Tracing the magnetic field and other properties of G351.417+0.645 at subarcsecond scales with the Long Baseline Array

T. Chanapote^{1,2,3★}, K. Asanok^{1,3★}, R. Dodson^{1,2}, M. Rioja^{1,2,4,5}, J. A. Green⁶ and B. Hutawarakorn Kramer^{3,7}

¹Department of Physics, Faculty of Science, Khon Kaen University, 123 Moo 16, T. Nai-Muang, A. Muang, Khon Kaen 40002, Thailand

²International Centre for Radio Astronomy Research, The University of Western Australia, M468, 35 Stirling Highway, Crawley, Perth, WA 6009, Australia

³National Astronomical Research Institute of Thailand, 260 Moo 4, T. Donkaew, A. Maerim, Chiangmai 50180, Thailand

⁴CSIRO Astronomy and Space Science, 26 Dick Perry Avenue, Kensington WA 6151, Australia

⁵Observatorio Astronómico Nacional (IGN), Alfonso XII, 3 y 5, E-28014 Madrid, Spain

⁶CSIRO Astronomy and Space Science, Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia

⁷Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

Accepted 2018 October 11. Received 2018 October 11; in original form 2018 April 17

ABSTRACT

We present the results from the Australian Long Baseline Array (LBA) observations of the ground- and excited-state OH masers (1.7- and 6.0-GHz lines) at high spatial and velocity resolution towards the high-mass star-forming region G351.417+0.645. We obtained accurate spatial gradient magnetic fields from 21 and 23 Zeeman pairs at ground and excited states, respectively, providing magnetic field measurements between -6.4 and $+4.4$ mG. In addition, we verify the reliability of magnetic field strengths measured from previous lower resolution observations. We found that OH maser features at 1665- and 6035-MHz reveal the same trend of a reversal of magnetic field which we attribute, based on recent infrared observations to cloud fragmentation. In comparison with previous LBA observations 11 yr prior, we identify several matched Zeeman pairs. We found no significant changes of magnetic field strengths, directions, or radial velocities from the matched Zeeman pairs between these two epochs (although there were small internal proper motions). This implies quite stable physical conditions in this region. Moreover, we also analysed the physical conditions from the coincidence of OH maser features from different transitions based on current OH maser models.

Key words: masers – polarization – methods: data analysis – astrometry – ISM: kinematics and dynamics – ISM: magnetic fields.

1 INTRODUCTION

The study of the early stages of high-mass ($\geq 8 M_{\odot}$) stars is limited by their dense and thick environments (opaque to visible light) and scarcity (short lifetime). However, the increasing development of the instruments for multiwavelength (i.e. infrared (IR), millimetre (mm), submillimetre (submm), radio) observations allows for better understanding of this field (Beuther et al. 2000; Marseille et al. 2010; Sakai et al. 2010). At radio wavelengths, cosmic masers – naturally occurring beamed radiation from molecules in interstellar mediums – become a crucial tool to study high-mass star-forming regions (HMSFRs), for example, tracing their evolutionary sequences (Ellingsen et al. 2007; Breen & Ellingsen 2012). Various species of cosmic maser are often detected towards HMSFRs including hydroxyl (OH), methanol (CH₃OH), water (H₂O) (Fish 2007;

Bartkiewicz & van Langevelde 2012); among them, OH are of several strong maser lines and easily detectable with large Zeeman splitting coefficients suitable for magnetic field study (Fish et al. 2003). There are many properties, we can study through maser observations, especially in the case of OH, including (1) morphology (Slysh et al. 2002; Hutawarakorn & Cohen 2005); (2) magnetic fields (Davies 1974; Fish & Reid 2007; Caswell, Kramer & Reynolds 2011); (3) kinematics (Argon, Reid & Menten 2003; Trinidad et al. 2013); and (4) physical properties (Etoka, Cohen & Gray 2005).

This paper reports the results from OH maser observations obtained in 2012 towards the well-known HMSFR G351.417+0.645. This source is located inside the cometary ultra compact HII (UCHII) region NGC 6334F – the smallest and youngest clump within the optically thin molecular cloud complex NGC 6334 (Rodríguez, Canto & Moran 1982) one of the nearest HMSFRs to the Sun at a parallax measured distance of $1.34^{+0.15}_{-0.12}$ kpc (Reid et al. 2014). Based on far-infrared (FIR) observation of McBreen et al. (1979), NGC 6334F is within the NGC 6334I cluster that is

* E-mail: t.chanapote@gmail.com (TC); kitiyane@narit.or.th (KA)

extremely complex and associated with multifrequency emissions with multiple emitting systems including near-infrared (NIR; Persi et al. 1996), mid-infrared (MIR; Persi et al. 1998; Kraemer & Jackson 1999; De Buizer, Pina & Telesco 2000; De Buizer et al. 2002), FIR (Harvey & Gatley 1983), and mm (Hunter et al. 2006; Brogan et al. 2016). Besides, this region is also abundant in maser emission, and these have been continuously observed for a long period of time by single dishes, interferometric arrays and very long baseline interferometers (VLBI) including OH (Lo et al. 1975; Kent & Mutel 1982; Gaume & Mutel 1987; Zheng 1989; Caswell & Vaile 1995; Argon, Reid & Menten 2000; Caswell 2003; Caswell et al. 2011; Caswell, Green & Phillips 2013; Hunter et al. 2018), CH₃OH (Caswell 1997; Walsh et al. 1998; Brogan et al. 2016; Hunter et al. 2018), and H₂O (Forster & Caswell 1989; Migenes et al. 1999; Brogan et al. 2016). Within the UCHII region NGC 6334F, OH and CH₃OH masers are distributed along the north-western boundary while H₂O masers were only detected in the north.

Caswell et al. (2011) performed the first VLBI high spatial and velocity resolution observations (~ 0.05 arcsec and ~ 0.1 km s⁻¹, respectively) of excited state OH masers (6030 and 6035 MHz) inside NGC 6334F using the Australian Long Baseline Array (LBA). They provided the first well-characterized spatial gradient magnetic field measurements in this region.

In the current study, we present follow-up OH maser observations of this region in both ground and excited states using the LBA with compatible high spatial and velocity resolutions. There are three main purposes for this work: (1) to obtain the first spatial gradient magnetic field measurements from both ground (1665, 1667, and 1720 MHz) and excited (6030 and 6035 MHz) transitions and compare with previous comparable and lower resolution observations; (2) to study magnetic field variations and kinematics over an 11-yr time span through the comparison between comparable LBA high resolution observations; and (3) to study the physical conditions in this region by comparing our observational results with current OH maser models.

In Sections 2 and 3 of this paper, we describe our observations, data reduction process, and data analysis. In Section 4, we present the results and discussions of our observations together with the comparisons with previous observations and models. In Section 5, we summarize our findings from this study.

2 OBSERVATIONS

Experiments V452A and V452B were observed using the Australian VLBI antennas including the Australia Telescope Compact Array (ATCA), Ceduna (Cd), Hobart (Ho), Mopra (Mp), and Parkes (Pa) as part of the LBA as summarized in Table 1. The experiment consisted of observations at two bands, on the 8th and 10th of 2012 August, covering the 6030- and 6035-MHz lines together with 6.7-GHz CH₃OH line and 1665-, 1667-, and 1720-MHz lines, respectively. ATCA, Mp, and Pa are run by CSIRO and all are in New South Wales on the east coast of Australia. Ho and Cd are run by the University of Tasmania and are in Tasmania and South Australia, respectively. The baseline lengths range from ~ 100 km (ATCA to Mp) to ~ 1400 km (ATCA to Ho) and ~ 1500 km (ATCA to Cd) for 1.7 and 6.0 GHz, respectively, providing good sensitivity to both compact and more extended emission. Note that, however, Cd only observed the excited-state OH main lines (i.e. 6030 and 6035 MHz) and Ho only observed the CH₃OH line (i.e. 6668 MHz) while, at 1.7 GHz, Cd did not observe and Ho only observed the ground-state OH main lines (i.e. 1665 and 1667 MHz). The observing set-up comprised four 16-MHz (wide-band) intermediate frequen-

Table 1. The experiments V452A and V452B.

