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A Synchronized Variation of the 6.7 GHz Methanol Maser in Cepheus A

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Abstract

We present the results of monitoring observations of a 6.7 GHz methanol maser in Cepheus A (Cep A) using the Yamaguchi 32 m radio telescope and of imaging observations conducted with the JVN (Japanese VLBI Network). We identified five spectral features, which are grouped into two groupes: redshifted (-1.9 and $-2.7\,\mathrm{km\,s^{-1}}$) and blueshifted ($-3.8$, -4.2, and $-4.9\,\mathrm{km\,s^{-1}}$). We detected rapid variabilities in these maser features within a monitoring period of 81 d. The redshifted features decreased in flux density to 50% of the initial value, while the blueshifted ones rapidly increased within 30 d. The time variation in these maser features had two remarkable properties: synchronization and negative correlation between the redshifted and the blueshifted. Based on the JVN observations, we found that the maser spots were associated with the Cep A HW2 object and had an arched structure with a scale of ~ 1400 AU; also, separations of the five maser features were found to be larger than 100 AU. These properties of the masers, namely, the synchronization of the flux variation and the spectral and spatial isolations of the features, suggest that collisional excitation by a shock wave from a common exciting source is unlikely to happen. Instead, the synchronized time variation of the masers can be explained if all of the maser features are excited by infrared radiation from the dust that is heated by a common exciting source with a rapid variability.

Key words: ISM: H II regions — ISM: individual (Cepheus A) — masers

1. Introduction

The $5_1 \rightarrow 6_0 A^+$ methanol maser transition at 6.7 GHz has the strongest flux densities among methanol lines. The methanol maser emission is thought to be produced by radiative excitation in an infrared radiation field, which is formed by the dust near the protostar with a temperature of $\sim$100–200 K (Sobolev et al. 1997; Sutton et al. 2001; Cragg et al. 2005). Some sources, however, are associated with shocked gas (Walsh et al. 1998; De Buizer 2003; Dodson et al. 2004). Collisional excitation by a shock wave may produce the methanol maser emission.

A number of 6.7 GHz methanol masers have been found to exhibit long-term variability. Caswell et al. (1995) found that the sources vary on a time scale of several months. Szymczak, Hrynek, and Kus (2000) showed that about 65% of methanol masers in their sample exhibit moderate or strong variability on time scales of about four and eight years. A long-term monitoring program to investigate the variability in 54 methanol maser sources at 6.7 GHz has been conducted using the Hartebeesthoek 26 m radio telescope by Goedhart, Gaylard, and van der Walt (2004). They divided the variable sources into six types according to the behavior of the variability. For G 9.62+0.20 E in their sample, the periodic variations associated with massive star formation were discovered for the first time (Goedhart et al. 2003). Very Long Baseline Interferometer (VLBI) monitoring at seven epochs over three months for G 9.62+0.20 E was conducted within the period of the time variation (Goedhart et al. 2005). Neither appearance of new spots nor change in the morphology was found, suggesting that the flares were caused by a change in either the seed or the pump photon levels. They proposed a binary system as an origin of the periodic flares. MacLeod and Gaylard (1996) continuously observed G 351.78−0.54, and found flares at least seven times with time delays in the range of 10–35 d between the variability of redshifted spectral feature and blueshifted one. They discussed the delay, which can possibly be explained in terms of the light-crossing time due to the spatial distribution of spots.

