Astrometry of Galactic Star-Forming Region G48.61+0.02 with VERA

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Abstract

We performed the astrometry of H₂O masers in the Galactic star-forming region G48.61+0.02 with the VLBI Exploration of Radio Astrometry (VERA). We derived a trigonometric parallax of 199 ± 7 μas, which corresponds to a distance of 5.03 ± 0.19 kpc. The distance to G48.61+0.02 is about a half of its far kinematic distance, which was often assumed previously. This distance places G48.61+0.02 in the Sagittarius-Carina arm and near the active star forming region and the supernova remnant W51. We also obtained the three dimensional motion of G48.61+0.02, and found that it has a large peculiar motion of 40 ± 5 km s⁻¹. This peculiar motion would be originated with the multiple supernovae explosions in W51, or the streaming motion across the Sagittarius-Carina arm.

Key words: Galaxy: kinematics and dynamics — stars: individual (G48.61+0.02)

1. Introduction

It is important to measure the distance accurately, because most physical properties of individual sources, such as sizes, masses, luminosities depend critically on the distance. The kinematic distance, which is derived from the observed radial velocity and the Galactic rotation model, is widely used to estimate the distance from Sun to the source in the Milky Way Galaxy (MWG). However, the kinematic distance would be different from the real distance, in the case that the source motion is affected by the local activities such as supernova (SN) and the super-bubble, the potential of Galactic bar, and the streaming motion of the spiral arm. Recent Very Long Baseline Interferometry (VLBI) astrometric observations determined the distances of the numerous maser sources directly from the parallax measurements. Some of VLBI observations report that there is a difference between the parallactic distance and the kinematic distance (Sato et al. 2008; Brunthaler et al. 2009; Sanna et al. 2009). This is because that these observed sources have large peculiar motions possibly originated with the expanding super-bubble (Sato et al. 2008), the gravitational perturbations from the Galactic bar (Brunthaler et al. 2009), and the expanding 3 kpc arm (Sanna et al. 2009).

G48.61+0.02 is a massive star-forming region located within 1° (100 pc at the distance of 5 kpc) from W51, which is one of the most energetic sources in the MWG. However, the local standard of rest (LSR) velocities of two sources are different by approximately 40 km s⁻¹. The LSR velocities of G48.61+0.02 and W51 are v_{LSR} = 19 ± 1 km s⁻¹ (Bronfman et al. 1996; López-Sepulcre et al. 2009; Codella et al. 2010) and 58 ± 4 km s⁻¹ (Sato et al. 2010), respectively. Therefore, their kinematic distances are also different. The near and far kinematic distances of G48.61+0.02 are derived to be 1.4 and 9.8 kpc, respectively, in the case that IAU recommended values of the Galactic constants, R₀ = 8.5 kpc and Θ₀ = 220 km s⁻¹, and the flat rotation are assumed. The 21 cm wavelength HI absorption measurements suggest that G48.61+0.02 is located at the far kinematic distance (Sato 1973). The parallactic distance of W51 is measured to be 5.41 ± 0.31 kpc by the H₂O maser astrometric observations with the Very Long Baseline Interferometry (VLBA) (Sato et al. 2010), and it is consistent with the kinematic distance. Therefore, it is suggested that G48.61+0.02 is far away from W51 in the line of sight direction, and these two sources are not physically associated (Sato 1973). However, W51 is composed of the active sources such as two complex H II regions W51 A and W51 B, and the SN remnant W51 C (Koo et al. 2002). It would be possible that G48.61+0.02 has a large peculiar motion affected by their activities. We can measure the distance of G48.61+0.02 directly by the parallax, since the H₂O masers are associated with G48.61+0.02 (Kurtz & Hoñer 2005). In order to determine the accurate distance and the reliable location of G48.61+0.02 in the MWG, we conducted multi-epoch phase referencing observations of the H₂O masers with VERA.

