Research in Astron. Astrophys. **2013** Vol. **13** No. **3**, 270–276
http://www.raa-journal.org *http://www.iop.org/journals/raa*

Research in Astronomy and Astrophysics

High resolution observations of the 6 cm H_2CO maser in NGC 6240 *

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Received 2011 November 18; accepted 2012 October 10

Abstract We present high resolution ($\sim 1''$) H_2CO maser and 5 GHz radio continuum observations toward nearby merging galaxy NGC 6240 made with the Very Large Array in an A configuration. Two concentrations of H_2CO emission at about a 6σ level have been detected, one of which is associated with the strongest CO peak in the overlap region while the other is about $2''$ southwest of the southern galaxy. Both H_2CO concentrations are associated with near infrared H_2 emission, which is thought to be from shocked molecular gas. The total H_2CO line luminosity in NGC 6240 is about 60% of that in Arp 220. Based on the distribution of H_2CO emission in NGC 6240, which has both active galactic nuclei and an extreme starburst, the H_2CO megamaser is likely to be related to the effect of the starburst instead of nuclear activity. Radio continuum cannot be the inversion mechanism of H_2CO megamasers, because the two H_2CO concentrations in NGC 6240 are not associated with radio continuum emission. Instead, with the association of near infrared H_2 emission, shock dynamics may produce the inverted population of H_2CO needed to generate megamasers.

Key words: galaxies: ISM — galaxies: kinematics and dynamics — galaxies: individual (NGC 6240)

1 INTRODUCTION

Formaldehyde (H_2CO) was first detected in the Milky Way in absorption at 4.8296569 GHz ($1_{11}\rightarrow1_{10}$) (Snyder et al. 1969), but emission of this line is rare both in the Milky Way and in other galaxies (Araya et al. 2004). There are so far seven maser regions that have been reported in the Milky Way (Araya et al. 2007a) and about ten detections of H_2CO $1_{11}\rightarrow1_{10}$ line emission in other galaxies, but only three (Arp 220, IC 860 and IR 15107+0724) of them have been confirmed independently (Baan et al. 1986, 1993; Araya et al. 2004; Mangum et al. 2008). H_2CO $1_{11}\rightarrow1_{10}$ emission in galaxies was thought to be from megamasers instead of thermal emission (Baan et al.

* Supported by the National Natural Science Foundation of China.

1986). Because of the small number of extragalactic sources that have been detected emitting H_2CO $1_{11}\rightarrow 1_{10}$ and only one high resolution observation which was done toward Arp 220 with the Very Large Array (VLA) (Baan & Haschick 1995), it is hard to determine if this maser emission is due to nuclear activity, which is thought to produce H_2O megamasers, or a starburst, like OH megamasers (Lo 2005). High spatial resolution observations toward H_2CO emitting galaxies with both Active Galactic Nuclei (AGNs) and starbursts are necessary for possibly disentangling the origin of H_2CO megamasers.

NGC 6240 is the first identified double AGN with a separation of 1.4″ (Komossa et al. 2003) at a distance of 107 Mpc (Iono et al. 2007). With detection of strong H_2CO emission (Baan et al. 1993), it is an ideal source for determining the origin of H_2CO emission using high resolution observations. Most of the molecular gas, traced by CO 2–1, is concentrated in the overlap region between the two galaxies, but the 1.3 mm continuum emission is dominated by the southern nucleus and was thought to be non-thermal synchrotron emission (Tacconi et al. 1999). Warm molecular gas traced by CO 3–2 is also concentrated in the area where the strongest CO 2–1 emission is detected, as well as 860 μm continuum emission which is thought to be mainly from thermal dust emission (Iono et al. 2007). High spatial resolution observations toward NGC 6240 can help to determine the origin of H_2CO megamasers: is it from off-nuclear starburst regions between the two merging nuclei like OH megamasers, or from disks around an AGN like H_2O megamasers (Lo 2005)?

