. Periodic Flux Variation of the 6.7 GHz Methanol Maser Emission in G036.70

The 6.7 GHz methanol maser in G036.70 was first detected through the unbiased survey with the Torun 32 m radio telescope (Szymczak et al. 2002), which showed seven spectral components in the LSR velocity range from +52 to $+63 \text{ km s}^{-1}$ (Szymczak et al. 2002; Pandian et al. 2007; Breen et al. 2015). This methanol maser has been monitored with the Hitachi 32 m radio telescope since 2013 January 3 (MJD 56295) as a target in the Ibaraki 6.7 GHz Methanol Maser Monitor (iMet) program (Yonekura et al. 2016). We compiled the flux monitoring data until October 28, 2019 (MJD 58784) in this paper, consisting of 328 observation data sets, as shown in Figure 2. During the monitoring term, there is a lack of observations on some blank dates when the monitoring was temporarily not performed due to system maintenance or other observations as follows: 2014 January 8–May 7 (MJD 56665–56784), 2017 March 6–June 14 (MJD 57818–57918), and 2018 April 15–June 7 (MJD 58223–58276). As an example of the spectrum, in the time from 2016 February to April, the brightest spectral components at an LSR velocity of $+61.99 \text{ km s}^{-1}$ (determined at the beginning of this monitoring) showed a minimum flux density of 1.26 Jy, which is just equal to $4 \sigma$ (rms noise level) on 2016 February 4 (MJD 57422) and a maximum flux density of 5.10 Jy on 2016 March 5 (MJD 57452; Figure 2(a)). In the maximum phase, another five spectral components at LSR velocities of $+52.46$, $+53.16$, $+53.60$, $+55.18$, and $+62.82 \text{ km s}^{-1}$ were brightened up beyond 3σ. In other different phases, a remaining spectral component at $+52.29 \text{ km s}^{-1}$ occasionally came up in the spectra.

These methanol maser emissions present a periodic flux variation with a continuous pattern, as shown in Figure 2(b). This periodicity was discovered through the iMet program, which was reported in Sugiyama et al. (2015, 2018, 2019), via compiling the monitoring data until mid-2016. We readopted the Lomb-Scargle (L-S) periodogram (Lomb 1976; Scargle 1982) to update the period of each cycle in the flux variation until 2019 October 28 (MJD 58784). The L-S periodogram is the most reliable method to search for the periodicity in flux variations of methanol masers, as verified in Goedhart et al. (2014). With an oversampling factor of four and a false-alarm probability $\leq 10^{-4}$ as significant that were used in the adoptions so far for other periodic sources (e.g., Goedhart et al. 2014; Sugiyama et al. 2017), this readoption resulted in a period of 53.0 day (corresponding to a frequency of 0.01888 cycle day$^{-1}$) for the brightest spectral component at $+61.99 \text{ km s}^{-1}$, with a normalized power in the periodogram of 64.0 that was significantly beyond the power level of 15.0 corresponding to a false-alarm probability of $10^{-4}$ (the dashed horizontal line), as shown in Figure 2(c). The L-S periodogram applied to other spectral components at $+53.16$, $+55.18$, and $+53.60$, $+62.82 \text{ km s}^{-1}$ also presented periods of 53.0 and 53.2 days, respectively, which were significantly detected beyond a false-alarm probability of $10^{-4}$. These periods were calculated from the neighboring frequency points in the L-S periodogram, in which the frequency resolution was 0.0001 cycle day$^{-1}$ or $\sim 0.3$ day.

We summarize the properties for the periodic flux variation of the 6.7 GHz methanol maser in G036.70 with the continuous pattern discovered through the iMet program as follows: (i) its period is 53.0–53.2 days, (ii) this periodicity was detected for most of the spectral components, and (iii) this continuous periodic flux variation has lasted for 47 cycles in the whole monitoring term of 2489 days from 2013 January 3 to 2019 October 28 (MJD 56295–58784), although a part of these observations was not directly verified due to the lack of observations in the following durations: MJD 56665–56784, 57818–57918, and MJD 58223–58276.