We conducted daily monitoring for some maser sources to investigate any short time-scale variability with the Yamaguchi 32 m radio telescope. Cepheus A (Cep A) was observed as one of our sample sources. Cep A is a CO condensation at a distance of 725 pc (Johnson 1957), and some radio continuum sources were detected. Methanol masers are associated with Cep A HW2, defined by Hughes and Wouterloot (1984), which is the brightest radio continuum source detected in the region. The HW2 object has a radio continuum jet along a position angle (PA) of $\sim 45°$ (Rodríguez et al. 1994; Hughes et al. 1995; Torrelles et al. 1996, 1998; Curiel et al. 2006). Based on submillimeter observations of both dust and CH_3CN line emissions, a flattened disklike structure was found (Patel et al. 2005). The structure has a size of about 1000 AU and is perpendicular to the jet. Recently, it has been revealed that NH_3 and SO_2 line emissions coincided with the CH_3CN disk, although the SO_2 structure was about 2 times smaller (Torrelles et al. 2007; Jiménez-Serra et al. 2007). The 22.2 GHz water masers observed by Torrelles et al. (1996) were distributed in an elongated structure perpendicular to the radio jet, which possibly traces the circumstellar disk around the HW2 object. A spatial distribution of the water maser is similar to that of the SO_2 disk. The methanol maser at 6.7 GHz in Cep A shows variability. It was 1420 Jy in 1991 (Menten 1991), but 815 Jy in 1999 (Szymczak et al. 2000). Galt (2003) has found that the amplitude ratio of the lines at radial velocities of $-3.8\,\mathrm{km\,s^{-1}}$ and $-4.2\,\mathrm{km\,s^{-1}}$ changed from 1.4 to 0.8 over two years. The spatial distribution of the masers at 6.7 GHz for Cep A have been already reported (Sugiyama et al. 2008) with the Japanese VLBI Network (JVN: Doi et al. 2006). However, the image quality was not enough to investigate the relationships between the spectral features and the spatial distribution.

In this paper, we present the spectral variability with the spectral monitoring observations and a new VLBI map. In section 2, we describe the details of these observations and data reduction, and present the results in section 3. In section 4, we discuss interpretations of the rapid variability and excitation mechanism of this maser in Cep A.

2. Observations and Data Reduction

2.1. *Spectral Monitoring*

A daily monitoring program with the Yamaguchi 32 m radio telescope was conducted from August 4 [corresponding to the day of the year (DOY) 216] to 2007 October 24 (DOY 297). The full-width at half maximum (FWHM) of the beam is $5'$ at 6.7 GHz. The pointing error of the antenna is smaller than $1'$. The spectrometer consists of the IP-VLBI system (Kondo et al. 2003) and a software spectrometer. Both left and right circular polarizations were recorded with 2-bit sampling. The recorded data with a bandwidth of 4 MHz, covering a velocity range of $180\,\mathrm{km\,s^{-1}}$, were divided into 4096 channels, yielding a velocity resolution of $0.044\,\mathrm{km\,s^{-1}}$. The integration time was 14 min until DOY 244, and then 10 min from DOY 245. The rms noise level was typically 1.2 Jy and 1.4 Jy with an integration time of 14 min and 10 min, respectively. Amplitude and gain calibrations were performed by measuring the system noise temperatures by injecting the signal from noise-sources with known temperatures. The accuracy of the calibration was estimated to be 10%. The stability of the system was checked by daily monitoring of the G 12.91−0.26 methanol maser emission, which showed relatively small variability in the sample of Goedhart, Gaylard, and van der Walt (2004).

2.2. *VLBI Observation*

A VLBI observation at 6.7 GHz of Cep A was made on 2006 September 9 from 15:00 to 22:00 UT with four telescopes (Yamaguchi 32 m, Usuda 64 m, VERA-Mizusawa 20 m, and VERA-Ishigaki 20 m) of the JVN. The projected baselines covered a range of $9\,\mathrm{M}\lambda$ (Usuda–Mizusawa) to $50\,\mathrm{M}\lambda$ (Mizusawa–Ishigaki), corresponding to a fringe spacing of 23 mas and 4.1 mas, respectively. Left-circular polarization was received at Yamaguchi and Usuda stations, while linear polarization was received at Mizusawa and Ishigaki stations. A special amplitude calibration for different polarizations was made by the same procedure as described in Sugiyama et al. (2008). The data were recorded on magnetic tapes using the VSOP-terminal system at a data rate of 128 Mbps with 2-bit quantization and 2 channels, and correlated at the Mitaka FX correlator (Shibata et al. 1998). From the recorded 32 MHz bandwidth, 2 MHz (6668–6670 MHz) was divided into 512 channels for maser reduction, yielding a velocity resolution of $0.176\,\mathrm{km\,s^{-1}}$. This resolution is four times broader than that of the single-dish observation.