2. Observations and Data Reductions

We observed H₂O masers in the Galactic star-forming region G48.61+0.02 with VERA at 12 epochs from...
2005 January to 2006 March. We present the data of 8 epochs that were obtained with full 4-station array (Mizusawa, Iriki, Ogasawara, and Ishigaki-jima) under relatively good conditions. The epochs are as follows (day of year): 024, 052, 141, 299, 334, 341 in 2005, and 050, 086 in 2006. During about 10 hours at each epoch, the H$_2$O 6$_{16}$-5$_{23}$ maser at a rest frequency of 22.235080 GHz in G48.61+0.02 and two background sources, J1922+1530 and J1924+1540 were simultaneously observed using the dual-beam system of VERA. The typical flux densities of J1922+1530 and J1924+1540 are 240 and 480 mJy, respectively. The separation angles between G48.61+0.02 and two background sources, J1922+1530 and J1924+1540, are 1$^\circ$66 and 2$^\circ$02, respectively. During the observations, the instrumental phase difference between the two beams was measured continuously by injecting artificial noise sources into both beams (Honma et al. 2008). The left-hand circular polarizations were recorded onto magnetic tapes at a rate of 1024 Mbps (Honma et al. 2008). The left-hand circular polarizations were assigned to position reference sources, respectively. The filtering of IF-sub-bands was made using the VERA digital filter (Iguchi et al. 2005). One IF sub-band was assigned to G48.61+0.02, and the other 15 IF sub-bands were assigned to position reference sources, respectively. Correlation processing was carried out on the Mitaka FX correlator. The frequency and velocity resolutions for G48.61+0.02 were 15.625 kHz and 0.21 km s$^{-1}$, respectively.

Data reduction was conducted using the NRAO Astronomical Image Processing System (AIPS). The amplitude calibration was performed using the system noise temperatures logged during the observations and the antenna gains. For phase-referencing, a fringe fitting was made using the AIPS task FRING on J1922+1530 and J1924+1540 with a typical integration time of 1 min and a time interval of 30 sec. The solutions of the fringe phases, group delays, and delay rates were applied to G48.61+0.02 in order to calibrate the visibility data. Phase and amplitude solutions obtained from self-calibration of background sources were also applied to G48.61+0.02. Visibility phase errors caused by the Earth's atmosphere were calibrated based on GPS measurements of the atmospheric zenith delay, which is mostly due to tropospheric water vapor (Honma et al. 2008). We made spectral-line image cubes using the AIPS task IMAGR around masers with 1024 $\times$ 1024 pixels of size 0.05 milliarcsecond (mas) after the calibration. The typical size of the synthesized beam was 1.3 $\times$ 0.9 mas with position angle of $-40^\circ$. The rms noises for each images were approximately 0.1–1 Jy beam$^{-1}$. The signal-to-noise ratio of 7 was adopted as the detection criterion.

3. Results

Figure 1 shows the scalar-averaged cross-power spectrum of H$_2$O masers in G48.61+0.02 observed with the Mizusawa-Iriki baseline on 2005/334. The maser emissions were detected in the LSR velocity range from 8 to 32 km s$^{-1}$. The middle of this velocity range is consistent with the LSR velocity of the associated molecular cloud at 19 $\pm$ 1 km s$^{-1}$ observed in CS, C$^{18}$O, and NH$_3$ lines (Bronfman et al. 1996; López-Sepulcre et al. 2009; Codella et al. 2010). Figure 2 shows the distributions of H$_2$O masers in G48.61+0.02. The masers are distributed within approximately 500 $\times$ 600 mas area. Nine maser features were detected at more than five epochs and seven of them were detected at all eight epochs. They are used to measure the parallax.

In order to measure the parallax and proper motion of G48.61+0.02, we conducted a combined parallax fit, in which the positions of nine maser features relative to the two background sources J1922+1530 and J1924+1540 were fitted simultaneously with one common parallax, but different proper motions and position offsets for individual features. Table 1 and Figure 3 show the results of the parallax and proper motion fit. Since systematic errors generally dominate over random noise, formal position errors are usually unrealistically small. This results in relatively high reduced $\chi^2$ per degree of freedom of parallax fit (typically values between 4 and 10). Therefore, we assigned independent "error floors" in quadrature with the formal position fitting uncertainties. Trial combined fits were conducted and a separate reduced $\chi^2$ statistic was calculated for the right ascension and declination residuals. The error floors of 55$\mu$as in the right ascension and 158$\mu$as in declination were then adjusted iteratively so as to make the reduced $\chi^2 \simeq 1.0$ for each coordinate. The resulting parallax is 199 $\pm$ 7 $\mu$as.