In this paper, we describe the observations and data reduction in Section 2, present our main results in Section 3, discuss findings related to the origin of an H_2CO megamaser with single dish H_2CO observations and multi-wavelength properties in Section 4, and give a brief summary in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

H_2CO maser and 5 GHz radio continuum emission observations of NGC 6240 were made with the NRAO VLA C band in A configuration on 2007 June 21 for 8 h. 3C 286 was used as a flux and bandpass calibrator, while 1658+052 was used as a phase calibrator with cycling of 2 min and 20 min between phase calibrator and source, respectively. The correlator was configured in 2AC mode with a bandwidth of 25 MHz, yielding 15 channels and 1.5625 MHz frequency resolution for each polarization. The frequency at the band center was set at the frequency 4.7148495 GHz, which gave the optical velocity of 7305 km s^{-1} for the H_2CO ($1_{10} - 1_{11}$, rest frequency 4.8296569 GHz) line and had a velocity coverage of about 1500 km s^{-1}. The data were calibrated and imaged after combining dual polarization data with AIPS. Line-free channels were used for continuum subtraction with the task 'uvlsf' and for making a continuum image, which gave the beam size of $0.5'' \times 0.48''$ and position angle of 12.6° with natural weighting. To avoid an edge channel effect and possible line emission, we used the 3rd and 12th channels, which corresponded to the velocity of 7790 km s^{-1} and 6916 km s^{-1} respectively, as line free channels for continuum subtraction. Then we integrated eight channels from 4 to 11, which corresponded to the velocity width of ~ 780 km s^{-1}, to produce the image for H_2CO emission. To improve the signal to noise ratio, we performed 'uvtaper' for the continuum subtracted data and obtained a larger beam size ($1.0'' \times 0.93''$ with position angle of $29°$) than that of the continuum map, with a noise level of 0.06 mJy $beam^{-1}$. We also obtained the data cube of H_2CO emission with and without continuum subtraction.

3 RESULTS

We detected two concentrations of H_2CO emission in NGC 6240 at about the 6σ level (see Fig. 1), neither of which is directly associated with the two nuclei. H_2CO emission at the position of $\alpha = 16^{\rm h}52^{\rm m}58.88^{\rm s}$, $\delta = 02°24'03.75''$ (J2000) is in between the two nuclei but closer to the southern galaxy than to the northern galaxy, while the second H_2CO emission component, with $\alpha = 16^{\rm h}52^{\rm m}58.76^{\rm s}$, $\delta = 02°24'02.65''$ (J2000), is located to the southwest of the southern galaxy.

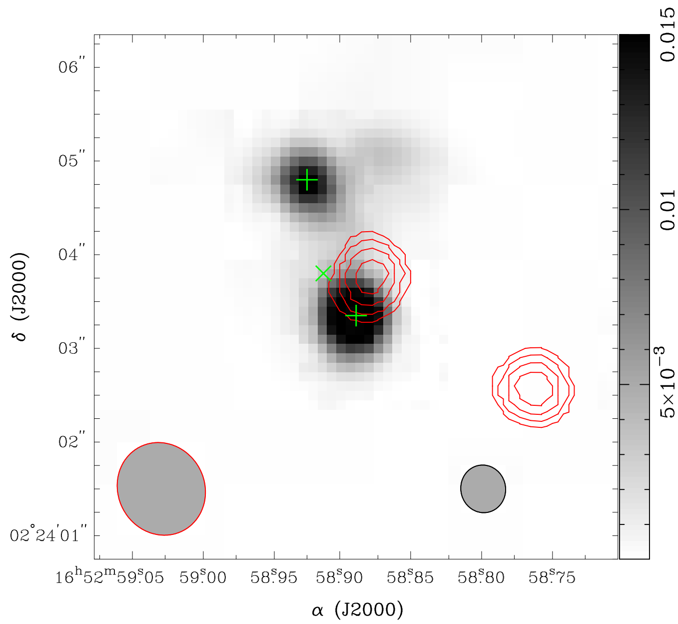

Fig. 1 H_2CO (*contour*) overlaid on 5 GHz radio continuum emission (*gray scale*) obtained simultaneously with our VLA observation. The two '+' symbols are the continuum peaks of the two galaxies from our data, while the '×' is the peak of CO 3–2 (Iono et al. 2007). The beam size of H_2CO emission is $1.0'' \times 0.93''$ with position angle of $29°$, while it is $0.5'' \times 0.48''$ with a position angle of $12.6°$ for the 5 GHz continuum. The contour levels are 0.04 mJy beam^{-1} × 6, 7, 8 and 9, and the rms is 0.06 mJy for H_2CO maser emission.

The fluxes of the two H_2CO emission components are 0.38 Jy km s^{-1} and 0.35 Jy km s^{-1} respectively.

Figure 1 shows the overlay of H_2CO and 5 GHz radio continuum emission obtained simultaneously with our VLA observation. Apparently, they have little correspondence in terms of spatial distribution except for the northern part of the southern nucleus region. However, the continuum distribution is similar to the results of C band continuum morphology which has been well presented and discussed in Colbert et al. (1994).

