RADIO OBSERVATIONS OF THE STAR FORMATION ACTIVITIES IN THE NGC 2024 FIR 4 REGION

MINHO CHO1, MIJU KANG1,2,3, AND JEONG-EUN LEE4

1 Korea Astronomy and Space Science Institute, 776 Daeedokdaeoro, Yuseong, Daejeon 305-348, Korea; minho@kasi.re.kr
2 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
3 Korea University of Science and Technology, 217 Gajeongro, Yuseong, Daejeon 305-350, Korea
4 School of Space Research, Kyung Hee University, Yongin, Gyeonggi 446-701, Korea

Received 2015 February 16; accepted 2015 May 21; published 2015 July 7

ABSTRACT

Star formation activities in the NGC 2024 FIR 4 region were studied by imaging centimeter continuum sources and water maser sources using several archival data sets from the Very Large Array. The continuum source VLA 9 is elongated in the northwest–southeast direction, consistent with the FIR 4 bipolar outflow axis, and has a flat spectrum in the 6.2–3.6 cm interval. The three water maser spots associated with FIR 4 are also distributed along the outflow axis. One of the spots is located close to VLA 9, and another one is close to an X-ray source. Examinations of the positions of compact objects in this region suggest that the FIR 4 cloud core contains a single low-mass protostar. VLA 9 is the best indicator of the protostellar position. VLA 9 may be a radio thermal jet driven by this protostar, and it is unlikely that FIR 4 contains a high-mass young stellar object (YSO). A methanol 6.7 GHz maser source is located close to VLA 9, at a distance of about 100 AU. The FIR 4 protostar must be responsible for the methanol maser action, which suggests that methanol class II masers are not necessarily excited by high-mass YSOs. Also discussed are properties of other centimeter continuum sources in the field of view and the water masers associated with FIR 6n. Some of the continuum sources are radio thermal jets, and some are magnetically active young stars.

Key words: ISM: individual objects (NGC 2024) – ISM: jets and outflows – ISM: structure – masers – stars: formation

1. INTRODUCTION

The NGC 2024 molecular ridge is a filamentary cloud exhibiting various star formation activities (Mezger et al. 1988; Visser et al. 1998; Matthews et al. 2002), at a distance of 415 pc from the Sun (Anthony-Twarog 1982). The molecular ridge consists of dense cores FIR 1–7, and they contain the youngest objects in the NGC 2024 region (Mezger et al. 1992; Wilson et al. 1995; Chandler & Carlstrom 1996). Mezger et al. (1988, 1992) suggested that the FIR 1–7 cores are isothermal protostars without luminous stellar objects, but later studies showed that some of them are associated with young stellar objects (YSOs) and molecular outflows (Chandler & Carlstrom 1996). While the structures and star formation activities of FIR 5 and FIR 6 are known relatively well (Richer 1990; Richer et al. 1992; Wiesemeyer et al. 1997; Lai et al. 2002; Alves et al. 2011; Choi et al. 2012b), the nature of the other FIR cores are not clearly known. Recent detections of molecular masers and X-ray emission suggest that FIR 4 is yet another active site of star formation, showing interesting physical phenomena at small scales (Minier et al. 2003; Skinner et al. 2003; Choi et al. 2012a; Green et al. 2012).

The dense core FIR 4 contains a low-mass protostar and exhibits star formation activities such as a reflection nebulosity and a molecular outflow (Moore & Chandler 1989; Lis et al. 1991; Moore & Yamashita 1995; Chandler & Carlstrom 1996). By contrast, Minier et al. (2003) detected a CH3OH class II maser source and suggested that FIR 4 contains an intermediate/high-mass YSO. It is unclear whether or not the outflow-driving protostar and the CH3OH-exciting YSO are the same object. High-resolution imaging is needed to identify the YSO in the FIR 4 region and to investigate its nature. Interferometric observations in the radio continuum can increase our understanding of the FIR 4 region, but the imaging of compact sources is hampered by the strong emission from the extended Hα region (Crutcher et al. 1986; Gaume et al. 1992). The effects of the extended emission can be reduced by excluding the visibility data of short baselines (Rodríguez et al. 2003; Choi et al. 2012b), but the resulting images contain artifacts introduced by the filtering and need to be analyzed carefully.

The 1.3 cm H2O maser of low-mass protostars is a rarely detectable phenomenon (Kang et al. 2013). Once detected, however, the maser indicates the existence of shocked gas and can provide important information about the star formation activities of YSOs driving the shock (Genzel & Downes 1977; Elitzur 1992; Furuya et al. 2003). Particularly, the small source size and high intensity allow interferometric observations, which is essential in the investigation of small-scale structures. The H2O maser associated with FIR 4 was first reported by Choi et al. (2012a). They used a single-dish telescope, however, and the large beam size made it difficult to understand the relation between the H2O maser source and other compact objects in the region.

In this paper, we present the results of archival observations of the NGC 2024 FIR 4 region in the centimeter continuum or in the H2O maser line with the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO). The archival data sets are described in Section 2. In Section 3, we report the results of the radio imaging. In Section 4, we discuss the star-forming activities of FIR 4. In Section 5, we describe other objects in the field of view. A summary is given in Section 6.