To check the consistency among the parallax motions for individual maser feature, we also estimated the parallaxes individually. In Table 1, we also show the obtained parallaxes using individual fitting for their maser features. We made the fitting only for seven maser features which are detected at all eight epochs. The 14 obtained values of the parallax using seven features and two background sources are consistent with each other, from 175 to 223 $\mu$as. The error-weighted mean of these values is
Table 1. The measured values of parallax and proper motion for H$_2$O maser features in G48.61+0.02.

| $v_{\text{LSR}}$ (km s$^{-1}$) | $\Delta \alpha$ (mas) | $\Delta \delta$ (mas) | Detected epochs | Background source | $\pi$ (mas) | $\mu_\alpha \cos \delta$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | $\sigma_\alpha$ (mas) | $\sigma_\delta$ (mas) |
|-------------------------------|------------------------|------------------------|------------------|-------------------|------------|--------------------------------|----------------|----------------|----------------|
| 8.5                           | 475                    | -201                   | 10111100         | J1922+1530        | -2.08 ± 0.10 | -5.58 ± 0.11                      | 79 ± 8        | 130 ± 27       | 3               |
|                               |                        |                        |                  | J1924+1540        | -1.88 ± 0.10 | -5.67 ± 0.19                      | 75 ± 14       | 32 ± 3         | 0              |
|                               |                        |                        |                  | Average           | -1.98 ± 0.07 | -5.61 ± 0.10                      | 77 ± 11       | 11 ± 1         | 0              |
| 13.3                          | 109                    | 303                    | 11111111         | J1922+1530        | 220 ± 26     | -3.20 ± 0.04                      | -4.95 ± 0.16  | 49 ± 18        | 1               |
|                               |                        |                        |                  | J1924+1540        | 223 ± 25     | -3.25 ± 0.04                      | -5.05 ± 0.15  | 46 ± 13        | 0              |
|                               |                        |                        |                  | Average           | 222 ± 18     | -3.23 ± 0.03                      | -5.00 ± 0.11  | 48 ± 12        | 0              |
| 16.2                          | 303                    | 77                     | 00011111         | J1922+1530        | -2.42 ± 0.07 | -5.63 ± 0.23                      | 24 ± 7        | 303 ± 5        | 3               |
|                               |                        |                        |                  | J1924+1540        | -2.21 ± 0.19 | -5.43 ± 0.23                      | 64 ± 7        | 111 ± 1        | 1               |
|                               |                        |                        |                  | Average           | -2.36 ± 0.07 | -5.53 ± 0.16                      | 44 ± 7        | 17 ± 0         | 0              |
| 17.3                          | 123                    | 299                    | 11111111         | J1922+1530        | 216 ± 28     | -2.79 ± 0.05                      | -5.05 ± 0.15  | 51 ± 17        | 3               |
|                               |                        |                        |                  | J1924+1540        | 213 ± 30     | -2.75 ± 0.05                      | -4.94 ± 0.09  | 57 ± 10        | 0              |
|                               |                        |                        |                  | Average           | 215 ± 20     | -2.77 ± 0.04                      | -4.98 ± 0.08  | 54 ± 13        | 0              |
| 20.7                          | 130                    | -81                    | 11111111         | J1922+1530        | 196 ± 24     | -2.71 ± 0.04                      | -5.23 ± 0.15  | 45 ± 17        | 2               |
|                               |                        |                        |                  | J1924+1540        | 175 ± 23     | -2.79 ± 0.04                      | -5.32 ± 0.12  | 43 ± 13        | 0              |
|                               |                        |                        |                  | Average           | 185 ± 17     | -2.75 ± 0.03                      | -5.28 ± 0.09  | 44 ± 15        | 0              |
| 22.6                          | 125                    | 299                    | 11111111         | J1922+1530        | 218 ± 30     | -2.29 ± 0.05                      | -5.07 ± 0.17  | 56 ± 19        | 2               |
|                               |                        |                        |                  | J1924+1540        | 199 ± 32     | -2.36 ± 0.05                      | -4.95 ± 0.16  | 60 ± 18        | 0              |
|                               |                        |                        |                  | Average           | 209 ± 22     | -2.33 ± 0.04                      | -5.01 ± 0.12  | 58 ± 18        | 0              |
| 25.5                          | 0                      | 0                      | 11111111         | J1922+1530        | 187 ± 31     | -3.27 ± 0.05                      | -5.15 ± 0.12  | 58 ± 13        | 3               |
|                               |                        |                        |                  | J1924+1540        | 187 ± 29     | -3.26 ± 0.05                      | -5.06 ± 0.16  | 55 ± 18        | 4               |
|                               |                        |                        |                  | Average           | 187 ± 21     | -3.27 ± 0.04                      | -5.11 ± 0.10  | 57 ± 16        | 1               |
| 27.2                          | 3                      | -12                    | 11111111         | J1922+1530        | 207 ± 26     | -3.25 ± 0.04                      | -5.47 ± 0.18  | 49 ± 20        | 3               |
|                               |                        |                        |                  | J1924+1540        | 193 ± 27     | -3.27 ± 0.04                      | -5.44 ± 0.12  | 50 ± 14        | 0              |
|                               |                        |                        |                  | Average           | 200 ± 19     | -3.26 ± 0.03                      | -5.45 ± 0.10  | 50 ± 17        | 2              |
| 31.6                          | 21                     | -172                   | 11111111         | J1922+1530        | 201 ± 26     | -2.91 ± 0.03                      | -5.50 ± 0.15  | 49 ± 16        | 2               |
|                               |                        |                        |                  | J1924+1540        | 216 ± 28     | -2.90 ± 0.05                      | -5.63 ± 0.14  | 52 ± 16        | 2              |
|                               |                        |                        |                  | Average           | 208 ± 19     | -2.91 ± 0.03                      | -5.57 ± 0.10  | 51 ± 16        | 4               |
| Combined Fit                  |                        |                        |                  | J1922+1530        | 202 ± 10     |                                                     | 53 ± 16        | 166 ± 2         | 1               |
|                               |                        |                        |                  | J1924+1540        | 196 ± 11     |                                                     | 56 ± 15        | 150 ± 1         | 0              |
|                               |                        |                        |                  | All               | 199 ± 7      |                                                     | 55 ± 18        | 158 ± 2         | 0              |
| Average                       |                        |                        |                  | J1922+1530        | 206 ± 10     | -2.77 ± 0.05                      | -5.29 ± 0.16  | 51 ± 15        | 4               |
|                               |                        |                        |                  | J1924+1540        | 200 ± 10     | -2.74 ± 0.07                      | -5.28 ± 0.15  | 56 ± 14        | 4               |
|                               |                        |                        |                  | All               | 203 ± 7      | -2.76 ± 0.04                      | -5.28 ± 0.11  | 53 ± 14        | 4               |