The location of the stronger H_2CO emission is near the peak of CO 3–2 (Iono et al. 2007) and 2–1 (Tacconi et al. 1999), with an offset of about $0.5''$ toward the west. The second component of the H_2CO maser is associated with the 'A' component of CO 2–1 emission (Tacconi et al. 1999) as well as with the extended CO 3–2 and HCO^+ 4–3 (Iono et al. 2007), and also with near-IR H_2 emission observed by HST and Keck (Max et al. 2005). In a high resolution CO 3–2 map (Vivian U et al., private communication), the strongest CO 3–2 peak is essentially at the position identical to the stronger H_2CO.

Single dish H_2CO observations toward NGC 6240 have been done with Arecibo (Baan et al. 1993; Araya et al. 2004) and Green Bank Telescope (GBT) (Mangum et al. 2008), which showed different results in these three observations. Baan et al. (1993) claimed a detection of strong emission with the peak intensity of ∼2.6 mJy and a width of ∼ 600 km s^{-1}, but the new observation with Arecibo (Araya et al. 2004) did not detect this emission due to a bandpass problem, and the observation with GBT (Mangum et al. 2008) showed the absorption line of H_2CO instead of emission. For comparison, we produced our VLA data cube without subtracting continuum emission and obtained

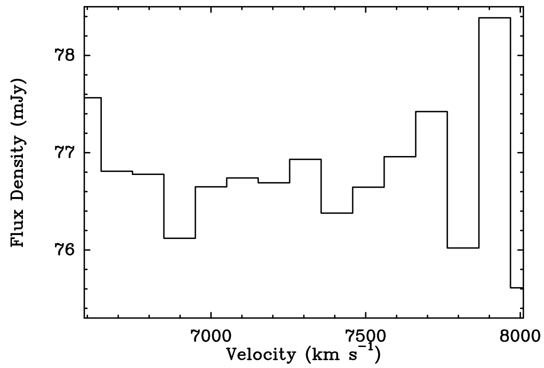

Fig. 2 Integrated spectrum of the H_2CO line over the whole NGC 6240 emission region.

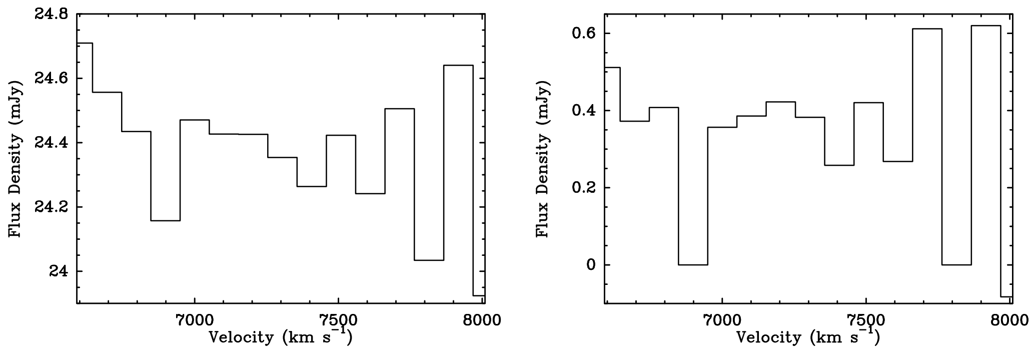

Fig. 3 Spectra of the concentration at the peak position between the two nuclei, without (*left*) and with (*right*) 'uvlsf.'

the integrated spectrum of the whole system. Our result is somewhat similar to that of the GBT observation (Mangum et al. 2008), showing the absorption line instead of the emission line of H_2CO. The continuum flux obtained in our observation is similar to that from the VLA A configuration at 4.885 GHz (Colbert et al. 1994), which means that our flux calibration is correct. But the 6 cm continuum flux from our data and the previous data from the VLA A configuration only recover $\sim 60\%$ of the flux compared to data from the VLA B configuration (Colbert et al. 1994) and single dish measurement (Gregory & Condon 1991; Griffith et al. 1995), which reveals that missing flux from the extended continuum emission is a serious problem in our high resolution data. With the continuum subtracted image of H_2CO and the integrated spectrum of the entire source without continuum subtraction shown in Figure 2, we found that NGC 6240 had both the emission and absorption line of H_2CO, which were mixed in single dish observations because the beams were much larger than the size of NGC 6240. Even though, due to the bandwidth limitation of the VLA correlator, only the 3rd and 12th channels have been used as line-free channels for continuum subtraction, we have already avoided the edge channels to obtain line emission of H_2CO. The data cube made without continuum subtraction shows that only the first and last channels have significantly higher rms than that of other channels, but other channels, including the 3rd and 12th channels, are at the same noise level.