A continuum source, J2302+6405 ($2\overset{\circ}{.}19$ from Cep A), whose coordinates are known with an accuracy of 0.62 mas in the third VLBA Calibrator Survey (VCS3) catalog (Petrov et al. 2005), was used as a phase-reference calibrator. We observed alternately the Cep A methanol maser and the continuum source with the switching observational mode with a cycle of 5 min (2 min on Cep A and 1.6 min on the continuum source). Cep A was sometimes continuously observed for more than 30 min to improve the UV-coverage. The total on-source times were 2.8 hr for Cep A and 0.7 hr for J2302+6405. Bright continuum sources, 3C 454.3 and 3C 84, were also observed every one and a half hours for clock and bandpass calibrations. The synthesized beam had a size of 9.0×3.5 mas with a PA of $-70°$.

The data were reduced using the Astronomical Image Processing System (AIPS: Greisen 2003) and the Difmap software (Shepherd 1997). The visibilities of all velocity channels were phase-referenced to the reference maser spot at an LSR velocity of $-2.64\,\mathrm{km\,s^{-1}}$, which is the brightest spot. The absolute coordinates of the spot of $-2.64\,\mathrm{km\,s^{-1}}$ were obtained by applying the solution of the phase for the velocity channel to the phase-reference source, J2302+6405.

3. Results

3.1. *Spectral Variability*

We detected a rapid variability in the spectrum of the 6.7 GHz methanol maser of Cep A. Five spectral features, at radial velocities of -1.9, -2.7, -3.8, -4.2, and $-4.9\,\mathrm{km\,s^{-1}}$, were identified during the whole observing period, as shown in figure 1. The maser features were labeled as I, II, III, IV, and V, respectively. Feature II had a shoulder at $-2.5\,\mathrm{km\,s^{-1}}$, corresponding a second component. Since we could not clearly distinguish the two components of feature II, we do not discuss the second component in this paper.

The maser features are divided into two groups: two redshifted features (I, II) and three blueshifted features (III, IV, V). These two groups are clearly separated in the

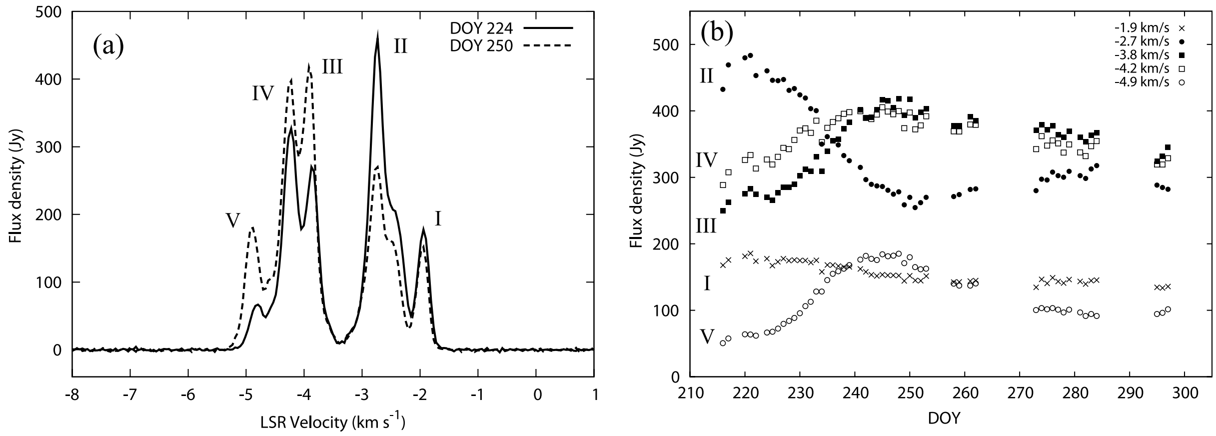

Fig. 1. The 6.7 GHz methanol maser in Cep A. The labels I, II, III, IV, and V correspond to each spectral feature in each panel. (a) The spectra obtained in the monitoring observations. The solid and dashed lines show the spectra obtained in DOY 224 and DOY 250 observations, respectively. (b) Time variation of each spectral feature.

Table 1. Correlation coefficients from DOY 216 to 250.