2. DATA

The VLA data sets presented in this paper were retrieved from the NRAO Data Archive System in the form of raw telescope data files. Table 1 gives a summary of the data sets.
Table 1
Summary of the VLA Data Analyzed

| Project | Observation Date | Configuration | Data Type | $F_{\nu}$ a |
|---------|------------------|---------------|-----------|-------------|
| AG 421b | 1994 Aug 13      | B             | 2.0, 3.6, and 6.2 cm continuum | 0.97 Jy at 3.6 cm |
|         | 1994 Oct 24      | C             | 2.0 and 3.6 cm continuum       | 1.00 Jy at 3.6 cm |
|         | 1995 Aug 17      | A             | 2.0, 3.6, and 6.2 cm continuum | 1.30 Jy at 3.6 cm |
| AF 354  | 1999 Feb 26      | DnC           | 1.3 cm H$_2$O line             | 0.83 Jy at 1.3 cm |
| AR 465  | 2002 Mar 2, 3, 8 | A             | 3.6 cm continuum               | 0.76 Jy at 3.6 cm |
| AM 749  | 2003 Mar 14      | D             | 1.3 cm H$_2$O line             | ... |
| AM 780  | 2003 Sep 15      | A             | 1.3 cm H$_2$O line             | 0.83 Jy at 1.3 cm |

Note.

a Flux density of the phase calibrator (QSO B0539–057), showing the time variability.

b The AG 421 data set presented in this paper is a subset of the full AG 421 data set (see Section 2.1.1).

The calibration and imaging were done using the Astronomical Image Processing System software package of NRAO.

2.1. Centimeter Continuum

We searched VLA data sets in the NRAO Data Archive System for continuum observations of the FIR 4 region to investigate the nature and structure of the continuum source associated with the FIR 4 protostar. Two data sets were found to be useful.

2.1.1. Project AG 421

The NRAO observing project AG 421 includes data from observations made in various array configurations. Since we are mainly interested in compact sources, D-array and DnC-array data were ignored, and data from more extended configurations were considered. The B-array, C-array, and A-array observations were made in 1994 August, 1994 October, and 1995 August, respectively.

The NGC 2024 region was observed in the standard continuum modes of the C band (4.86 GHz or $\lambda = 6.2$ cm), X band (8.44 GHz or $\lambda = 3.6$ cm), $U$ band (14.94 GHz or $\lambda = 2.0$ cm), and $K$ band (22.46 GHz or $\lambda = 1.3$ cm). The phase-tracking center was $\alpha_{1950} = 05^h43^m14.1^s$, $\delta_{1950} = 0^\circ 55'55.7''$, which corresponds to IRS 2. The phase was determined by observing the nearby quasar 0539–057 (QSO B0539–057). The flux was calibrated by observing the quasar 0134+329 (3C 48) or 1328+307 (3C 286). The flux densities of 0539–057, derived from a comparison of amplitudes, were 0.96/1.0/1.23 Jy at 6.2 cm, 0.97/1.00/1.30 Jy at 3.6 cm, and 0.94/1.00/1.16 Jy at 2.0 cm for the B-array/C-array/A-array observations, respectively. The observations were made with relatively short scans. A typical on-source integration time in each array configuration was $\sim$14 minutes for each waveband.

Maps were made using a CLEAN algorithm. To avoid the adverse effects of the strong extended emission associated with the nearby ionization fronts, the visibility data of short baselines ($\nu \lambda < 50$ k$\lambda$) were excluded. This filtering was applied to the data of all array configurations. For the 6.2 cm continuum, the C-array data were not used because all the baselines were short ($\nu \lambda < 53$ k$\lambda$). For the 2.0 cm continuum, a $\nu$ taper of 750 k$\lambda$ was applied to make the beam size comparable to that of the 3.6 cm continuum. The 1.3 cm continuum data did not produce a useful map. With a robust weighting, the 6.2 cm, 3.6 cm, and 2.0 cm continuum data produced synthesized beams of $0''51 \times 0''46$, $0''33 \times 0''29$, and $0''33 \times 0''29$, respectively, in FWHM.

As a result of the short integration time and the exclusion of short-spacing data, the images have relatively low qualities and contain numerous artifacts in a form of spurious intensity peaks. Detection of sources is limited by confusion with these unreal peaks. Therefore, we focused on measuring the flux densities of the sources at known positions (Rodríguez et al. 2003) and did not try to identify new sources. The AG 421 data set is useful for constructing the continuum spectra of relatively strong sources, and the AR 465 data set (see below) is useful for studying source positions and structures.

2.1.2. Project AR 465

The NRAO observing project AR 465 includes data from three tracks of A-array observations made in 2002 March. The NGC 2024 region was observed in the standard X-band continuum mode (8.46 GHz or $\lambda = 3.6$ cm). The phase-tracking center was $\alpha_{2000} = 05^h41^m44^s90$, $\delta_{2000} = -01^\circ 55'55.0''$. Details of the observations and results were presented by Rodríguez et al. (2003). The calibration was done in the way as described by Rodríguez et al. (2003). The total on-source integration time was 5.8 hr.

The visibility data from the tree tracks were combined, and a map was made using a CLEAN algorithm. The visibility data of short baselines ($\nu \lambda < 50$ k$\lambda$) were excluded. With a robust weighting, the 3.6 cm continuum data produced a synthesized beam of FWHM $= 0''25 \times 0''23$. (The map presented by Rodríguez et al. 2003 was made using data with $\nu \lambda > 100$ k$\lambda$, and the data from the three tracks were combined in the image space.)