We also obtained the spectra at peak positions of the two concentrations from the data cube with and without continuum subtraction through 'uvlsf.' The spectra of the concentration in be-

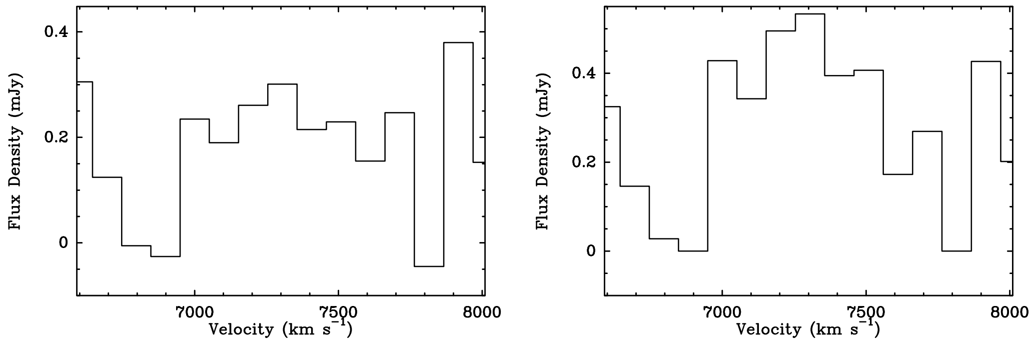

Fig. 4 Spectra of the concentration at the second component associated with the peak position, without (*left*) and with (*right*) 'uvlsf.'

tween the two galaxies are shown in Figure 3, while the others are shown in Figure 4. Since the concentration between the two nuclei is affected by the continuum emission from the southern nucleus, which is about 100 times that of the line flux, H_2CO emission obtained with and without continuum subtraction show different line shapes. On the other hand, the spectra with and without continuum subtraction of the second concentration show a similar line shape, but the spectrum with continuum subtraction has a higher line flux than that without continuum subtraction. The spectrum with continuum subtraction is at the 3σ level, with an rms of about 0.15 mJy at the velocity resolution ~ 90 km s^{-1}, but the theoretical rms at such velocity resolution is about 0.08 mJy. The higher rms of our result compared to the theoretical number may be caused by a side lobe of the strong continuum emission from the two nuclei.

4 DISCUSSION

As NGC 6240 is a galaxy merger with both nuclear activity and extreme starburst activity, and our results showed that neither of the two H_2CO maser concentrations was directly associated with the nuclei, we would like to suggest that H_2CO megamasers are not necessarily related to nuclear activity. With our $\sim 1''$ resolution beam and limited S/N ratio, it is hard to study detailed structures of the two H_2CO concentrations. But we know that they are not point sources, because we obtained a better S/N ratio map with 'uvtaper' than that without 'uvtaper.' Both H_2CO concentrations are associated with strong near-IR H_2 emission (Max et al. 2005), which is thought to be from shocked molecular gas. Such results imply that H_2CO megamasers may be from shocked gas regions. With a high resolution observation of absorption (Baan et al. 2007), HI column density peaked at the southern nucleus, while OH column density peaked in between the two nuclei, near to our H_2CO maser concentration in between the two nuclei. On the other hand, the H_2CO concentration southwest of the southern nucleus is associated with extended HI absorption and an off-nuclear OH concentration based on the results from the VLA observation (Baan et al. 2007). So the two H_2CO concentrations in NGC 6240 are related to molecular gas traced not only by CO emission but also by OH absorption.