Feature	Feature			
	I	II	III	IV
II	0.94			
III	−0.83	−0.96		
IV	−0.63	−0.84	0.92	
V	−0.83	−0.97	0.98	0.94

Table 2. Correlation coefficients for all days.

Feature	Feature			
	I	II	III	IV
II	0.89			
III	−0.65	−0.91		
IV	−0.08	−0.50	0.77	
V	−0.28	−0.68	0.84	0.92

spectrum. They also followed different trends of variation, as shown in figure 1b. During the first 30 d of the monitoring, the redshifted group decreased in flux density to 50% of the initial value (feature II), while the blueshifted one increased by 300% (feature V). The correlation coefficients for all combinations of the spectral features for the data from DOY 216 to 250 are given in table 1. The absolute values of the correlation coefficients are larger than 0.80, with the only exception being 0.63 for I versus IV. The variation shows a strong positive correlation within each group, and a negative correlation between these two groups.

A trend of the variation suddenly changed on around DOY 250. The redshifted group started to increase and the blueshifted one to decrease. The rate of variation was smaller than that of the previous period. This change in the variation trend was clearly synchronized.

Correlation coefficients of the variation during the whole period are shown in table 2. The coefficients show essentially the same trends as those during the first period. Feature II shows a strong and positive correlation (0.89) with feature I, while a negative correlation was seen with features III, IV, and V. The correlation coefficients are −0.91, −0.50, and −0.68, respectively. Figure 2 shows correlation plots for combinations with respect to feature II. The positive (I) and negative (III, IV, V) correlations are obvious.

The flux variations of features III and IV are quite similar, but feature IV is slightly advanced in variation. The cross-correlation of the time series of the features showed small time delays. The largest delay was 6 d for II to IV, and the smallest was 1 d for II to III and for V to IV. We ignored feature I because of its small variation.

3.2. *Spatial Distribution*

With the VLBI observation, 117 spots of the methanol maser emission were detected. The peak intensities of the spots ranged from $\sim$650 mJy beam^{-1} to 122 Jy beam^{-1}, while the rms of the image noise (1σ) in a line-free channel was 160 mJy beam^{-1}. The correlated flux accounted for over 90% of the single-dish flux. The spatial distribution of the maser spots (figure 3) showed an arched structure. The size from edge to edge of the arched structure is $\sim$1900 mas or $\sim$1400 AU at a distance of 725 pc.

The coordinates of the spot at $-2.64\,\mathrm{km\,s^{-1}}$ obtained from our observation are α(J2000.0) $= 22^{\mathrm{h}}56^{\mathrm{m}}17\overset{\mathrm{s}}{.}9042$ and δ(J2000.0) $= +62^{\circ}01'49\overset{''}{.}577$, with errors of 1 mas. This is the origin of the image. The peak of 43 GHz continuum emission (star symbol in figure 3), which may be an exciting source (Curiel et al. 2006), is located near the center of the arched structure of the 6.7 GHz methanol maser spots. The elongation of the arched structure is nearly perpendicular to the radio jet. The overall distribution of the maser spots coincides with the CH_3CN and NH_3 disks (Patel et al. 2005; Torrelles et al. 2007) and the velocity range of the spots is similar to that of these disks, although a simple velocity gradient was not detected in the maser spots. The water maser disk reported by Torrelles et al. (1996) is located at almost the same position as the methanol arched structure, although the size of the water maser disk is about 2 times smaller. The ground-state