3.3. Comparison of the MIR and 6.7 GHz Maser Light Curves

To compare the MIR and radio light curves using different timescales, two graphs were plotted, as shown in Figure 3. Hereafter, the integrated flux density is used as characteristic data of 6.7 GHz maser fluxes in comparison to MIR data. First, the long, year-scale variability is compared in the left panel. In this plot, MIR single-exposure data are averaged over each scanning epoch for WISE, which is approximately a one-day duration and whose scanning period is twice a year. The radio data are binned over 50 days, which is almost equivalent to the period of 53.0–53.2 days. In addition to binning, the known periodic flux variation of 53.0–53.2 days in the radio data is removed in advance, assuming sinusoidal flux variation, because we focus on the comparison of the longer timescale
variability. The left panel of Figure 3 shows that both of the flux changes at the W1 and W2 bands are qualitatively consistent with long-scale radio time variability such as stochastic variability with certain peaks and valleys and almost simultaneous flux variation in the year-scale plot. A time delay between the MIR and radio bands is not seen clearly in this plot. We also investigate a shorter, day-long time variability and the correlation between the MIR and radio data. We cross-correlate the closest 6.7 GHz maser data with the WISE data, at least between the W1 and W2 bands.

Figure 3 presents a light curve of G036.70 during the preceding 10 yr period. The gray cross indicates that there is no significant color variability in the G036.70 NEOWISE data, at least between the W1 and W2 bands.

3.4. Color Variation in the MIR

The WISE color variability is a good proxy for deciphering two possible origins of variability: extinction and intrinsic flux variability (e.g., Uchiyama & Ichikawa 2019). The left panel of Figure 5 presents a light curve of W1–W2 color throughout the whole WISE data with a 1σ error bar. The resulting plot indicates that there is no significant color variability in the G036.70 NEOWISE data, at least between the W1 and W2 bands.

The middle and right panels of Figure 5 show the two color–magnitude diagrams (CMDs) of W1/2 and W1–W2 for G036.70 during the preceding 10 yr period. The gray cross...
represents the data for a single exposure, and the black cross represents the averaged data binned for each epoch. It should be noted that the correlation seen in the gray cross in the middle panel is made by the artificial trend because both of the W1 versus W1−W2 data contains the W1 band magnitude, and therefore the noise fluctuation by W1 produces an artificial y = −x linear sequence. Considering that we are interested in the year-scale long-term variability, we focus here on the trend of the binned data. The middle panel indicates that the averaged data do not display a clear color-dependent trend. To determine the details, we also developed the right plot of W2 versus W1−W2. This plot indicates that the W1−W2 color does not change significantly, and its behavior seems to be stochastic, whereas the W2 flux changes by as much as 0.4 mag. These results indicate that the MIR color of W1−W2 does not change significantly with the flux variation in G036.70. We considered that this flux variation without color change would be intrinsic, while we cannot totally rule out the situation that this trend occurred by line-of-sight extinction.

4. Discussion

4.1. Stellar Physical Parameters of G036.70

To discuss the flux variability of G036.70 in detail, we first investigated the stellar physical parameters through stellar model fitting using the IR spectral energy distribution (SED). The IR photometric data consist of archived data from Spitzer, WISE, and Herschel (Spitzer Science 2009; Cutri et al. 2012; Gutermuth & Heyer 2015; Elia et al. 2017) by cross-matching the coordinates of the maser emission of G036.70 with a search radius of 2′.5. The obtained IR SED spans the wavelengths from ∼3 to 350 μm, as summarized in Table 1, which covers the dust emission peak at 100 μm.

We applied the SED fitting tool to the IR SED provided by Robitaille et al. (2007). It contains various combinations of stellar and accretion disk parameters, such as extinction, total bolometric luminosity, stellar mass, effective temperature, and disk mass.

Figure 6 depicts the model SED (gray area) obtained from the SED fitting provided by Robitaille et al. (2007) as well as the obtained data points (black points). The SED model reproduces the peak emission at ∼100 μm and the expected deep silicate absorption at ∼10 μm well, and it also reproduces the strong dust extinction at λ < 2 μm. The obtained best-fit stellar parameters are tabulated in Table 2, assuming a distance range of 4–7 kpc from the gas kinematic distance measurement (Pandian & Goldsmith 2007; Szymczak et al. 2007). The obtained parameters indicate that G036.70 is essentially a massive and obscured YSO with a mass of 10 M⊙. The derived effective temperature is lower than 10⁴ K and is well consistent with previous observations of the absence of H II regions (Svoboda et al. 2016). Note that the SED fitting provides a
crude estimate of the stellar parameters because all the measurements used to fit SED originate from different measurement epochs, and most of the parameters listed in Table 2 should be treated with care.