Maser emissions in NGC 6240 are not associated with radio continuum based on our high resolution map. After checking with the low resolution B configuration C band data (Colbert et al. 1994), the southwest concentration at the position of $\alpha = 16^{\rm h}52^{\rm m}58.76^{\rm s}$, $\delta = 02^\circ24'02.65''$ (J2000) has very weak or no C band continuum emission, at the level of less than 3 mJy beam^{-1}. So the radio continuum, which has been proposed by Boland & de Jong (1981) and Pratap et al. (1992) for the H_2CO maser in Galactic massive star forming regions, is not the only inversion mechanism of H_2CO

megamasers. It has been pointed out that the inversion mechanism cannot explain the H_2CO maser in NGC 7538 with high resolution VLA, VLBA or MERLIN observations (Hoffman et al. 2003). After we convolved our continuum data to the same beam size as data from the VLA B configuration (Colbert et al. 1994) and overlaid one set with the other, we found that the emissions of the two data sets are almost the same near the two nuclei, which means that missing flux of extended emission is not important near the two nuclei and we can use our high resolution data to estimate continuum flux at the position of H_2CO emission in between the two nuclei. From our map, continuum emission at that H_2CO concentration is mainly from the Gaussian beam extension from the southern nucleus. So even though we cannot rule out extended C band continuum emission at the concentration in between the two nuclei, C band continuum there is much weaker than that in the two nuclei. We would like to suggest that radio continuum pumping is not likely to be the inversion mechanism of H_2CO even for the concentration in between the two nuclei. The association of the H_2CO maser with near-IR H_2 emission in NGC 6240 indicates shock dynamics, which have been suggested for explaining the H_2CO maser near NGC 7538, a Galactic HII region (Hoffman et al. 2003), and might be the inversion mechanism for H_2CO megamasers. Higher resolution and higher sensitivity H_2CO data in NGC 6240 may also help us search for H_2CO masers in the Milky Way. The most luminous H_2CO megamaser detected in the nearest ULIRG Arp 220 (Baan et al. 1986, 1993; Baan & Haschick 1995) has a luminosity of 61 $L_\odot$ and an integrated line flux of ~ 1.8 Jy km s^{-1}, which is similar to the flux of a Galactic H_2CO maser in NGC 7538 (Araya et al. 2007b). The luminosity of the H_2CO maser in Arp 220 is about $5{\times}10^8$ ($\sim 3 \times 10^8$ for NGC 6240) times of that in NGC 7538. With the extremely low detection rate of H_2CO masers in massive star forming regions (Araya et al. 2007a), it is difficult to believe that most H_2CO megamasers come from massive star forming regions in those galaxies. Since the H_2CO maser in NGC 6240 associated with near-IR H_2 emission (Max et al. 2005) is thought to be from a shocked gas region, Galactic molecular clouds surrounding supernova remnants may be good candidates for searching for H_2CO masers in the Milky Way.

5 SUMMARY AND PROSPECTS

With high resolution observations of an H_2CO maser using the VLA in A configuration toward the nearby merging galaxy NGC 6240, we detected two concentrations of H_2CO maser emission in off-nuclear regions. The integrated flux of H_2CO emission is much less than that reported with the observation of Arecibo (Baan et al. 1993). The integrated spectrum without continuum subtraction is similar to that with the observation of GBT (Mangum et al. 2008). We suggest that the result from Arecibo (Baan et al. 1993) has not been correctly interpreted because it was detected with a single dish.

H_2CO maser emissions in NGC 6240 are associated with shocked gas traced by near-IR H_2 emission. As the second galaxy observed with VLA at high resolution ($\sim 1''$) containing an H_2CO maser, based on the distribution of H_2CO, radio continuum and H_2 emission, in NGC 6240, we suggest that H_2CO megamasers in galaxies do not necessarily arise from nuclear activity, and the radio continuum should not come from the inversion mechanism of H_2CO megamasers. Such an inverted population, which is necessary to produce H_2CO megamasers in galaxies, may be due to shocks in molecular clouds.

Since the H_2CO $1_{11}{\rightarrow}1_{10}$ maser can be confused with the absorption line, which can be produced in cold molecular gas, we need to use a radio interferometer with a high resolution to distinguish emission components from an absorption spectrum, instead of a large single dish radio telescope, when searching for H_2CO megamasers in galaxies. Due to the low detection rate of H_2CO masers near massive star forming regions in the Milky Way, we need to search for H_2CO masers near other types of sources, such as the interaction regions between supernova remnants and molecular clouds, with shocked molecular gas, and with less absorption attenuation due to smaller H_2CO column density than that in massive star forming regions. Observations with radio interferometers such as EVLA and WSRT near gas rich galaxies and molecular clouds near supernova remnants in the Milky Way can help us better understand H_2CO masers.

Acknowledgements This work is supported by the National Basic Research Program of China (973 Program, 2012CB821800) and the Natural Science Foundation of China (Grant Nos. 10833006 and 11173013). The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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