2.2. Water Maser

We searched VLA data sets for H$_2$O maser observations of the FIR 4 region to investigate the relation between the maser source and the FIR 4 protostar. Three data sets were found to have pointing centers close to FIR 4. In these observations, FIR 4 is located near the edge of the field of view.

2.2.1. Project AF 354

The NRAO observing project AF 354 includes data from the DnC-array observations made in 1999 February. Details of the observations and results were presented by Furiya et al. (2003). For the H$_2$O $616 \rightarrow 5_{23}$ line (22.25077 GHz), the spectral window was set to have a velocity resolution of 0.33 km s$^{-1}$. The phase-tracking center was $\alpha_{1950} = 05^h39^m13.35^s$, $\delta_{1950} = -01^\circ$
The brightest object in the infrared image is IRS 2 (Figure 1) and FIR 4 is
the phase calibrator was the quasar 0541
between the phase-tracking center and FIR 4 is

\[ \begin{align*}
5^\circ \text{19'}0. & \\
\text{The angular distance between the phase-tracking center} & \\
\text{and FIR 4 is } \sim70'' & \text{ (Figure 1). For comparison, the antenna} \\
\text{primary beam has an FWHM = 122''}. & \\
\text{The phase calibrator was} & \\
\text{the quasar 0539–057 (QSO B0539–057). The flux was} \\
\text{calibrated by setting the flux density of 0539–057 to 1.73 Jy,} & \\
\text{which makes the flux scale consistent with that of} & \\
\text{Furuya et al. (2003).} & \\
\text{Maps were made using a CLEAN algorithm. With a natural} & \\
\text{weighting, the H}_2\text{O line data produced a synthesized beam of} & \\
\text{FWHM = } 3'' 1 \times 2'' 1. & \\
\text{The imaging was done in a square box of } 160'' \times 160'', & \\
\text{which is larger than the size of the primary} & \\
\text{beam, in order to include FIR 4 in the imaging area.} &
\end{align*} \]

2.2.2. Project AM 749

The NRAO observing project AM 749 includes data from the D-array observations made in 2003 March. For the H$_2$O line, the spectral window was set to have a velocity resolution of 1.3 km s$^{-1}$. The phase-tracking center was $\omega_{2000} = 05^{h} 41^{m} 44^{s}.765, \delta_{2000} = -01^\circ 55' 53''.76$. The angular distance between the phase-tracking center and FIR 4 is $\sim70'$. The phase calibrator was the quasar 0541–056 (QSO B0539–057), the same as that of AF 354. The flux was calibrated by setting the flux density of 0541–056 to 0.828 Jy (see below).

Maps were made using a CLEAN algorithm in the area as described above. With a natural weighting, the H$_2$O line data produced a synthesized beam of FWHM = $4''3 \times 3''4$.

2.2.3. Project AM 780

The NRAO observing project AM 780 includes data from the A-array observations made in 2003 September. The velocity resolution, phase-tracking center, and phase calibrator were the same as those of AM 749. The flux was calibrated by setting the flux density of the quasar 0137+331 (3C 48) to 1.281 Jy. A comparison of the amplitude gave a flux density of 0.828 Jy for 0541–056.

Maps were initially made in the area as described above, which revealed detectable emission near FIR 6n only. Final maps were made in a square box of 37'' $\times$ 37'' around the phase-tracking center. With a natural weighting, the H$_2$O line data produced a synthesized beam of FWHM = $0''10 \times 0''11$.

3. RESULTS

3.1. Centimeter Continuum

Several sources were detected in the centimeter continuum images of the AG 421 data set. Table 2 lists the flux densities of the sources detected in multiple wavelength bands. VLA 9 is the radio source associated with FIR 4, and Figure 2 shows the images in the three bands. The source position agrees with that of the 3.6 cm source reported by Rodríguez et al. (2003).

The 3.6 cm continuum image from the AR 465 observations shows that VLA 9 has an extended structure (Figure 3). The peak position is $\omega_{2000} = 05^{h} 41^{m} 44^{s}.137, \delta_{2000} = -01^\circ 54' 46''.06$, consistent with Rodríguez et al. (2003). The total flux density is 0.57 ± 0.02 mJy. The source is elongated in the northwest–southeast direction. The extent of elongation is larger than the effective beam (synthesized beam degraded owing to the bandwidth smearing). In addition, the intensity distribution is slightly curved and asymmetric with respect to the peak position. An elliptical Gaussian fit gives a deconvolved size of FWHM = $0''.37 \times 0''.09$ with a position angle (P.A.) = $-25^\circ$ (deconvolved with the effective beam). The major axis corresponds to FWHM = 150 AU.

The spectrum of VLA 9 in the 6.2–3.6 cm interval is flat (Table 2), which suggests that the centimeter continuum is optically thin–free–free emission. This spectrum rules out the possibility of VLA 9 being an ultracompact/hypercompact H ii region. The elongated structure and the flat spectrum suggest that VLA 9 is a radio thermal jet. The 2.0 cm flux density is higher than those of the longer wavelengths, and the spectral index in the 3.6–2.0 cm interval is $\sim$1.2 (Figure 4), which suggests that a fraction of the 2.0 cm flux may come from dust.