In addition to the SED profile, the Spitzer archival color image of G036.70 shows a green and extended feature, similar to one of the extended green objects (Cyganowski et al. 2008). This suggests that G036.70 is an actively accreting object with powerful outflows and has a nearly edge-on disk, which is also indicated by the deep silicate feature in the IR SED.

4.2. Possible Origins of MIR and Maser Variability in G036.70

The results presented in Section 3 indicate that G036.70 has (i) a year-scale stochastic MIR and maser flux variability, (ii) no significant color variability in the MIR, and (iii) is clearly correlated with the 6.7 GHz maser intensity for the year- and day-long timescales. In this section, we discuss the possible origins of the MIR variability of G036.70. It should be noted that we do not discuss the known periodic variability of 53.0–53.2 days in masers because the time cadence of the WISE MIR data is not high enough to compare with this periodic variability. Future high-cadence MIR monitoring observations will enable us to discuss the possible origins of the periodic variability with MIR short-timescale variability.

The year-scale flux variability suggests nonperiodic events such as changes in the mass accretion rate or line-of-sight extinction owing to the nonaxisymmetric dust density distribution in the rotating accretion disk. In contrast, the stochastic MIR flux variability rules out stellar and/or planet occultation.

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**Table 1**

| Filter   | \( \lambda \) (\( \mu \)m) | \( f_\nu \) (Jy) | Aperture (arcsec) |
|----------|-----------------------------|-----------------|-------------------|
| IRAC3.6  | 3.6                         | 0.0141          | 2.4               |
| IRAC4.5  | 4.5                         | 0.0598          | 2.4               |
| IRAC5.8  | 5.8                         | 0.0669          | 2.4               |
| IRAC8.0  | 8.0                         | 0.0536          | 2.4               |
| WISE12   | 12.0                        | 0.1420          | 8.25              |
| MIPS24   | 24.0                        | 3.0600          | 6.50              |
| PACS70   | 70.0                        | 40.5460         | 6.00              |
| PACS160  | 160.0                       | 24.2280         | 12.00             |
| SPIRE350 | 350.0                       | 14.1190         | 24.00             |

**Note.** Columns: The four columns are defined as follows. Filter: Filter name used for SED fitting. \( \lambda \): Central wavelength with units of \( \mu \)m. \( f_\nu \): Flux density in units of Jy. Aperture: Aperture size of each photometry.

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**Table 2**

| Col. | Parameter | G036.70 |
|------|-----------|---------|
| (1)  | \( A_V \)/mag | 25.9\( ^{+28}_{-19} \) |
| (2)  | \( L_{bol}/L_\odot \) | 2.9\( ^{+97}_{-10} \) \times 10^3 |
| (3)  | \( M_\ast/M_\odot \) | 10.0\( ^{+0.8}_{-0.8} \) |
| (4)  | \( R_\ast/R_\odot \) | 35.0\( ^{+18}_{-18} \) |
| (5)  | \( T_\ast/K \) | 7.4\( ^{+27}_{-27} \) \times 10^3 |
| (6)  | \( M_{disk}/M_\odot \) | 1.6\( ^{+0.9}_{-1.1} \) \times 10^{-2} |
| (7)  | \( R_{disk,in}/\text{au} \) | 4.3\( ^{+0.7}_{-1.3} \) |
| (8)  | \( R_{disk,out}/\text{au} \) | 1.8\( ^{+1.3}_{-1.3} \) \times 10^2 |

**Note.** Columns: (1) Foreground dust extinction. (2) Total bolometric luminosity of G036.70. (3) Central stellar mass. (4) Central stellar radius. (5) Central stellar temperature. (6) Central stellar mass. (7) Disk mass. (8) Disk outer radius.

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**Figure 6.** Obtained SED for G036.70 and the best-fitting result. The black points with error bars correspond to the obtained IR photometries from Spitzer, Herschel/PACS, and SPIRE. The best-fitting SED is represented by the solid black line.
origins that indicate no MIR color variations. Therefore, a possible scenario is a change in mass accretion rate or in the line-of-sight extinction owing to the nonaxisymmetric dust density distribution of the edge-on-like accretion disk, with no significant color variation. This may occur because the color change caused by these scenarios is considered to be not as large as $\Delta W1-W2 < 0.5$ mag (Wang et al. 2014; Caratti o Garatti et al. 2017). We cannot rule out an origin in dust extinction because of the large scatter depicted in Figure 5. Thus, the trend is still consistent with the interstellar dust extinction vector.