Projects	V452A	V452B
Observing dates	2012 August 8	2012 August 10
Target sources	G351.417+0.645 G351.445+0.660 G351.581−0.353 G351.775−0.536	G351.417+0.645 G351.445+0.660 G351.581−0.353 G351.775−0.536
Calibrators	1718−649 1729−373 J1640−3727 1921−293 1934−638	1718−649 1729−373 J1640−3727 1921−293 1934−638
Antennas	ATCA, Cd, Ho Mp, Pa	ATCA, Ho, Mp Pa
Shortest baseline	113 km	113 km
Longest baseline	1504 km	1396 km
Transitions (MHz)	6030 6035 6668	1665 1667 1720
Bandwidth (MHz)		
−Wide band	16	16
−Narrow band	4	2
Subbands (IFs)		
−Wide band	4	4
−Narrow band	3	3
Spectral channels		
−Wide band	32	32
−Narrow band	2048	4096
Velocity resolution	0.10 km s ⁻¹	0.09 km s ⁻¹

cies (IFs) and three narrow-band IFs with bandwidths of 4- and 2-MHz for 6.0/6.7- and 1.7-GHz lines, respectively. The IFs were spread to cover the maser lines at 6030, 6035, and 6668 MHz and 1665, 1667, and 1720 MHz, respectively. The observed data in nominal Left- and Right-Hand Circular Polarizations (LHCP and RHCP) were recorded to the LBA disc-based recorder system. For the observation, 10-min scans on fringe finding sources 1934−638 and 1921−293 were observed for bandpass and clock offset calibrations, along with 2-min scans on delay calibrator sources 1729−373 and 1718−259. The four well-known OH masers sources were observed: G351.417+0.645, G351.445+0.660 (observed communally with the previous source), G351.581−0.353 and G351.775−0.536. This paper reports only on the G351.417+0.645 observations at the pointing centre RA = 17^h20^m53^s.37 and Dec. = −35°47′1″.2 (J2000), while the results of the other target sources together with the methanol line will be separately published later. Compact strong polarization, phase-referencing, and amplitude calibrators were also observed with each maser source, with a cycle time of about 30 minutes. The data were correlated using DiFX. The narrow-band IFs were split into 4096 and 2048 channels, providing channel separations of 0.488 and 1.953 kHz or velocity resolutions of 0.09 and 0.1 km s⁻¹ at 1.7 and 6.0 GHz, respectively.

3 DATA REDUCTION AND ANALYSIS

The calibration process was mainly performed using the AIPS (Astronomical Image Processing System) reduction package (Greisen 2003). We have followed the standard data reduction process for spectral line (Caswell 1997; Caswell et al. 2011) for both 1.7 and 6.0 GHz including (1) flagging of data, (2) instrument and environment corrections, (3) phase and amplitude corrections, (4) realignment of the channels, (5) phase referencing to the calibra-

tor, and then to the brightest features. The first three steps were performed with continuum data. The source 1921–293 was used as phase tracking and amplitude calibrator. All solutions were applied to the spectral line data before proceeding to the last two steps. For the spectral line data, the systemic velocity was set to -10 km s^{-1} at rest frequencies for all five OH lines: 6030.7470, 6035.0920, 1665.4018, 1667.3590, and 1720.5300 MHz. For the final step, firstly the brightest features at 1665 and 6035 MHz were phase referenced to the nearest calibrator 1729–373 in which we obtain the interband astrometric errors (see Section A2). Finally, the Stokes LL high-quality images of the brightest channels at 1665 and 6035 MHz, created using DIFMAP (an interactive editing and mapping software) (Shepherd 1997), were used to self-calibrate for 1665- and 6035-MHz lines and phase reference to 1665-, 1667-, and 6030-MHz lines; this provides the intraband astrometric errors (see Section A3).

All procedures and criteria for data analysis are defined as follows:

Image Cubes: After finishing data calibration, image cubes were created using IMAGR task in AIPS with image size 4096×4096 pixels, cell size $0.002 \text{ arcsec} \times 0.002 \text{ arcsec}$ for all transitions consisting of 100 and 150 channels for 1.7 and 6.0 GHz covering their ranges of radial local standard of rest (LSR) velocity (V_{LSR}),¹ approximately from -15 to -6 and -17 to -3 km s^{-1} , respectively. Note that for 6.0 GHz, we excluded the Cd antenna in imaging (due to the low sensitivity from Cd long baselines) to improve the SNR. The restoring beamwidths at 1665/1667 and 6030/6035 MHz are $\sim 0.03 \text{ arcsec} \times 0.013 \text{ arcsec}$ and $\sim 0.05 \text{ arcsec} \times 0.015 \text{ arcsec}$ with position angles of $\sim 88^\circ$ and 75° , respectively, while at 1720 MHz, lacking of Ho antenna, the restoring beamwidth is $\sim 0.13 \text{ arcsec} \times 0.05 \text{ arcsec}$ with position angle of $\sim -78^\circ$. In all considered channels, the image rms noise varies from 0.01 to 0.80 Jy depending on the peak intensities; the average values at 1665/1667 and 1720/6030/6035 MHz are ~ 0.1 and 0.03 Jy , respectively.

Maser feature: We used CASA viewer (in CASA package) to search and perform 2D Gaussian fitting to all emission peaks across images. Maser features were defined based on two main following criteria: (1) their emissions are detected at least in three successive frequency channels with minimum SNR^2 of three and (2) the peak position offsets are within the restoring beamwidths. Then we calculated intensity-weighted position and velocity together with the positional standard deviations (σ) for each feature from its component spots. The average σ for 1665-, 1667-, 6030-, and 6035-MHz images is $\sim 2 \text{ mas}$, while for 1720-MHz images the value is increased to $\sim 5 \text{ mas}$ due to its wider restoring beamwidth.

Coincidence of maser features: Maser features from different transitions are defined to be coincident if they lie within their absolute positional uncertainty which is the quadrature sum of all positional errors including thermal noise, interband and intraband (only for 1667-, 1720-, and 6030-MHz images) astrometric errors

¹The velocity with respect to the LSR which is the perfectly circular orbit around the galactic centre at the sun distance (Schönrich, Binney & Dehnen 2010). The V_{LSR} is derived from Doppler shift of the observed spectral frequency with respect to the rest frequency:

$$V_{\text{LSR}} = V_c - \left(\frac{f_s - f_r}{f_r} \right) \times c, \quad (1)$$

where V_c is the central reference LSR velocity, f_s and f_r are the observed source frequency and rest frequency, respectively, and c is the speed of light.

²Signal-to-noise ratio, the ratio between peak flux density and rms noise.