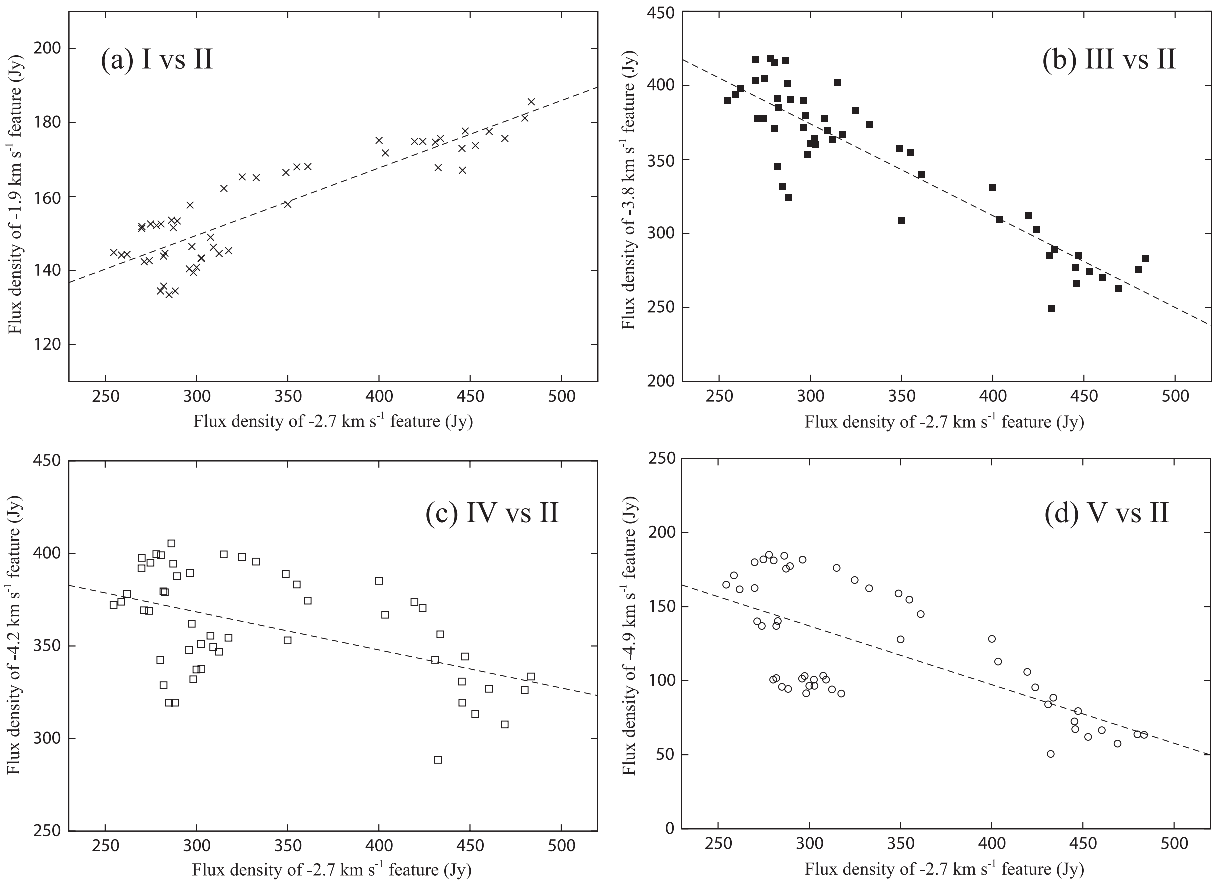

Fig. 2. Correlation plots with respect to the spectral feature II. The symbols in each panel correspond to the spectral features in figure 1b. The dashed lines in each panel indicate the best fits to the data.