3.2. Water Maser

The image from the AF 354 data set revealed detectable H$_2$O maser spots near FIR 4 and FIR 6n. The FIR 6n maser source was already reported by Furuya et al. (2003), and we will omit descriptions of this source. (Also see the clarification of source identification in Choi et al. 2012a.) No maser source was detected from the AM 749 data set. The $3\sigma$ detection limits are 8 mJy beam$^{-1}$ at FIR 6n and 19 mJy beam$^{-1}$ at FIR 4. The AM 780 data set revealed detectable H$_2$O maser spots near FIR 6n only. The detection limit at FIR 4 is 40 mJy beam$^{-1}$. The results are summarized in Table 3.

Three H$_2$O maser spots associated with FIR 4 were detected from the AF 354 observations: two weak sources (spots 1 and 2) near the systemic velocity of the ambient cloud ($v_{LSR} = 11.0$ km s$^{-1}$; Schulz et al. 1991) and a strong one (spot 3) at a
redshifted velocity (Figures 5 and 6). The velocity difference between them is \( \sim 8 \) km s\(^{-1}\). The H\(_2\)O maser source detected by the single-dish observations in 2012 had a velocity of \( V_{\text{LSR}} = 13 \) km s\(^{-1}\) (Choi et al. 2012a).

A Gaussian fit to spot 3 shows that it is slightly larger than a point source, with a deconvolved size of FWHM = 1\(^\prime\)0 \( \times \) 0\(^\prime\)2. The intensity distribution of spot 3 can be described as a combination of a strong point-source component and a weak (below \( \sim 10\% \)) of the peak) extended component. The weak component is elongated in the north–south direction (P. A. = \(-10\)^\circ), which caused the peak at \( \sim 19 \) km s\(^{-1}\) in the spectrum of spot 1 (Figure 6(a)). Since this low-level elongation of spot 3 is symmetric around the intensity peak and has a position angle exactly the same as that of spot 3 with respect to the phase-tracking center, it is probably an artifact of the imaging process, not a real source structure. It is probably owing to the position far from the phase-tracking center and the velocity near the edge of the bandpass.

### 4. DISCUSSION

The positions of the radio continuum source and the H\(_2\)O maser spots are shown in Figure 7, together with other compact objects in the FIR 4 region. Most of them are distributed along a straight line in the northwest–southeast direction, which suggests that they belong to a single protostar-outflow system. The extended infrared feature in the 4.5 \( \mu \)m map (Figure 5), extending from the infrared peak position toward the northwest, can also be seen in the Spitzer maps of other bands (3.6, 5.8, and 8.0 \( \mu \)m), suggesting that it is seen in continuum emission. The position and morphology of this feature agree with those of the reflection nebulosity seen in the \( H \) and \( K \) bands (Moore & Chandler 1989).

### 4.1. FIR 4 Protostar

The nature of the YSO embedded in the FIR 4 cloud core has been controversial (Mezger et al. 1988, 1992; Moore &
move toward the southeast with increasing wavelength, along the outflow axis. They tightly follow the straight line defined by VLA 9 and the 2MASS source position. This position shift suggests that the detected near-IR emission comes from the scattered light escaping through the outflow cavity. The near-IR polarimetry is consistent with this interpretation (Kandori et al. 2007). This finding solves the extinction problem pointed out by Mezger et al. (1992). They argued that the expected extinction of the FIR 4 cloud core is too high for any embedded YSO to be directly detectable in near-IR. The central protostar is indeed invisible in near-IR. Judging from the trend of the infrared position shift, the true position of the protostar may lie somewhere to the southeast of the 8.0 μm peak position. The best candidate is the peak position of the radio thermal jet VLA 9.

High-resolution interferometric imaging in the millimeter continuum can provide additional information on the position of the protostar. Known from interferometric observations are the 3 mm source positions reported by Chandler & Carlstrom (1996) and Eisner & Carpenter (2003). Their positions of FIR 4 are inconsistent and different by ~2′′2 (comparable to their beam sizes). A comparison of the positions of FIR 5 and 6 in the literature (Wiesemeyer et al. 1997; Lai et al. 2002; Alves et al. 2011; Choi et al. 2012b) shows that the positions of Eisner & Carpenter (2003) are accurate to within the beam size, but those of Chandler & Carlstrom (1996) are systematically shifted with respect to those of the other references. The amount of shift is ~3″ toward the northwest. This astrometric problem caused some confusion in source identifications (Minier et al. 2003; Skinner et al. 2003). The FIR 4 position of Eisner & Carpenter (2003) agrees with VLA 9 within the beam size (Figure 7). Therefore, VLA 9 is the best indicator of the position of the FIR 4 protostar and there is no evidence for multiple YSOs in the FIR 4 dense core.

Setting aside the CH$_3$OH maser issue (Section 4.2), most of the evidence indicates that FIR 4 contains a low-mass protostar. Mezger et al. (1992) derived 10 $M_\odot$ for the mass of the cloud core assuming that there is no internal heating and the core is cold (~19 K). However, this assumption is inconsistent with recent findings. Later studies showed that the temperature is higher (50–80 K; Mangum et al. 1999; Watanabe & Mitchell 2008). Then the mass of the FIR 4 core may be much smaller: 0.8–1.7 $M_\odot$ (Chandler & Carlstrom 1996; Visser et al. 1998; Watanabe & Mitchell 2008). Considering that FIR 4 is in an early stage of protostellar evolution, the core mass seems to be too small to form a high-mass/intermediate-mass star.