(see the Appendix) and σ written as following equations with average values (in mas unit):

$$\begin{aligned} 1665 \text{ MHz} : \sqrt{1.6^2 + 11.4^2 + \sigma^2} &\approx 12, \\ 1667 \text{ MHz} : \sqrt{1.6^2 + 11.4^2 + 0.5^2 + \sigma^2} &\approx 12, \\ 1720 \text{ MHz} : \sqrt{1.6^2 + 11.4^2 + 13.2^2 + \sigma^2} &\approx 19, \\ 6030 \text{ MHz} : \sqrt{1.0^2 + 1.3^2 + 0.3^2 + \sigma^2} &\approx 3, \\ 6035 \text{ MHz} : \sqrt{1.0^2 + 1.3^2 + \sigma^2} &\approx 3. \end{aligned} \quad (2)$$

Zeeman pairs: The Zeeman pairs are established from LHCP and RHCP maser features of the same transitions having position offsets within their absolute positional uncertainties. The magnetic field strengths are calculated from following equation:

$$B = (V_{\text{RR}} - V_{\text{LL}})/C_Z, \quad (3)$$

where V_{RR} and V_{LL} are the velocities of RHCP and LHCP maser features, respectively, and C_Z is the Zeeman splitting coefficient. The Zeeman splitting coefficients used in this work were adopted from Green et al. (2012), Caswell et al. (2011), Caswell (2004), and Caswell (2003) that are 0.590, 0.354, 0.113, 0.079, $0.0564 \text{ km s}^{-1} \text{ mG}^{-1}$ for 1665, 1667, 1720, 6030, and 6035 MHz, respectively. The negative and positive signs of magnetic field strength from this equation imply the magnetic direction directed towards and away from us, respectively. We have adopted the IEEE definition for RHCP and LHCP and the IAU convention for Stokes V, i.e. RHCP would be seen by an observer as counterclockwise circular polarization.

Radial velocity: We considered only the maser features having their matched Zeeman pairs and averaged the velocities of RHCP and LHCP features from each Zeeman pair to estimate the demagnetized velocity which we determined to represent the velocity of the maser emission if there was no magnetic field present.

Proper motion: Proper motion is defined when the position difference of the same maser features from different epochs are larger than their positional uncertainties. In this work, we compared the same OH maser features in the 6.0-GHz lines with Caswell et al. (2011). The brightest LHCP feature at 6035 GHz of two epochs was used as a reference feature, as a result, this is the internal proper motion with respect to the reference feature. Then, the positional uncertainties includes only intraband astrometric errors of 0.3 mas when applying from 6035 MHz $\rightarrow$ 6030 MHz and σ as following equations with average values (in mas unit),

$$\begin{aligned} 6030 \text{ MHz} : \sqrt{0.3^2 + \sigma^2} &\approx 3, \\ 6035 \text{ MHz} : \sigma &\approx 2. \end{aligned} \quad (4)$$

The positional uncertainties of maser features from Caswell et al. (2011) are assumed to be equivalent to those from this work. The criteria for defining the same OH features between the two epochs are location proximity, trend of spatial distribution with respect to the reference feature and relevance of their radial velocities. Linear displacement ($\vec{S}$) that each OH maser feature moves in 11-yr time span is calculated by adopting the target source distance (D) of $1.34^{+0.15}_{-0.12} \text{ kpc}$ from Reid et al. (2014) as follow:

$$\vec{S} = \vec{\theta} D, \quad (5)$$

where $\vec{\theta}$ is the angular displacement. The transverse velocities ($\vec{V}_T$) along the sky plane are calculated from the linear displacement ($\vec{S}$) divided by length of time (t) between the two epochs:

$$\vec{V}_T = \vec{S}/t. \quad (6)$$

Figure 1. The vector averaged spectra of the ground and excited state transitions with respect to LSR velocities from the shortest baseline with the highest sensitivity, i.e. ATCA and Mp. The systemic velocity is set to -10 km s^{-1} at the rest frequencies of all transitions shown as the vertical dot line.

4 RESULTS AND DISCUSSION

4.1 OH spectra

The vector averaged spectra from the ground and excited state transitions with respect to LSR velocities are shown in Fig. 1. The correlated spectra are chosen from the shortest baseline (i.e. ATCA and Mp) to obtain the highest sensitivity. OH maser spectra from all transitions show the same trend of higher flux density in the LHCP than in the RHCP. The strongest lines in the ground- and excited-state transitions are 1665 and 6035 MHz that have flux densities in the order of a few hundred Jy.

The OH maser features were searched within the velocity range between -14 and -6 km s^{-1} . The properties of this region analysed from those maser features are divided into four sections as follows: Section 4.2 – Morphology, Section 4.3 – Magnetic fields, Section 4.4 – Kinematics, and Section 4.5 – Physical properties.

4.2 Morphology

The OH maser distributions at all observed transitions from both LHCP and RHCP are shown in Fig. 2. The reference position is taken to be the location of the 6035-MHz brightest LHCP feature at $\text{RA(J2000)} = 17^{\text{h}}20^{\text{m}}53^{\text{s}}.3716$ and $\text{Dec. (J2000)} = -35^{\circ}47'1''.608$ to which all OH maser features at 6.0 GHz are phase-referenced. The 1665-MHz brightest LHCP feature position is at $\text{RA (J2000)} = 17^{\text{h}}20^{\text{m}}53^{\text{s}}.3713$ and $\text{Dec. (J2000)} = -35^{\circ}47'1''.612$ approximately 0.006 arcsec offset from the 6035-MHz reference feature

and similarly all OH maser features at 1.7 GHz are phase-referenced to this position. Additionally, the brightest LHCP features from both 1.7 and 6.0 GHz are phase-referenced to the common external quasar 1729–373. Based on this process, all OH maser features are well astrometrically registered as described in the Appendix. There are 142 OH maser features detected from all five transitions as listed in Tables 2–5. We found 56, 24, 10, 10, and 42 features at 1665 (black), 1667 (green), 1720 (magenta), 6030 (red), and 6035 (blue) MHz, respectively, including both LHCP and RHCP features. All OH maser features in this source are distributed over an area of $\sim 2.0 \text{ arcsec} \times 3.5 \text{ arcsec}$ (or $2680^3 \text{ au} \times 4690^3 \text{ au}$). The distribution of all OH masers from both 1.7 and 6.0 GHz transitions trace an arc-shape along the north-west boundary of the UCHII region NGC 6334F observed with the VLA at 5-cm wavelength and the 3-mm ALMA dust continuum clump MM3 (red dash and black solid contours in Fig. 2, respectively) (Brogan et al. 2016).

We compared our OH maser features in the ground-state transitions with previous lower spatial and velocity resolution observations of Argon et al. (2000) and Gaume & Mutel (1987) obtained with the VLA. Argon et al. (2000) found 17, 14, and 3 features at 1665, 1667, and 1720 MHz, respectively, as listed in their table 85, while Gaume & Mutel (1987) detected 14, 8, and 4 features at 1665, 1667, and 1720 MHz, respectively, as listed in their table 1. Our considerably larger number of OH maser features probably results from the finer spatial and velocity resolution of our observations, which resolve some blended features from previous ground-state observations at lower resolution. For the positional comparisons, due to their large absolute position uncertainties ($\sim 0.3 \text{ arcsec}$), we set the 1665-MHz brightest LHCP features from our work and their works to the same position. However, there are uncertainties to be considered as following. Using the VLA, Argon et al. (2000) reported Gaussian fitting errors of 0.01 arcsec , while those of Gaume & Mutel (1987)’s work are much higher $\sim 0.15 \text{ arcsec}$. Our Gaussian fitting errors are much smaller (in micro-arcsecond scale), and σ_{RA} and σ_{Dec} are in mas scale (generally less than 10 mas). From the comparison plot (not shown), we found the same trend of maser distributions at 1665 and 1667 MHz along the north-west boundary of the UCHII region NGC 6443F where there is a sharp increase in flux density as shown in figs 35 and 24 of Argon et al. (2000) and Gaume & Mutel (1987), respectively. At 1720 MHz, there are obvious position shifts of OH maser features between our results and Argon et al. (2000)’s because the positions of OH maser features do not overlap within each other’s errors.⁴ However, some of our 1720-MHz OH maser features below the reference centre are coincident with those of Gaume & Mutel (1987) and we detected new 1720-MHz features above the reference centre.