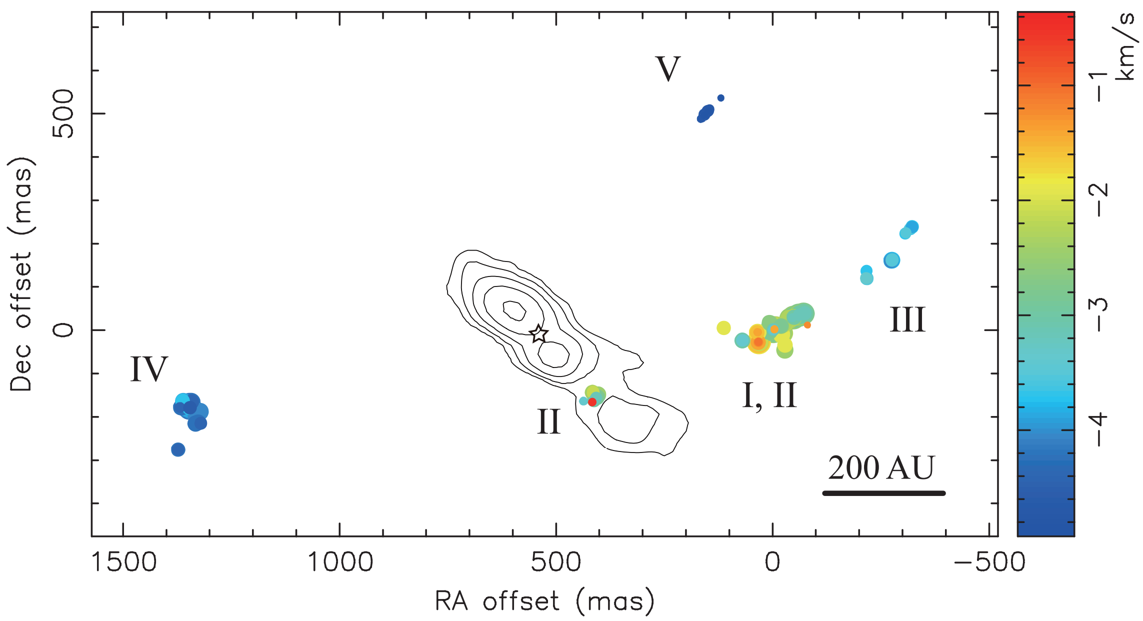

Fig. 3. Spatial distribution of the 6.7 GHz methanol maser spots (filled circle) of Cep A. The spot size and color indicate its peak intensity in logarithmic scale and its radial velocity (see color index at the right), respectively. The contours indicate the VLA 22 GHz continuum observed by Torrelles et al. (1998) and re-reduced by Gallimore et al. (2003). A star indicates the peak of 43 GHz continuum emission with a positional uncertainty of about 10 mas. It is thought to be the location of an exciting source (Curiel et al. 2006). The origin of this map corresponds to the coordinates of the 6.7 GHz methanol maser [α(J2000.0) = 22$^{\rm h}$56$^{\rm m}$17$\overset{\rm s}{.}$9042, δ(J2000.0) = +62°01′49$\overset{\prime\prime}{.}$577] obtained from our observation.

hydroxyl masers around the HW2 object (Migenes et al. 1992; Bartkiewicz et al. 2005), whose internal proper motions were mainly directed away from the central source, are distributed surrounding the methanol maser distribution. The radial velocities of both masers (water: -27.3 to $+8.9\,\mathrm{km\,s^{-1}}$; hydroxyl: -25.2 to $-0.6\,\mathrm{km\,s^{-1}}$) cover the range of the methanol maser (-4.93 to $-0.36\,\mathrm{km\,s^{-1}}$).

The cluster of spots that is located near the origin of the VLBI map corresponds to spectral features I and II, and a cluster at $0\farcs45$ east and $0\farcs10$ south from the origin corresponds to feature II. The correspondences of the other clusters and the spectral features are as follows: the western cluster ($0\farcs30$ west, $0\farcs20$ north) is III, the eastern cluster ($1\farcs35$ east, $0\farcs20$ south) IV, and the northern cluster ($0\farcs10$ east, $0\farcs50$ north) V. Clusters II ($0\farcs45$ east, $0\farcs10$ south) and V were detected for the first time in VLBI observations. Some weak spots with radial velocities of -0.53 to $-0.36\,\mathrm{km\,s^{-1}}$, which are a part of cluster II, were detected only in the VLBI observation, and not detected in the spectral observation with the Yamaguchi 32 m telescope. The redshifted (I, II) and the blueshifted (III, IV, V) features are isolated in the spatial distribution by more than 100 AU, and the redshifted features are surrounded by the blueshifted features.

4. Discussions

The time variation of the methanol maser features of Cep A was synchronized, and correlated. The synchronized variation occurred in spatially isolated maser features. The separation of the clusters is larger than 100 AU in the overall spatial distribution of ~ 1400 AU, and it is not likely that there are some mechanical interactions among the features that cause a synchronized variation. The synchronized variation may be caused by a shock wave from a central star, that arrived at the clusters simultaneously. If we assume an outflow velocity of $4.5\,\mathrm{km\,s^{-1}}$, which corresponds to the radial-velocity range of the Cep A methanol maser, it takes more than 1000 yr to propagate through a spatial scale of 1000 AU. The synchronized arrival at the separated clusters with a time delay of less than several days requires a very fine tuning of the arrival time ($6\,\mathrm{d}/1000\,\mathrm{yr} \sim 0.002\%$), which is highly unlikely. The synchronization, the spatial isolation, and the spectral separation of the maser features suggest that it is difficult to excite the maser by collisions with a shock wave from a common exciting source.