In addition, a promising origin must describe the observed MIR-maser variability correlation in our study. Variability caused by a change in the accretion rate triggers changes in stellar luminosity and disk surface temperature distribution, and thus the disk IR emission intensity distribution. This phenomenon was reported in the S255-NIR3 accretion burst (Caratti o Garatti et al. 2017). Therefore, the change in accretion rate can explain the MIR-maser variability correlation because a class II methanol maser is considered to be pumped up by disk IR emission (Cragg et al. 2005). We can examine this scenario more precisely in the future through spectroscopic monitoring of the NIR and MIR bands covering accretion tracer emission lines, such as the hydrogen recombination lines. For variability caused by changes in line-of-sight extinction, some of the main scenarios cannot describe the observed MIR-maser correlation, such as the occultation of the flaring outer disk or infalling gas and dust, because these events do not affect the disk IR emission intensity. One possible origin is a puffed-up inner rim (Dullemond et al. 2001). The nonaxisymmetric dust density distribution of the inner rim can change the line-of-sight extinction through occultation, and it can also change the disk IR emission intensity by creating a shaded area on the accretion disk. In this case, it is essential to monitor the MIR emission at longer wavelengths to examine whether color variability occurs, which was previously reported in a lower-mass puffed-up inner rim YSO system.

### 4.3. Importance of the Correlation of the MIR and Maser Variability Detection in G036.70

As we discussed above, an MIR-maser variability correlation in MYSOs was first suggested in S255-NIR3 during the accretion burst phase (Caratti o Garatti et al. 2017). Caratti o Garatti and collaborators reported the appearance of accretion tracers during changes in the SED. Soon after this report, Stecklum (2018) and Olech et al. (2020) showed a correlation of the periodic MIR-maser variability in the intermediate-mass YSO G107.298+5.639. Therefore, our finding of a correlation of the MIR-maser variabilities in G036.70 is the second case for MYSOs and the first case in a nonburst phase MYSO. This detection further confirms the proposed scenario that the class II methanol maser in MYSOs is pumped up by disk IR emission (Cragg et al. 2005), not by an outflow-related shock.

Our results also indicate that the time delay between MIR and maser flux variation is shorter than a few days. This short time delay suggests a scenario in which the variations in the mass accretion rate of an MYSO can trigger a change in accretion luminosity and hence in MIR flux. This immediately affects the temperature distribution of the accretion disk, which in turn triggers the change in maser flux. The scenario hence suggests that the outflow cavity is a real cavity that does not contain MIR optically thick gas or dust, causing a significant time delay. Further precise measurements of time delay and more multiwavelengths monitoring of MYSOs will reveal characteristics and mechanisms of the correlation of the MIR and maser flux variability in MYSOs.

### 5. Conclusions

We identified a stochastic colorless yearly variability of G036.70 in the WISE W1 (3.4 $\mu$m) and W2 (4.6 $\mu$m) bands using the ALLWISE and NEOWISE archival data that cover a time period of 10 yr with a cadence of 6 months. We also found the flux variability correlation of the obtained WISE W1/W2 bands and the 6.7 GHz class II methanol maser fluxes using high-cadence monitoring data obtained using the Hitachi 32 m radio telescope: the Ibaraki 6.7 GHz Methanol Maser Monitor (iMet) program (Yonekura et al. 2016; Sugiyama et al. 2019). The correlation can be seen in the year-scale light curve and on the much shorter daily timescale. This MIR-maser variability correlation was reported for the first time in nonburst MYSOs. Our results support the scenario in which a class II methanol maser is pumped up by IR emission from accreting disks of MYSOs.

We also discussed possible origins of the MIR and maser variability. Considering the observed phenomena, such as yearly stochastic flux variation, almost colorless variability, and MIR-maser correlation, a change in the mass accretion rate or line-of-sight extinction caused by crossing the puffed-up inner rim may describe the situation. Monitoring observations through spectroscopy can help to further investigate the origin of the variability in G036.70.

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**Facilities**: WISE.

**Software**: astropy (Astropy Collaboration et al. 2013), Matplotlib (Hunter 2007), Pandas (McKinney 2010).

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