In the excited-state transitions, in comparison with recent VLA observations (epoch 2016) from Hunter et al. (2018) inside NGC 6334F with comparable velocity resolution of $\sim 0.1 \text{ km s}^{-1}$ and lower angular resolution of $0.79 \text{ arcsec} \times 0.25 \text{ arcsec}$, we found that their seven groups of 6.0-GHz OH masers (OH1–OH7) as shown in their fig. 5 reproduce the features detected in our epoch

³This is calculated from the NGC 6334 distance of $\sim 1.34 \text{ kpc}$ from maser parallax measurements of Reid et al. (2014).

⁴Our approximate uncertainty of the relative positions of 1720 MHz transitions to the brightest features at 1665 MHz is approximately 13.2 mas as described in Section A3. Argon et al. (2000) suggested the uncertainties in relative position between different transitions should be from $1/4$ to $1/2$ of the absolute position errors providing the approximate errors of 0.15 arcsec and 0.50 arcsec in RA and Dec., respectively, while the total errors of Gaume & Mutel (1987) are $\sim 0.3 \text{ arcsec}$.

Figure 2. The top left image shows the OH masers at 1.7 GHz (circle and cross represent LHCP and RHCP, respectively) and 6.0 GHz (point-up and point-down triangles represent LHCP and RHCP, respectively) overlaid on the 5-cm UCHII NGC 6334F continuum [red dash contours: 4.2×10^{-5} Jy (4, 50, 100, 200, 300, 400, 500, 600, 700)] and 3-mm dust continuum [black solid contours: 5×10^{-5} Jy (4, 10, 20, 50, 100, 150, 200)] of the NGC 3664I multiclump system from Brogan et al. (2016) where the dust clump MM3 is coincident with the UCHII region NGC 6334F. The beamwidths of the continuum data with corresponding colours are displayed in the bottom-right corner. The top right image presents a magnification of the region where the masers are found where different symbols and colours represent different OH lines: 1665 MHz (black circle and cross), 1667 MHz (green square and plus), 1720 MHz (magenta diamond and sparkle), 6030 MHz (red up- and down-triangle), and 6035 MHz (blue pentagon and star). The absolute positional uncertainties with the same colours as the symbols are also shown. The four lower panels present a magnification of three compact areas: (a), (b), and (c).

Table 2. OH maser features from both LHCP and RHCP for G351.417+0.645 at 1665 MHz. Position offsets are relative to the brightest 6035 LHCP feature at RA (J2000) = 17^h20^m53^s.3716 and Dec. (J2000) = −35°47′1″.608.

Feature no.	V_{LSR} (km s ^{−1})	R.A. (arcsec)	Dec. (arcsec)	RA err. ^a (arcsec)	Dec. err. ^b (arcsec)	Peak flux ^c (Jy beam ^{−1})	Zeeman pairs	Avg. vel. ^d (km s ^{−1})	B^e (mG)	Matching features	TOC ^f
1665 LHCP											
1	−6.30	0.506	−1.065	0.012	0.012	0.60	Z ₁	−7.90	−5.4	37*	A
2	−6.64	0.787	0.121	0.012	0.012	0.76	Z ₂	−8.09	−4.9	38*, 74, 107, 127	J
3	−7.12	0.768	0.090	0.012	0.012	1.23				112, 130	G
4	−7.27	0.529	−1.298	0.012	0.012	1.40				113, 132	G
5	−7.27	0.123	0.057	0.012	0.012	6.67	Z ₃	−8.96	−5.7	5, 10, 11, 42*	A
6	−7.27	0.125	0.093	0.012	0.012	1.03				—	A
7	−7.41	0.758	0.020	0.012	0.012	1.90				—	A
8	−7.49	0.758	−0.014	0.012	0.012	27.05	Z ₄	−8.83	−4.5	39, 40*, 57, 58, 76, 114, 133	J
9	−7.52	0.193	−0.938	0.012	0.012	1.22				—	A
10	−7.54	0.142	0.045	0.012	0.012	1.20				5, 11, 42	A
11	−7.68	0.108	0.046	0.012	0.012	2.95				5, 10, 42	A
12	−7.84	0.762	0.064	0.012	0.012	7.45				60	F
13	−8.67	−0.570	−0.928	0.012	0.012	5.15				—	A
14	−8.71	0.061	0.033	0.012	0.012	3.05				—	A
15	−8.73	−0.246	−1.072	0.012	0.012	6.41				—	A
16	−8.74	−0.022	−1.394	0.012	0.012	6.84				—	A
17	−8.76	0.037	−0.054	0.012	0.012	10.40				—	A
18	−8.80	−0.004	−0.004	0.012	0.012	207.75	Z ₅	−10.29	−5.0	21, 28, 30, 47*, 51 61, 67, 70, 78, 79 95, 100, 119, 121, 140, 142	L
19	−8.82	−0.005	0.038	0.012	0.013	21.58	Z ₆	−10.28	−4.9	46*, 75	F
20	−9.28	−0.028	−0.340	0.012	0.012	1.40	Z ₇	−10.95	−5.7	54*	A
21	−9.70	−0.002	−0.008	0.012	0.012	5.70	Z ₈	−11.00	−4.4	18, 28, 30, 47, 51* 61, 67, 70, 78, 79 95, 100, 119, 121, 140, 142	L
22	−9.77	0.065	−0.067	0.012	0.012	3.01	Z ₉	−11.22	−4.9	55*	A
23	−9.92	0.190	0.575	0.012	0.012	0.78				71, 118, 138	J
24	−10.36	0.158	0.258	0.012	0.012	3.86	Z ₁₀	−9.43	+3.2	33*	A
25	−10.97	0.953	−0.880	0.012	0.012	1.22				117, 136	G
26	−11.50	0.316	0.739	0.012	0.012	0.62				139	G
27	−11.67	1.049	1.020	0.012	0.012	1.86	Z ₁₁	−10.44	+4.2	35*, 77	F
28	−11.81	0.006	−0.000	0.012	0.012	1.15				18, 21, 30, 47, 51 61, 67, 70, 78, 79 95, 100, 119, 121, 140, 142	L
29	−11.92	0.310	0.766	0.012	0.012	0.54				—	A
30	−12.27	0.009	−0.001	0.012	0.012	0.66				18, 21, 28, 47, 51 61, 67, 70, 78, 79 95, 100, 119, 121, 140, 142	L
1665 RHCP											
31	−6.25	1.309	1.016	0.012	0.012	1.34				—	A
32	−8.48	0.296	0.722	0.012	0.012	1.37				—	A
33	−8.49	0.159	0.258	0.012	0.012	2.63	Z ₁₀	−9.43		24*	A
34	−8.50	0.250	0.673	0.012	0.012	1.74				—	A
35	−9.21	1.048	1.020	0.012	0.012	3.08	Z ₁₁	−10.44		27*, 77	F
36	−9.26	0.526	−1.119	0.012	0.012	1.53				91, 96, 103, 124	K
37	−9.49	0.509	−1.068	0.012	0.012	1.70	Z ₁	−7.90		1*	A
38	−9.54	0.785	0.118	0.012	0.012	4.30	Z ₂	−8.09		2*, 74, 107, 127	J
39	−9.95	0.770	−0.012	0.013	0.012	4.80				8, 40, 57, 58, 76, 114, 133	J
40	−10.17	0.757	−0.016	0.012	0.012	9.41	Z ₄			8, 39, 57, 58, 76, 114, 133	J
41	−10.45	0.167	0.104	0.012	0.012	1.57				43	A
42	−10.64	0.120	0.064	0.012	0.012	1.00	Z ₃	−8.96		5*, 10, 11	A
43	−10.77	0.173	0.100	0.012	0.012	1.41				41	A
44	−11.65	0.087	−0.724	0.012	0.012	3.05				—	A