Column (2), (3): Offsets relative to the postion of the maser feature at $v_{\text{LSR}} = 25.5$ km s$^{-1}$, and $(\alpha, \delta)_{2000.0} = (19^h 20^m 31\fs 17724, 13^\circ 55' 25'' 2567)$ at 2005/024.

Column (4): ‘1’ for detection, and ‘0’ for non-detection.

Column (6): Parallax estimates.

Column (7), (8): Motions on the sky along the right ascension and declination.

Column (9), (10): Residuals of the parallax and proper motion fit.
derived to be $203 \pm 7 \mu\text{as}$, where the error is derived to be $\sigma^2 = 1/\sum(1/\sigma^2_i)$. This value is consistent with the result of the combined fit. We choose $199 \pm 7 \mu\text{as}$ as the parallax of G48.61+0.02. This parallax corresponds to a source distance of $5.03 \pm 0.19$ kpc.

The obtained distance is approximately 1/2 of the far kinematic distance, which was often assumed previously (Kurtz et al. 1994; Codella et al. 2010). Therefore, the physical size and the luminosity of this source have been overestimated by factors of 2 and 4, respectively. Figure 4 shows the position of G48.61+0.02 in the MWG, which is determined from the distance of $5.03 \pm 0.19$ kpc, the longitude of $l = 48^\circ.61$, and $R_0 = 8.5$ kpc. G48.61+0.02 appears to be located on the Sagittarius-Carina arm. We found that G48.61+0.02 is located near W51. The obtained distance of G48.61+0.02 is very close to the parallactic distance of W51 Main/South, which is measured to be $5.41 ^{+0.31}_{-0.28}$ kpc by the H$_2$O maser astrometric observations with VLBA (Sato et al. 2010).