Moore & Yamashita (1995) estimated a bolometric luminosity of ~25 $L_\odot$ for the YSO in FIR 4, but this value is uncertain because the far-infrared (far-IR) flux was not included in the calculation. Lis et al. (1991) estimated a luminosity of 3–7 $L_\odot$ for the internal heating source (or much smaller if the external radiation field is highly enhanced). Therefore, the luminosity also indicates that the FIR 4 core contains a low-mass protostar.

One of the major difficulties in understanding the nature of the FIR 4 protostar is that the nebulous association with the ionization front and the infrared-bright stars in the nearby region prevents accurate photometry in the far-IR band where the spectral energy distribution peaks. The luminosity from available data (discussed in the previous paragraph) and the lack of an ultracompact/hypercompact H II region firmly rule out the likelihood of FIR 4 containing a high-mass YSO. The

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Map of the 3.6 cm continuum emission toward the FIR 4 region, from the AR 465 data set. The contour levels are 1, 2, 4, and 8 x 0.03 mJy beam$^{-1}$, and the rms noise is 0.011 mJy beam$^{-1}$. Dashed contours are for negative levels. The map is corrected for the primary beam response. Filled ellipse: synthesized beam. FWHM = 0′′25 x 0′′23 with P.A. = −23°. Open ellipse: effective beam (apparent width of a point source, taking the bandwidth smearing into account) at the position of VLA 9, determined from other unresolved sources in the map. FWHM = 0′′33 x 0′′24 with P.A. = −10°. Large plus sign: H$_2$O maser spot 1 (Section 3.2). Orange filled circle: CH$_3$OH 6.7 GHz maser source (Green et al. 2012). The size of each marker represents the beam size of the corresponding observations. The straight line in the bottom left-hand corner corresponds to 100 AU at a distance of 415 pc.

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Spectral energy distributions of the sources detected in the three wavelength bands (Table 2). The flux uncertainties (including the uncertainty of the flux scale) are smaller than the sizes of the markers.
The CH$_3$OH maser source is closely associated with VLA 9 and H$_2$O maser spot 1 (Figure 3). The position marked in Figure 3 was taken from Figure 4 of Green et al. (2012), which is more accurate than the one given by Minier et al. (2003). The velocity of the CH$_3$OH maser line ($V_{\text{LSR}} = 12.3$ km s$^{-1}$; Minier et al. 2003; Green et al. 2012) is redshifted by 1.3 km s$^{-1}$ relative to the systemic velocity (11.0 km s$^{-1}$; Schulz et al. 1991) or by 1.0 km s$^{-1}$ relative to the velocity of the H$_2$O maser spot 1 (Table 3). The widths of the CS and H$_2$CO lines from the FIR 4 dense core are $\sim$2 km s$^{-1}$ (Schulz et al. 1991; Mangum et al. 1999). The line profiles of H$_2$CO are nearly symmetric and have no line wing (Mangum et al. 1999), which suggests that the line width mostly reflects the turbulent motion of dense molecular gas. Therefore, it is unclear if the velocity shift of the CH$_3$OH maser is related to the outflow, disk rotation, or any other motion in the cloud core.

The angular separation between the CH$_3$OH maser spot and the peak of the VLA 9 is $\sim$0$''$.21. (The beam size of the CH$_3$OH line observations of Green et al. (2012) is $\sim$0$''$.04. The position accuracy of the VLA 9 is usually better than 0$''$.1.) The separation may not be completely accurate because the source positions came from different observations. Simultaneous

Table 3
NGC 2024 FIR 4/6 Water Maser Source Parameters

| Region | Epoch | Spot | Peak Position* | Centroid Velocity | Peak Flux Densityb |
|--------|-------|------|----------------|-------------------|-------------------|
| FIR 4  | 1999 Feb 26 | 1    | 05 41 44.12, −01 54 46.4 | 11.3            | 0.16 ± 0.04       |
|        |       | 2    | 05 41 44.48, −01 54 48.9 | 11.4            | 0.10 ± 0.04       |
|        |       | 3    | 05 41 44.02, −01 54 43.3 | 19.1            | 4.29 ± 0.04       |
| FIR 6n | 2003 Sep 15 | 4    | 05 41 45.153, −01 56 00.64 | 10.7            | 3.536 ± 0.009     |
|        |       | 5    | 05 41 45.171, −01 56 00.60 | 13.7            | 0.897 ± 0.009     |
|        |       |      |                 | 17.1            | 1.546 ± 0.009     |
|        |       |      |                 | 21.9            | 0.987 ± 0.009     |

Note.

* Units of R.A. are hours, minutes, and seconds, and units of decl. are degrees, arcminutes, and arcseconds.

b Flux density at the peak channel, corrected for the primary beam response.

Figure 5. Maps of the H$_2$O maser emission in the FIR 4 region. The maser spot numbers are labeled. The violet contours show the intensity integrated over $V_{\text{LSR}} = (10.7, 11.7)$ km s$^{-1}$, and the contour levels are 0.5 and 0.75 times the peak intensity of spot 1 (0.14 Jy beam$^{-1}$ km s$^{-1}$). The red contours show the intensity integrated over (18.6, 19.6) km s$^{-1}$, and the contour levels are 0.25, 0.5, and 0.75 times the peak intensity (2.67 Jy beam$^{-1}$ km s$^{-1}$). The maps are corrected for the primary beam response. Shown in the bottom right-hand corner is the synthesized beam: FWHM $= 3''1 \times 2''1$ with a P.A. $= -84^\circ$. Gray dashed contours: map of the 4.5 $\mu$m emission from the Spitzer data archive. The contour levels are 1, 2, and 4 $\times$ 200 MJy sr$^{-1}$. Plus sign: 3.6 cm continuum source VLA 9 (Figure 3). Red arrow: direction of the redshifted CO outflow (Chandler & Carlstrom 1996).