Table 2 – *continued*

Feature no.	V_{LSR} (km s^{-1})	R.A. (arcsec)	Dec. (arcsec)	RA err. ^a (arcsec)	Dec. err. ^b (arcsec)	Peak flux ^c (Jy beam^{-1})	Zeeman pairs	Avg. vel. ^d (km s^{-1})	$\mathbf{B}^e$ (mG)	Matching features	TOC ^f
45	−11.74	0.071	−0.029	0.012	0.012	8.80				53	A
46	−11.74	−0.012	0.026	0.012	0.012	3.52	Z_6	−10.28		19*, 75	F
47	−11.77	−0.005	−0.006	0.012	0.012	41.71	Z_5	−10.29		18*, 21, 28, 30, 51 61, 67, 70, 78, 79 95, 100, 119, 121, 140, 142	L
48	−12.00	−0.130	−0.343	0.012	0.012	2.70				—	A
49	−12.11	−0.071	−0.178	0.012	0.012	4.20				—	A
50	−12.16	−0.014	−0.146	0.012	0.012	1.94				—	A
51	−12.29	−0.002	−0.007	0.012	0.012	26.95	Z_8	−11.00		18, 21*, 28, 30, 47 61, 67, 70, 78, 79 95, 100, 119, 121, 140, 142	L
52	−12.32	−0.056	−0.455	0.012	0.012	7.66				120, 141	G
53	−12.33	0.071	−0.031	0.012	0.012	4.80				45	A
54	−12.62	−0.036	−0.344	0.012	0.012	2.30	Z_7	−10.95		20*	A
55	−12.67	0.064	−0.066	0.012	0.012	5.40	Z_9	−11.22		22*	A
56	−12.69	0.129	−0.062	0.012	0.012	1.15				—	A

Notes. ^{a,b}The absolute positional errors in RA and Dec offsets.

^cThe peak flux of the brightest component was taken to be the peak flux density of the maser feature. The average rms noise of 1665-MHz images is ~ 0.06 Jy with maximum value of 0.7 Jy (~ 0.4 per cent of the peak flux) in the brightest channel.

^dThe average (demagnetized) velocity from the velocities of LHCP and RHCP features of each Zeeman pair. ^eThe strength of magnetic field ($\mathbf{B}$) can be calculated from equation (3) and the maximum uncertainty of $\mathbf{B}$ measurement ($\Delta\mathbf{B}$) is ± 0.2 mG.

^fTypes of coincidence (TOC) including A (only 1665 MHz), B (only 1667 MHz), C (only 1720 MHz), D (only 6030 MHz), E (only 6035 MHz), F (1665 & 1667 MHz), G (1665 & 6035 MHz), H (1667 & 6035 MHz), I (6030 & 6035 MHz), J (1665 & 1667 & 6035 MHz), K (1665 & 6030 & 6035 MHz) and L (1665 & 1667 & 6030 & 6035 MHz).

*The matched Zeeman pairs.

2012 observations distributed along the north-west boundary of the UCHII region NGC 6334F.

Moreover, we also compare the position of our 6.0-GHz OH maser features (epoch 2012) with those of Caswell et al. (2011) (epoch 2001; cf. their table 1) obtained with comparable high resolution observations. The phase reference feature of Caswell et al. (2011) is at RA (J2000) = $17^{\text{h}}20^{\text{m}}53^{\text{s}}.38$ and Dec. (J2000) = $-35^{\circ}47'1''.5$. However, Caswell et al. (2011) reported a minimum absolute position uncertainty of ~ 0.2 arcsec.⁵ In order to make a comparison, we set the reference features of both epochs to be at the same position for more accurate comparison of the relative positions between two epochs. The overlay plot (not shown) of our 6.0-GHz maser features and those of Caswell et al. (2011) show almost exactly the same spatial distribution. 81 per cent (100 per cent matching features for the 6030-MHz transition and 76 per cent for the 6035 MHz) of all the features detected in this work in the 6.0-GHz transitions were also detected by Caswell et al. (2011). The matching features are given in column 1 of Tables 4 and 5. At 6035 MHz, 14 OH maser features observed in the 2001 epoch were not detected by us; 13 of the 14 features had fluxes in the range 0.06–1.3 Jy and represented the weakest features in Caswell et al. (2011), while one of 14 features has a high flux of 3.7 Jy. Four of the 14 features were spectrally close to bright features and may have been confused. On the other hand, the other features are in high sensitivity channels, so their disappearance might be from flux variations due to some environmental changes over an 11-yr period. Moreover, at 6035 MHz, there are 10 new OH maser features de-

tected in our observations, nine of which are weak (with fluxes in the range 0.2–0.7 Jy), and one of which (our feature 139) is a bright feature (4.7 Jy). This is also probably the result of maser variation.

4.3 Magnetic Fields

The well-characterized spatial gradient magnetic fields measured from 21 and 23 clearly matched Zeeman pairs at 1.7 and 6.0 GHz, respectively, are shown in Fig. 3. We estimate the magnetic field strengths ranging from -6.4 to $+4.4$ mG as listed in Tables 2–5. Overall, the magnetic field directions are directed towards us with a reversal of magnetic field just below and above Galactic longitude $351^{\circ}41'$; the assumption for the cause of the reversal will be explained in Section 4.3.1. The coincident Zeeman pairs from our results (located within each other's quadrature errors) tend to provide corresponding demagnetized velocities as listed in Table 6 that present the OH Zeeman pair associations, adding strength to their colocations.

In Group 1, there are two coincident Zeeman pairs, Z_2 and Z_{32} , from 1665- and 6035-MHz transitions, respectively, with correspondent averaged (demagnetized) velocities and magnetic field strengths. In Group 2, we found three coincident Zeeman pairs, Z_4 , Z_{12} , and Z_{38} from 1665-, 1667-, and 6035-MHz transitions, respectively. In Group 3, at the reference centre, we found several coincident Zeeman pairs from four transitions i.e. 1665, 1667, 6030, and 6035 MHz. Three Zeeman pairs, Z_5 , Z_6 , and Z_8 , are detected at 1665-MHz transition. The Z_6 , a separated Zeeman pair in the north, is not coincident with the other Zeeman pairs; however, it is noteworthy that the demagnetized velocity and magnetic field strength of this Zeeman pair are in good agreement with those of Z_5 . In addition, there are two Zeeman pairs from 1667-MHz transition, Z_{14}

⁵This uncertainty was calculated by averaging derived values from different observing sessions.

Table 3. OH maser features from both LHCP and RHCP for G351.417+0.645 at 1667 MHz. Position offsets are relative to the brightest 6035 LHCP feature.