The absolute proper motion of a maser feature is the sum of the internal motion of the maser feature, the Galactic rotation, the solar motion and the peculiar motion of the source. All motions, expect for the internal motion, are common to all maser features. Therefore, the average of the absolute proper motions of maser features should give the systemic motion of the whole source, in the case that the internal motion is random or symmetric. We consider that this is valid for G48.61+0.02 because of the following two reasons. The averaged radial velocity of all maser features is $20.3$ km s$^{-1}$, which is close to the systemic radial velocity derived from the associated molecular cloud. It suggests that the internal motion is symmetric. Figure 2(b) shows the residual vectors, where the average of absolute proper motions is subtracted. They should be the internal motion of maser features, and we did not find strongly asymmetric motion.

We can divide the absolute proper motions into the systemic and internal motions of G48.61+0.02. The absolute proper motions measured using two background sources are consistent with each other. The averages of absolute proper motions obtained using J1922+1530 and J1924+1540 are $(\mu_{\alpha}\cos\delta,\mu_{\delta}) = (-2.77 \pm 0.05, -5.29 \pm 0.16)$ and $(-2.74 \pm 0.07, -5.28 \pm 0.15)$ mas yr$^{-1}$, respectively. From the average of these values, the systemic motion of G48.61+0.02 is derived to be $(\mu_{\alpha}\cos\delta,\mu_{\delta}) = (-2.76 \pm 0.04, -5.28 \pm 0.11)$ mas yr$^{-1}$. The typical value of internal motion is obtained to be 0.5 mas yr$^{-1}$, corresponding 11.9 km s$^{-1}$ at 5.03 kpc. This value is consistent with a half of the radial velocity span of 24 km s$^{-1}$. The three-dimensional velocity of the internal motion is obtained to be 17 km s$^{-1}$.

4. Discussion

4.1. Peculiar Motion

G48.61+0.02 is located near W51 on the sky. We found that the distances of two sources are also close. However, there is a large velocity difference between them.

The peculiar motion of G48.61+0.02 is estimated to be $(U', V', W') = (11.2 \pm 1.9, -36.2 \pm 1.8, 6.7 \pm 1.5)$ km s$^{-1}$ from the measured distance of 5.03 $\pm 0.19$ kpc and proper motion of $(\mu_{\alpha}\cos\delta,\mu_{\delta}) = (-2.76 \pm 0.04, -5.28 \pm 0.11)$ mas yr$^{-1}$, and the radial velocity of $v_{\text{LSR}} = 19 \pm 1$ km s$^{-1}$. Here, $U'$ is the velocity component toward the Galactic Center, $V'$ is the component in the direction of the Galactic rotation, and $W'$ is the component toward the north.
 Galactic pole. The peculiar motion of W51 Main/South is estimated to be \((U', V', W') = (6.3 \pm 4.5, 5.2 \pm 4.4, 5.2 \pm 4.1)\) km s\(^{-1}\) from the distance, the proper motion, and the radial velocity measured by Sato et al. (2010). In these estimations, we used the Galactic constants of \(R_0 = 8.5\) kpc and \(\Theta_0 = 220\) km s\(^{-1}\) recommended by IAU, and assumed the flat rotation. We also used the solar motion based on a traditional definition of \((U_\odot, V_\odot, W_\odot) = (10.3, 15.3, 7.7)\) km s\(^{-1}\). The estimated peculiar motion vectors are shown in Figure 4. In the case that we used other Galactic constants of \(R_0 = 8.0\) kpc (Reid 1993) and \(\Theta_0 = 236\) km s\(^{-1}\), which is consistent with measured proper motion of Sgr A* (Reid & Brunthaler 2004), the peculiar motions of G48.61+0.02 and W51 Main/South are estimated to be \((U', V', W') = (-7.9 \pm 1.9, -39.4 \pm 1.8, 6.7 \pm 1.5)\) km s\(^{-1}\), and \((-16.2 \pm 4.5, 1.0 \pm 4.4, 5.2 \pm 4.1)\) km s\(^{-1}\), respectively. In both cases, we found that G48.61+0.02 has a large peculiar motion of \(40 \pm 5\) km s\(^{-1}\) at the three dimension, although W51 Main/South is nearly circular orbit with no large peculiar motion.

4.2. Origin of the Large Peculiar Motion

As mentioned in the previous subsection, G48.61+0.02 has the large peculiar motion of \(40 \pm 5\) km s\(^{-1}\). The kinetic energy of the peculiar motion is estimated to be \((2 \pm 1) \times 10^{51}\) erg from the mass of G48.61+0.02 molecular cloud of \((1.0 \pm 0.5) \times 10^5\ M_\odot\) at the distance of 5.03 kpc (Ohishi et al. 1984). What is the origin of this peculiar motion?