Figure 6. Spectra of the H$_2$O maser line in the FIR 4 region. (a) Spectrum of spot 1. The peak at $\sim$19 km s$^{-1}$ is owing to the emission from spot 3. (b) Spectrum of spot 2. (c) Spectrum of spot 3. Each spectrum was taken at a single pixel at the peak position of the corresponding maser spot. Vertical dotted line: velocity of the ambient dense gas ($V_{\text{LSR}} = 11.0$ km s$^{-1}$; Schulz et al. 1991).
observations in both the continuum and the CH$_2$OH maser line are necessary to measure the separation more accurately.

Minier et al. (2003) argued that FIR 4 contains a high-mass or intermediate-mass protostar, based on the assumption that the CH$_2$OH maser action may require warm (>175 K) gas heated by the protostar. They thought that the CH$_2$OH-rich gas in a low-mass star-forming region exists far (>100 AU) from the central YSO where the temperature is too low to drive a maser action. The proximity of the CH$_2$OH maser to VLA 9 suggests that this argument needs to be reexamined.

The usual assumption is that the maser spot is located in the heated envelope of a YSO (Minier et al. 2003). If the FIR 4 protostar is located exactly at the peak position of VLA 9, the projected separation between the CH$_2$OH maser source and the protostar is ~90 AU. The dust temperature at the CH$_2$OH maser-emitting region can be estimated using Equation (2) of Motte & André (2001). Assuming that the distance from the protostar to the maser spot is ~120 AU (considering the projection effect) and that the protostellar luminosity is 3–25 $L_\odot$ (Section 4.1), the dust temperature would be 40–70 K. However, models of class II masers suggest that mid-IR photons from warm (100–200 K) dust are necessary for radiative pumping (De Buizer et al. 2000; Cragg et al. 2005). Then the CH$_2$OH maser of FIR 4 suggests several possibilities. (1) The class II maser action may operate at temperatures lower than the theoretically expected range. (2) The FIR 4 maser spot may have an extra source of heating, such as the outflow or the external radiation field. (3) The maser spot may be on the circumstellar disk irradiated by photons coming directly from the protostar. High-resolution (~0.″2 or better) observations in the dust continuum may be helpful in understanding the relation between the protostar and the CH$_2$OH maser source. The flat radio spectrum, small mass, and low luminosity (Section 4.1) rule out the existence of a high-mass YSO in the FIR 4 region, and the CH$_2$OH maser must be excited by the FIR 4 low-mass protostar regardless of the detailed heating and pumping mechanisms.

4.3. FIR 4 Outflow

The three H$_2$O maser spots are distributed along a straight line in the northwest–southeast direction with a P.A. of about −23° (Figure 5). This line passes through VLA 9 and agrees with the axis of the outflow in this region: the northwestern lobe indicated by the reflection nebulosity and the southeastern lobe traced by the CO line (Moore & Chandler 1989; Chandler & Carlstrom 1996). The unipolar CO outflow is redshifted (Chandler & Carlstrom 1996). The southeastern CO outflow may be on the far side of the FIR 4 core, and the northwestern infrared nebulosity (outflow cavity) may be on the near side. Interestingly, the H$_2$O maser spot 3 in the northwest is redshifted, which may reflect the velocity of the local shocked gas.

The centimeter continuum source VLA 9 (Figure 3) is located close to H$_2$O maser spot 1. VLA 9 is elongated, and its major axis agrees with the direction of the outflow, which suggests that VLA 9 is a radio thermal jet at the base of the bipolar outflow. With respect to the intensity peak, the emission structure is more extended toward the northwest than toward the opposite direction.

One of the X-ray sources reported by Skinner et al. (2003) is located close to H$_2$O maser spot 3 (Figure 7). The separation is ~0.″7 or 300 AU. The H$_2$O maser and the X-ray emission are not necessarily coming from the same volume of gas, but the northwestern outflow of FIR 4 may be responsible for both phenomena. Only a few young protostars are known to show H$_2$O maser and X-ray emission together. The YSOs in the NGC 2071 cluster (IRS 1/3 and VLA 1) are notable examples (Torrelles et al. 1998; Skinner et al. 2009; Trinidad et al. 2009). High-resolution observations in the H$_2$O maser line and deeper observations in the X-ray are necessary to understand the physical relation between the maser-producing shocked gas and the X-ray-emitting hot plasma.

The four X-ray photons detected in the FIR 4 region were hard (~5.9 keV; Skinner et al. 2003), and the emission mechanism is difficult to explain. Skinner et al. (2003) suggested that the emission may be caused by stellar flares, and additional possibilities (mainly relevant to NGC 2071 IRS 1) are listed in Section 5.2 of Skinner et al. (2009). The large separation (~2″8) between the X-ray source and the protostar (VLA 9) seems to rule out all of these possibilities but the outflow model. However, if the X-ray-emitting plasma is produced by the outflow shocking dense ambient gas, the required shock speed is ~2200 km s$^{-1}$ (see the discussion in Section 5.2.1 of Skinner et al. 2009). This speed is unreasonably high for a YSO outflow. Yet another model was proposed by López-Santiago et al. (2013) to explain the X-ray emission of HH 80. In this model the hard X-ray emission is synchrotron radiation produced by nonthermal processes in the magnetized jet. It is unclear if this model applies to the case of FIR 4, because there is no detection of synchrotron radiation or strong magnetic fields. Therefore, the origin of the hard X-ray remains a puzzle.