Feature no.	V_{LSR} (km s ⁻¹)	RA (arcsec)	Dec. (arcsec)	RA err. ^a (arcsec)	Dec err. ^b (arcsec)	Peak flux ^c (Jy beam ⁻¹)	Zeeman pairs	Avg. vel. ^d (km s ⁻¹)	B^e (mG)	Matching features	TOC ^f
1667 LHCP											
57	-7.76	0.761	-0.015	0.012	0.012	0.90	Z ₁₂	-8.57	-4.6	8, 39, 40, 58, 76*, 114, 133	J
58	-8.14	0.756	-0.015	0.012	0.012	3.07				8, 39, 40, 57, 76, 114, 133	J
59	-8.36	0.401	0.881	0.012	0.012	0.98	Z ₁₃	-8.39	-0.2	73*	B
60	-8.45	0.761	0.062	0.012	0.012	1.81				12	F
61	-9.19	-0.007	-0.001	0.012	0.012	24.56	Z ₁₄	-10.10	-5.1	18, 21, 28, 30, 47, 51, 67, 70, 78*, 79 95, 100, 119, 121, 140, 142	L
62	-9.20	0.051	-0.002	0.012	0.012	3.67				66, 69	B
63	-9.47	0.020	-0.759	0.012	0.012	2.07				-	B
64	-9.52	-0.080	0.339	0.012	0.012	2.95				-	B
65	-9.55	-0.069	0.569	0.012	0.012	3.07				-	B
66	-9.60	0.050	-0.006	0.012	0.012	3.43				62, 69	B
67	-9.62	-0.006	-0.007	0.012	0.012	14.40	Z ₁₅	-10.58	-5.4	18, 21, 28, 30, 47, 51, 61, 70, 78, 79* 95, 100, 119, 121, 140, 142	L
68	-9.69	0.070	-0.370	0.012	0.012	3.22				-	B
69	-10.29	0.055	-0.011	0.012	0.012	2.50				62, 66	B
70	-10.30	-0.003	-0.011	0.012	0.012	15.48				18, 21, 28, 30, 47, 51, 61, 67, 78, 79 95, 100, 119, 121, 140, 142	L
71	-10.68	0.187	0.572	0.012	0.012	1.02				23, 118, 138	J
72	-11.03	-0.150	-1.534	0.013	0.012	0.93	Z ₁₆	-11.67	-3.6	80*	B
1667 RHCP											
73	-8.42	0.400	0.881	0.013	0.012	1.34	Z ₁₃	-8.39		59*	B
74	-8.89	0.785	0.120	0.012	0.012	1.93				2, 38, 107, 127	J
75	-9.17	-0.026	0.017	0.012	0.012	0.62				19, 46	F
76	-9.37	0.769	-0.011	0.012	0.012	2.04	Z ₁₂	-8.57		8, 39, 40, 57*, 58, 114, 133	J
77	-9.70	1.050	1.021	0.012	0.012	0.93				27, 35	F
78	-11.01	-0.008	-0.003	0.012	0.012	20.27	Z ₁₄	-10.10		18, 21, 28, 30, 47, 51, 61*, 67, 70, 79 95, 100, 119, 121, 140, 142	L
79	-11.53	-0.007	-0.009	0.012	0.013	23.40	Z ₁₅	-10.58		18, 21, 28, 30, 47, 51, 61, 67*, 70, 78, 95, 100, 119, 121, 140, 142	L
80	-12.30	-0.153	-1.534	0.013	0.012	0.90	Z ₁₆	-11.67		72*	B

Notes. ^{a,b,d,f,*} See Table 2.^cThe peak flux of the brightest component was taken to be the peak flux density of the maser feature. The average rms noise of 1667-MHz images is ~ 0.07 Jy with maximum value of 0.5 Jy (~ 2 per cent of the peak flux) in the brightest channel.^e ΔB is ± 0.3 mG.

Table 4. OH maser features from both LHCP and RHCP for G351.417+0.645 at 1720 and 6030 MHz. Position offsets are relative to the brightest 6035 LHCP feature.

Feature no. (epoch 2001) [†]	V_{LSR} (km s^{-1})	RA (arcsec)	Dec. (arcsec)	RA err. ^a (arcsec)	Dec. err. ^b (arcsec)	Peak flux ^c (Jy beam^{-1})	Zeeman pairs	Avg. vel. ^d (km s^{-1})	B^e (mG)	Matching features	TOC ^f
1720 LHCP											
81	−9.79	−0.278	−0.479	0.020	0.018	13.70	Z ₁₇	−10.15	−6.4	88*	C
82	−9.79	−0.193	−0.482	0.018	0.018	16.20	Z ₁₈	−10.14	−6.1	86*	C
83	−9.81	−0.149	−0.416	0.018	0.019	12.00	Z ₁₉	−10.15	−6.0	87*	C
84	−9.81	−0.137	0.478	0.019	0.019	14.20	Z ₂₀	−10.17	−6.3	89*	C
85	−9.82	−0.243	−0.772	0.018	0.019	44.50	Z ₂₁	−10.18	−6.3	90*	C
1720 RHCP											
86	−10.48	−0.194	−0.477	0.018	0.019	3.40	Z ₁₈	−10.14		82*	C
87	−10.49	−0.149	−0.411	0.021	0.020	2.20	Z ₁₉	−10.15		83*	C
88	−10.51	−0.296	−0.473	0.019	0.018	2.90	Z ₁₇	−10.15		81*	C
89	−10.51	−0.127	0.478	0.018	0.019	4.50	Z ₂₀	−10.17		84*	C
90	−10.53	−0.240	−0.770	0.018	0.020	12.30	Z ₂₁	−10.18		85*	C
6030 LHCP											
91 (e)	−7.36	0.533	−1.125	0.003	0.003	0.62	Z ₂₂	−7.57	−5.3	36, 96*, 103, 124	K
92 (d)	−7.89	0.543	−1.140	0.002	0.002	0.20	Z ₂₃	−8.06	−4.3	97*, 106, 126	I
93 (b)	−8.44	0.511	−1.109	0.004	0.003	0.41	Z ₂₄	−8.64	−5.1	99*, 110, 131	I
94 (c)	−8.49	0.560	−0.402	0.004	0.002	0.37	Z ₂₅	−8.63	−3.4	98*, 111, 129	I
95 (a)	−10.32	0.000	0.001	0.004	0.003	11.92	Z ₂₆	−10.52	−4.9	18, 21, 28, 30, 47, 51, 61, 67, 70, 78 79, 100*, 119, 121, 140, 142	L
6030 RHCP											
96 (E)	−7.78	0.535	−1.126	0.004	0.002	0.66	Z ₂₂	−7.57		36, 91*, 103, 124	K
97 (D)	−8.23	0.539	−1.139	0.007	0.003	0.25	Z ₂₃	−8.06		92*, 106, 126	I
98 (C)	−8.76	0.557	−0.402	0.003	0.002	0.38	Z ₂₅	−8.63		94*, 111, 129	I
99 (B)	−8.84	0.507	−1.109	0.004	0.003	0.36	Z ₂₄	−8.64		93*, 110, 131	I
100 (A)	−10.71	−0.001	0.002	0.003	0.003	8.59	Z ₂₆	−10.52		18, 21, 28, 30, 47, 51, 61, 67, 70, 78 79, 95*, 119, 121, 140, 142	L

Notes. ^{a,b,d,f}*See Table 2.

^cThe peak flux of the brightest component was taken to be the peak flux density of the maser feature. The average rms noise of 1720-MHz images is ~ 0.02 Jy with maximum value of 0.8 Jy (~ 0.6 per cent of the peak flux) in the brightest channel, while for 6030-MHz images, the average rms noise is ~ 0.01 Jy with maximum value of 0.07 Jy (~ 0.6 per cent of the peak flux) in the brightest channel.

^eAt 1720 and 6030 MHz, ΔB are ± 0.8 and ± 1.3 mG, respectively.

[†]The matching OH maser features detected by Caswell et al. (2011) are also given.

and Z₁₅. Besides, there are one 6030-MHz Zeeman pair, Z₂₆, and two 6035-MHz Zeeman pairs, Z₄₃ and Z₄₅. Note that Z₄₅ has the bluest demagnetized velocity of -11 km s^{-1} towards us implying that it is possibly from different location in the line of sight direction compared with the other Zeeman pairs in this group. In this case, higher spatial resolution observation is needed for verification.