The first is the star formation activity of W51, such as the multiple SN explosions and the radiation pressures of OB stars. W51 C centered \((\alpha, \delta)_{2000} = (290^\circ 818, 14^\circ 145)\) and extended with \(0^\circ 22 \pm 0.02\) (Abdo et al. 2009) is the nearest SN remnant from G48.61+0.02. Figure 5(a) shows the position of G48.61+0.02 superimposed on Fermi LAT counts map in 2–10 GeV around W51 C. The separation between G48.61+0.02 and the center of W51 C is \(0^\circ 70\) (62 pc). Figure 5(b) and (c) show the integrated intensity and the position velocity maps in the \(^{13}\text{CO} J = 1-0\) line around W51 C (Jackson et al. 2006). Nakamura et al. (1984) suggest that the molecular cloud (named “cloud 6” by them) located approximately \(0^\circ 6\) east from W51 C is physically related with the expanding shell of W51 C. Although the large peculiar motion of G48.61+0.02 probably cannot be driven by the single SN explosion of W51.

Fig. 3. Parallax signals for the H\(_2\)O masers in G48.61+0.02. The proper motion and the position offset are removed. The data for the different maser features are slightly shifted in time for clarity. The left two panels show the parallax motion obtained using J1922+1530, and the right two panels show the parallax motion obtained using J1924+1540.
The kinetic energy of the peculiar motion requires kinetic energy of W51 C is estimated to be kinetic enerty of W51 C of 0.090 sr (0.7% of 4π sr) from the explosion cloud can receive at this solid angle from the explosion 0.048 H2 O masers in G48.61+0.02 could be associated with the massive young stellar object (YSO) in the NH3 core. Codella et al. (2010) estimate the virial mass of this NH3 core to be 337 M⊙at their assumed distance of 9.7 kpc. This mass is re-estimated to be 173 M⊙at the distance of 5.03 kpc. In the case that we assume the typical star formation efficiency of ∼10–30% (Lada & Lada 2003), the stellar mass of YSOs formed in the NH3 core is estimated to be ∼17–52 M⊙. The bright infrared emission corresponding to this mass is detected in this region. The infrared luminosity is estimated to be 1.7 × 10^5 L⊙at the distance of 5.03 kpc (Verma et al. 2009).
5. Conclusions

We observed the H$_2$O masers in the Galactic star-forming region G48.61+0.02 with VERA. Our conclusions are summarized as follows:

1. We have determined the trigonometric parallax of G48.61+0.02 to be 199 ± 7 μas, corresponding to a distance of 5.03 ± 0.19 kpc. This distance places G48.61+0.02 in the Sagittarius-Carina arm and near the active star forming region and the SN remnant W51.

2. The observed distance, proper motion, and radial velocity of G48.61+0.02 indicate that it has a large peculiar motion of 40 ± 5 km s$^{-1}$. This large peculiar motion might be the result of the multiple SN explosions in W51, or the streaming motion across the Sagittarius-Carina arm.

3. The internal motions of H$_2$O masers in G48.61+0.02 exhibit the expanding outflow with the three-dimensional velocity of 17 km s$^{-1}$. The masers would be associated with the YSO with the mass of approximately 17–52 $M_{\odot}$ formed in the NH$_3$ core.

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Fig. 5. (a): Positions of G48.61+0.02, W51 Main/South (white circle), and OB stars in G49.5-0.4 (green cross) superimposed on Fermi LAT counts map in 2–10 GeV around W51 C (Green 2009). The crosses show the center of W51 C and the position of J1921+1419. The arrow shows the motion of G48.61+0.02 relative to W51 Main/South which is obtained to be $-0.12 \pm 0.16$ mas yr$^{-1}$ ($-2.9 \pm 3.9$ km s$^{-1}$) in right ascension and $-0.17 \pm 0.19$ mas yr$^{-1}$ ($-4.1 \pm 4.6$ km s$^{-1}$) in declination. (b): same as (a), but the background shows the integrated intensity map in the $^{13}$CO $J = 1$–0 line (Jackson et al. 2006). (c): Longitude-velocity map in the $^{13}$CO $J = 1$–0 line (Jackson et al. 2006).
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