5. NEARBY OBJECTS

5.1. Continuum Sources

Rodríguez et al. (2003) detected a cluster of 25 radio sources in the NGC 2024 region. Based on a statistical consideration, they suggested that practically all of these sources are physically associated with NGC 2024. Many of these radio
sources are indeed associated with infrared sources and other star formation activities such as outflows. The nature of each source can be examined with the spectrum of the centimeter continuum from ionized gas (Reynolds 1986; Anglada et al. 1998). Optically thin free–free emission (e.g., from a thermal radio jet) shows a small spectral index ($\alpha \lesssim 1$). Optically thick free–free emission (e.g., from a high-density H II region) shows a larger spectral index. (At shorter wavelengths, the emission can become optically thin, and the spectrum can become flat.) Nonthermal emission (e.g., from a magnetic flare) usually (but not always) shows a negative spectral index (Güdel 2002). Table 2 lists the spectral indices of 10 radio sources that were detected in both 6.2 and 3.6 cm maps. They can be classified into three categories depending on the spectral slope. The type of radio source is listed in the last column of Table 2. (Also see the descriptions of several sources in Rodríguez et al. 2003.)

### 5.1.1. Positive-spectrum Sources

Four sources (VLA 16, VLA 19, VLA 21, and VLA 25) have relatively large spectral indices. The centimeter continuum of these sources (except VLA 21) are probably (partially) optically thick free–free emission.

VLA 16 is elongated in the northwest–southeast direction (see Figure 5 of Rodríguez et al. 2003). An elliptical Gaussian fit gives a deconvolved size of FWHM = $0^\prime.38 \times 0^\prime.15$ with P.A. = $-39^\circ$. The nature of VLA 16 is unclear. It has an X-ray counterpart but remains undetected in the infrared (Skinner et al. 2003). Rodríguez et al. (2003) suggested that VLA 16 forms a binary system with VLA 15 (IRS 2b).

VLA 19 (IRS 2) is the brightest radio/infrared source in this region. The flux density increases steadily with the frequency, and the spectral index in the 6.2–2.0 cm interval is $\sim 1.0$ (Figure 4). Kurtz et al. (1994) listed VLA 19 (G206.543–16.347) as an ultracompact H II region containing a B2 star. Lenorzer et al. (2004) suggested that the radio emission comes from a stellar wind of an early-B-type star, recombining at a radius of $\sim 100$ AU.

VLA 21 is associated with an infrared source and an X-ray source (Figure 8). Based on the high flux variability in a timescale of a few days, Rodríguez et al. (2003) suggested that the 3.6 cm continuum is gyrosynchrotron emission, which seems to conflict with the positive spectral index. (Considering the flux variability, however, the uncertainty of the spectral index can be much larger than the value given in Table 2.) A possible explanation may be that the radio flux of VLA 21 has both thermal and nonthermal components. The quality of the multifrequency data is not good enough to understand this problem. Sensitive monitoring observations are necessary to understand the variability of the flux and the spectral index.

#### 5.1.2. Flat-spectrum Sources

Four sources (VLA 1, VLA 3, VLA 9, and VLA 24) have relatively small spectral indices. The centimeter continuum of these sources (except VLA 24) are probably optically thin free–free emission.

Among the eight YSOs listed in Table 2, only VLA 9 (FIR 4) is associated with a dense molecular cloud core (Chandler & Carlstrom 1996; Eisner & Carpenter 2003). VLA 9 is probably the youngest object among these YSOs.

Based on the circular polarization and mild flux variability, Rodríguez et al. (2003) suggested that VLA 24 may be a young low-mass star showing gyrosynchrotron emission. The positive spectral index suggests that the radio flux of VLA 24 may also be a mixture of thermal and nonthermal components.

#### 5.1.3. Negative-spectrum Sources

Two sources (VLA 2 and VLA 8) have significantly negative spectral indices. The centimeter continuum of these sources may be nonthermal emission.

VLA 8 is elongated in the north–south direction (see Figure 3 of Rodríguez et al. 2003). An elliptical Gaussian fit gives a deconvolved size of FWHM = $0^\prime.68 \times 0^\prime.31$ with a P.A. = $-6^\circ$. The spectral index in the 6.2–2.0 cm interval is about $-1.5$ (Figure 4). Based on the morphology and the orientation of the elongation, Rodríguez et al. (2003) suggested that VLA 8 may be an ionized proplyd. However, the proplyd model conflicts with the steeply decreasing radio spectrum. Considering the extended structure, no day-scale variability, and lack of infrared counterpart, it is unlikely that VLA 8 is a magnetically active YSO showing gyrosynchrotron emission.

![Figure 8](image-url)
emission. VLA 8 is probably a background object such as an extragalactic radio jet.

5.2. FIR 6n

Two H$_2$O maser spots associated with FIR 6n were detected from the AM 780 observations: one near the systemic velocity of the ambient cloud ($V_{LSR} = 10.8$ km s$^{-1}$; Choi et al. 2012a) and the other at redshifted velocities (Figure 9). The redshifted source (spot 5) shows three velocity components (Figure 10). The H$_2$O maser sources detected previously (Furuya et al. 2003; Choi et al. 2012b) positionally coincides with spots 4/5, but their beam sizes were too large to separate the two spots.