Although Groups 1–3 show a mix of 1665/1667-MHz and 6030/6035-MHz coincidental maser emission, Groups 4–7 only exhibit 6030/6035-MHz coincidental maser emission.

Some of the coincident Zeeman pairs from the same transitions detected in this work might be blended in previous lower resolution observations. However, due to the correspondence of magnetic field values of the blended Zeeman pairs, the blending should not significantly affect the accuracy of previous magnetic field measurements from this transition.

At 6.0 GHz, we found that all five 6030-MHz Zeeman pairs are coincident with 6035-MHz Zeeman pairs including Z₂₂ and Z₂₉ in Group 4, Z₂₃ and Z₃₁ in Group 5, Z₂₄ and Z₃₄ in Group 6, Z₂₅ and Z₃₅ in Group 7, and Z₂₆ and Z₄₃ in Group 3. The magnetic fields

and demagnetized velocities from 6030- to 6035-MHz matching Zeeman pairs are in good agreement with each other proving the co-propagation of both transitions. Note that the matching Zeeman pairs Z₂₄ and Z₃₄ provide the largest difference of 0.8 mG in magnetic field strength; however, this is still within the maximum uncertainties of magnetic field measurement at 6030 and 6035 MHz as listed in Table 6.

There are many previous magnetic field studies in this source. Fish et al. (2003) used Argon et al. (2000) data from the VLA observations (with compatible velocity resolution of $\sim 0.14 \text{ km s}^{-1}$ and the absolute position uncertainties of 0.3 arcsec and 1 arcsec in RA and Dec., respectively) to match possible Zeeman pairs only from the brightest LHCP and RHCP features and estimated the magnetic field value of -5.3 mG at 1665 MHz; this Zeeman pair is associated with our Group 3 at the reference centre as listed in Table 6. They also provided a wide range of possible magnetic field strengths from -2.2 to -5.2 mG at 1667 MHz due to ambiguous Zeeman pair matching ~ 0.1 arcsec away from the reference centre. Our magnetic field measurements at the reference centre from

Table 5. OH maser features from both LHCP and RHCP for G351.417+0.645 at 6035 MHz. Position offsets are relative to the brightest 6035 LHCP feature.

Feature no. (epoch 2001) [†]	V_{LSR} (km s ⁻¹)	RA (arcsec)	Dec. (arcsec)	RA err. ^a (arcsec)	Dec err. ^b (arcsec)	Peak flux ^c (Jy beam ⁻¹)	Zeeman pairs	Avg. vel. ^d (km s ⁻¹)	B ^e (mG)	Matching features	TOC ^f
6035 LHCP											
101 (w)	-5.23	0.776	1.163	0.003	0.002	0.66	Z ₂₇	-5.20	+1.2	122*	E
102	-6.65	0.669	-1.765	0.003	0.003	0.27	Z ₂₈	-6.81	-5.7	123*	E
103 (u)	-7.42	0.534	-1.126	0.003	0.002	2.57	Z ₂₉	-7.57	-5.3	36, 91, 96, 124*	K
104	-7.86	0.730	-1.905	0.002	0.002	0.28				-	E
105 (s)	-7.89	0.600	0.126	0.003	0.002	0.27	Z ₃₀	-7.98	-3.2	109*, 125*	E
106 (t)	-7.92	0.541	-1.138	0.002	0.002	0.42	Z ₃₁	-8.04	-4.3	92, 97, 126*	I
107 (r)	-8.09	0.790	0.116	0.003	0.003	0.21	Z ₃₂	-8.22	-4.4	2, 38, 74, 127*	J
108	-8.26	0.783	0.142	0.006	0.002	0.47	Z ₃₃	-8.38	-4.1	128*	E
109	-8.27	0.615	0.127	0.002	0.002	0.28				105, 125	E
110 (p)	-8.54	0.510	-1.108	0.004	0.003	0.78	Z ₃₄	-8.66	-4.3	93, 99, 131*	I
111 (o)	-8.57	0.558	-0.403	0.002	0.002	2.26	Z ₃₅	-8.66	-3.2	94, 98, 129*	I
112 (q)	-8.57	0.774	0.084	0.002	0.002	1.70	Z ₃₆	-8.66	-3.2	3, 130*	G
113 (m)	-8.60	0.541	-1.307	0.003	0.002	0.42	Z ₃₇	-8.74	-5.0	4, 132*	G
114 (j)	-8.81	0.764	-0.018	0.003	0.002	1.02	Z ₃₈	-8.93	-4.3	8, 39, 40, 57, 58, 76, 133*	J
115 (h)	-9.36	0.394	0.862	0.003	0.002	0.56	Z ₃₉	-9.31	+1.8	134*	E
116	-9.71	0.998	0.960	0.003	0.002	0.71	Z ₄₀	-9.60	+4.1	135*	E
117 (g)	-9.83	0.960	0.876	0.004	0.002	5.43	Z ₄₁	-9.71	+4.4	25, 136*	G
118 (f)	-10.00	0.192	0.565	0.002	0.002	2.95	Z ₄₂	-9.94	+2.1	23, 71, 138*	J
119 (e)	-10.31	0.000	0.000	0.004	0.003	133.00	Z ₄₃	-10.45	-4.8	18, 21, 28, 30, 47, 51, 61, 67, 70, 78 79, 95, 100, 121, 140*, 142	L
120** (b)	-10.61	-0.052	-0.460	0.004	0.002		Z ₄₄			52, 141*	G
121 (a)	-10.97	0.004	-0.014	0.003	0.004	18.48	Z ₄₅	-11.09	-4.3	18, 21, 28, 30, 47, 51, 61, 67, 70, 78 79, 95, 100, 119, 140, 142*	L
6035 RHCP											
122 (W)	-5.16	0.775	1.163	0.002	0.002	0.66	Z ₂₇	-5.20		101*	E
123	-6.97	0.667	-1.764	0.004	0.002	0.25	Z ₂₈	-6.81		102*	E
124 (U)	-7.72	0.534	-1.126	0.002	0.002	2.50	Z ₂₉	-7.57		36, 91, 96, 103*	K
125 (T)	-8.07	0.610	0.126	0.008	0.002	0.27	Z ₃₀	-7.98		105*, 109*	E
126 (S)	-8.16	0.543	-1.139	0.003	0.002	0.45	Z ₃₁	-8.04		92, 97, 106*	I
127 (R)	-8.34	0.793	0.115	0.004	0.002	0.35	Z ₃₂	-8.22		2, 38, 74, 107*	J
128	-8.49	0.782	0.143	0.002	0.002	0.55	Z ₃₃	-8.38		108*	E
129 (O)	-8.75	0.557	-0.402	0.002	0.002	2.08	Z ₃₅	-8.66		94, 98, 111*	I
130 (P)	-8.75	0.775	0.084	0.002	0.002	1.28	Z ₃₆	-8.66		3, 112*	G
131 (N)	-8.78	0.511	-1.109	0.004	0.003	0.93	Z ₃₄	-8.66		93, 99, 110*	I
132 (L)	-8.88	0.540	-1.306	0.003	0.003	0.38	Z ₃₇	-8.74		4, 113*	G
133 (I)	-9.05	0.764	-0.018	0.003	0.002	0.96	Z ₃₈	-8.93		8, 39, 40, 57, 58, 76, 114*	J
134 (H)	-9.26	0.393	0.861	0.005	0.002	0.65	Z ₃₉	-9.31		115*	E
135	-9.48	0.993	0.958	0.003	0.002	0.74	Z ₄₀	-9.60		116*	E
136 (G)	-9.58	0.960	0.875	0.004	0.002	4.38	Z ₄₁	-9.71		25, 117*	G
137	-9.58	0.948	0.843	0.007	0.003	0.50				-	E
138 (F)	-9.88	0.191	0.564	0.002	0.002	2.32	Z ₄₂	-9.94		23, 71, 118*	J
139	-10.04	0.321	0.735	0.002	0.002	4.70				26	G
140 (C)	-10.58	0.001	0.000	0.004	0.002	97.80	Z ₄₃	-10.45		18, 21, 28, 30, 47, 51, 61, 67, 70, 78 79, 95, 100, 119*, 121, 142	L
141** (B)	-11.07	-0.051	-0.461	0.002	0.002		Z ₄₄			52, 120*	G
142 (A)	-11.21	0.004	-0.014	0.002	0.003	13.16	Z ₄₅	-11.09		18, 21, 28, 30, 47, 51, 61, 67, 70, 78 79, 95, 100, 119, 121*, 140	L