These properties favor the widely accepted excitation model that the 6.7 GHz methanol masers are excited by infrared radiation from nearby warm dust (e.g., Sobolev et al. 1997). Infrared radiation from one variable exciting source can easily explain the synchronized variation with the spatial isolation and the spectral separation. The exciting source might correspond to that shown by Curiel et al. (2006). The bolometric luminosity of the Cep A region is about $2.5 \times 10^4\,L_\odot$ (Evans et al. 1981). Assuming that half of this luminosity is attributed to the HW2 object (Rodríguez et al. 1994; Hughes et al. 1995), we derived a dust temperature of 110 K at 700 AU from the exciting source. The distance of 700 AU is one from the supposed exciting source to the farthest maser spot. This temperature 110 K is consistent with the suitable one ($\sim$ 100–200 K) of regions producing 6.7 GHz methanol maser (e.g., Cragg et al. 2005). This time-variation model of one exciting source may be applicable to the periodic variations of the 6.7 GHz methanol maser for G 9.62+0.20 E.

The time variation of the Cep A methanol maser showed a negative correlation between the redshifted and the blueshifted features. The light-crossing time of ~ 1400 AU is 8 light days. It is consistent with the time delay (1–6 d) in the cross-correlation of the flux variation of the spectral features. However, the light-crossing time is too short to cause a negative correlation with a time scale of more than 20 d. The negative correlation could be understood in terms of the excitation environment. The 6.7 GHz methanol maser requires a suitable temperature range ($\sim$ 100–200 K). The dust temperature is high in the region close to the exciting source, and is low in the region far from the source. If the exciting source increases its luminosity, the temperature near the source would be too high to produce the maser emission, while the temperature far from the source would be suitable to produce it. Although the 3-dimensional distribution of the maser features is uncertain, the 2-dimensional distribution of the maser features of Cep A indicates that the redshifted features are close to the supposed exciting source, and the blueshifted ones are far from it. With this spatial distribution, the negative correlation of the variation could be explained by the change of the dust temperature caused by the variability of the exciting source; i.e., during the interval between DOY 216 and DOY 250, the dust in feature II, which is closer to the exciting source, increases in temperature beyond 200 K, outside of the range appropriate to the maser excitation, while feature III, IV, and V increased from 110 K, nearly the minimum temperature of maser excitation, to produce stronger maser emission.

Additional observations are required to confirm this model, particularly to know if a short time variation of the luminosity occurs in the exciting source. The distribution of the maser features is observed as a 2-dimensional projection. The velocity field would be a clue for understanding the 3-dimensional structure of this region. We are conducting VLBI monitoring observations to detect the internal proper motion of methanol maser spots; the results will be reported in the future.

5. Conclusion

We have detected a rapid variability of the 6.7 GHz methanol maser of Cep A. Five spectral features are grouped into redshifted (-1.9 and $-2.7\,\mathrm{km\,s^{-1}}$) and blueshifted ($-3.8$, -4.2, and $-4.9\,\mathrm{km\,s^{-1}}$). These two groups are clearly separated in the spectrum. They also exhibited different trends of variation. The time variation of these maser features showed two remarkable properties: synchronization and negative correlation between the redshifted and the blueshifted features. The spatial distribution of the maser spots obtained by the VLBI observation showed that the maser spots of each feature are largely separated. The synchronization and the spectral and the spatial isolations suggest that the collisional excitation by a shock wave from a common exciting source is unlikely to happen. We discussed that the time variation of the Cep A methanol maser could be produced by one variable exciting source, and that this maser could be excited by radiation from the exciting source. It is possibly thought that the negative correlation is caused by a variation of the dust temperature of the maser regions as a result of the distance to the exciting source and the time variation of the exciting source's luminosity.

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