Figure 11 shows the positions of the H$_2$O maser spots and other objects in the FIR 6 region. The maser spots coincide with the millimeter continuum source FIR 6n. The separation between the two spots is much smaller than the angular resolutions of the millimeter continuum maps available (Lai et al. 2002; Alves et al. 2011; Choi et al. 2012b). The centimeter continuum source VLA 14 (Rodríguez et al. 2003) coincides with H$_2$O maser spot 5 (Figure 9). VLA 14 is unresolved. The peak position and flux density given by Rodríguez et al. (2003) are consistent with those from our analysis.

The two maser spots are separated in the east–west direction (Figure 9). The separation ($0.0^\circ 24$) corresponds to 100 AU, and the relative position angle is $81^\circ$. This value is similar to the position angle of the $30^\circ$ scale bipolar outflow traced by the CS line and the high-velocity CO $J = 1 \rightarrow 0$ emission ($\sim 75^\circ$; Chandler & Carlstrom 1996). The extended infrared feature in the 4.5 $\mu$m map (Figure 11) shows two emission peaks, one in the east and the other in the west, and seems to be related to the outflow. The 4.5 $\mu$m emission feature is not obvious in the Spitzer maps of the other bands, suggesting that it probably comes from line emission in the 4.5 $\mu$m band. The separation between the 4.5 $\mu$m peaks is $\sim 10^\prime$, and the relative position angle is $\sim 106^\circ$, which is different from that of the CS/CO outflow by $\sim 30^\circ$. Alves et al. (2011) showed that the outflow traced by the CO $J = 3 \rightarrow 2$ line has a complicated morphology and suggested that the outflows of FIR 6n and FIR 5 may be interacting.

FIR 6n is the most active H$_2$O maser source in the whole NGC 2024 molecular ridge region (Choi et al. 2012a). The nature of the YSO in FIR 6n is unclear because, in the millimeter/infrared wavelengths, FIR 6n is often either undetectable or affected by FIR 6c. Considering that FIR 6n drives a strong outflow and is invisible in the near-IR, the FIR 6n cloud core may contain a low-mass protostar. The nature of the stronger millimeter/submillimeter source FIR 6c is even more unclear. There is no molecular outflow associated with FIR 6c, but a redshifted H$_2$O maser was detected (Choi et al. 2012b). FIR 6c was undetected in the 3.6 cm continuum. The spectral energy distribution of FIR 6c rises steeply around...
6.9 mm and is flat around 1 mm, which suggests that FIR 6c probably contains a hypercompact H II region (Choi et al. 2012b). If so, the central object may be an early-B type star. High-resolution imaging in the millimeter continuum is necessary to understand this peculiar object.

6. SUMMARY

The star formation activities in the NGC 2024 region were investigated by analyzing several archival data sets from the VLA. The nature of centimeter continuum sources was examined using a data set of multifrequency observations. The source positions and structures were inspected using the data set of 3.6 cm continuum observations previously published by Rodríguez et al. (2003). Outflow activities were studied using several data sets of H2O maser observations. Careful examinations of the positions of compact objects in the FIR 4 region provide a simple and comprehensible picture of the star formation activities around the FIR 4 protostar. The main results are summarized as follows.

1. The centimeter continuum source VLA 9, the source associated with FIR 4, shows a flat spectrum in the 6.2–3.6 cm interval. VLA 9 is elongated in the direction consistent with the FIR 4 outflow. VLA 9 is a radio thermal jet and the best indicator of the protostellar position. The flat spectrum rules out the possibility of a high-mass YSO in the FIR 4 region. Previously known mass and luminosity estimates suggest that the FIR 4 protostar is most likely a low-mass object.

2. The CH3OH 6.7 GHz maser source in FIR 4 is located close to VLA 9. The separation between them is \( \sim 0.2 \) arcsec. They must have a close physical relation, but the detailed amplification mechanism of the maser is unclear. The CH3OH maser of FIR 4 demonstrates that the class II maser phenomenon does not necessarily require the presence of a high-mass YSO.

3. The H2O maser spots of FIR 4 are distributed along the FIR 4 outflow axis. The strongest spot is associated with an X-ray source. The FIR 4 outflow is a rare example of protostellar outflows showing the H2O maser and X-ray emission together. Further studies are needed to understand the origin of the hard X-ray emission.

4. The properties of other radio sources in the field of view were investigated. VLA 1, VLA 3, and VLA 25 (IRS 4) may be radio thermal jets driven by YSOs. VLA 2, VLA 21, and VLA 24 may be magnetically active YSOs. VLA 8 may be a background object emitting nonthermal radiation. VLA 16 is a radio source of unknown nature. VLA 19 (IRS 2) may be an early-B-type star.

5. The two H2O maser spots of VLA 14 (FIR 6n) are distributed along an east–west line that is consistent with the axis of the FIR 6n molecular outflow. The FIR 6n cloud core may contain a low-mass protostar.

We thank Karl M. Menten for helpful discussions. M. C. was supported by the Core Research Program of the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT, and Future Planning of the Korean government (grant No. NRF-2011-0015816). J.-E. L. was supported by the Basic Science Research Program through NRF funded by the Ministry of Education of the Korean government (grant No. NRF-2012R1A1A2044689). NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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