Notes. ^{a,b,d,f,*}See Table 2.[†]See Table 4.^cThe peak flux of the brightest component was taken to be the peak flux density of the maser feature. The average rms noise of 6035-MHz images is ~0.06 Jy with maximum value of 0.7 Jy (~0.4 per cent of the peak flux) in the brightest channel.^e ΔB is ± 1.8 mG.^fThis feature can also be defined as the Zeeman pair of the feature 125 as its position is closer to the feature 125 than that of 105, but this Zeeman pair provides the magnetic field strength of +3.5 mG that contradicts to the value of -2.5 mG from Caswell et al. (2011). However, the Zeeman pair (105, 125) or Z₃₀ provides the corresponding value of +3.2 mG which is more sensible in spite of the larger position offset in RA.^{**}These features are incomplete because they are interfered by side lobes of the brightest features. However, it is still worth listing them for confirming the existence of the Zeeman pair b and B (for LHCP and RHCP, respectively) at 6035 MHz from epoch 2001 (Caswell et al. 2011).

Figure 3. The spatial gradient magnetic fields from all Zeeman pairs of OH masers at 1.7 GHz (1665, 1667, and 1720 MHz) and 6.0 GHz (6030 and 6035 MHz). The colours represent the magnetic field values (the negative and positive signs imply the magnetic field direction directed towards and away from us, respectively). The dash and solid contours are described in Fig. 2. The group numbers show different locations with an association of Zeeman pairs as explained in Table 6.

Table 6. OH Zeeman pair association (from the same TOC as listed in Tables 2–5) from different transitions at different locations.

Group no.	Transition (MHz)	Zeeman pair	RA ^g (arcsec)	Dec. ^g (arcsec)	Avg. vel. (km s ⁻¹)	B (mG)	Ref.	$\Delta\Theta^h$	ΔV^i (km s ⁻¹)	ΔB^e (mG)
1	1665	Z ₂	0.786	0.120	-8.09	-4.9	[0]	0.03 arcsec × 0.013 arcsec	0.09	±0.2
	6035	Z ₃₂	0.792	0.116	-8.22	-4.4	[0]	0.05 arcsec × 0.015 arcsec	0.1	±1.8
	6035	no. 18	0.791	0.120	-8.16	-4.2	[1]	0.05 arcsec × 0.015 arcsec	0.1	±1.8
2	1665	Z ₄	0.758	-0.015	-8.83	-4.5	[0]	0.03 arcsec × 0.013 arcsec	0.09	±0.3
	1667	Z ₁₂	0.765	-0.013	-8.57	-4.6	[0]			
	6035	Z ₃₈	0.764	-0.018	-8.93	-4.3	[0]			
	6035	no. 10	0.762	-0.016	-8.90	-4.3	[1]	0.79 arcsec × 0.25 arcsec	0.1	±1.8
	6035	UCHII-OH5-1	0.766	0.070	-8.78	-4.8	[2]?			
3	1665	Z ₅	-0.005	-0.005	-10.29	-5.0	[0]	not reported	1.1	±1 ^k
	1665	Z ₆	0.026	-0.009	-10.28	-4.9	[0] ^j			
	1665	Z ₈	-0.002	-0.008	-10.10	-4.4	[0]			
	1665	—	-0.029	0.016	-10.55	-5.6	[3]*			
	1665	—	-0.003	-0.020	-10.43	-5.3	[4]*			
	1665	—	-0.014	-0.009	-10.48	-6	[5]*	0.015 arcsec	0.2	±0.3
	1667	Z ₁₄	-0.008	-0.002	-10.58	-5.1	[0]	0.015 arcsec	0.2	±0.6
	1667	Z ₁₅	-0.007	-0.008	-10.52	-5.4	[0]			
	1667	—	0.021	-0.034	-11.11	-5	[5]*			
	6030	Z ₂₆	-0.001	0.002	-10.45	-4.9	[0]			
	6030	no. 24	0.000	0.000	-10.47	-4.9	[1]			
	6030	UCHII-OH4-1b	0.000	0.010	-10.50	-5.0	[2]	0.79 arcsec × 0.25 arcsec	0.1	±1.3
	6035	Z ₄₃	0.001	0.000	-10.45	-4.8	[0]	0.05 arcsec × 0.015 arcsec	0.1	±1.3
	6035	no. 5	0.000	0.000	-10.40	-4.8	[1]			
	6035	UCHII-OH4-1b	0.000	0.000	-10.40	-4.9	[2]			
	6035	Z ₄₅	0.004	-0.014	-11.00	-4.3	[0]			
	6035	no. 1	0.005	-0.016	-11.07	-4.6	[1]			
	6035	UCHII-OH4-1a	0.000	0.000	-11.03	-4.6	[2]			
4	6030	Z ₂₂	0.534	-1.126	-7.57	-5.3	[0]	0.05 arcsec × 0.015 arcsec	0.1	±1.3
	6030	no. 28	0.534	-1.123	-7.56	-5.2	[1]			
	6030	UCHII-OH2-2c	0.535	-1.130	-7.54	-5.4	[2]			
	6035	Z ₂₉	0.534	-1.126	-7.57	-5.3	[0]			
	6035	no. 21	0.534	-1.123	-7.57	-5.5	[1]			
	6035	UCHII-OH2-2c	0.523	-1.130	-7.52	-5.3	[2]			
5	6030	Z ₂₃	0.541	-1.140	-8.06	-4.3	[0]	0.05 arcsec × 0.015 arcsec	0.1	±1.3
	6030	no. 27	0.542	-1.135	-8.04	-4.6	[1]			
	6030	UCHII-OH2-2b	0.535	-1.130	-8.00	-4.7	[2]			
	6035	Z ₃₁	0.542	-1.139	-8.04	-4.3	[0]			
	6035	no. 20	0.539	-1.131	-8.03	-4.3	[1]			
	6035	UCHII-OH2-2b	0.523	-1.130	-8.00	-4.4	[2]			
6	6030	Z ₂₄	0.509	-1.109	-8.64	-5.1	[0]	0.05 arcsec × 0.015 arcsec	0.1	±1.3
	6030	no. 25	0.509	-1.108	-8.67	-4.9	[1]			
	6030	UCHII-OH2-1b	0.511	-1.120	-8.59	-4.7	[2]			
	6030	UCHII-OH2-2a	0.535	-1.130	-8.59	-4.7	[2]			
	6035	Z ₃₄	0.511	-1.109	-8.66	-4.3	[0]			
	6035	no. 11	0.507	-1.105	-8.86	-4.3	[1]			
	6035	no. 16	0.510	-1.105	-8.63	-4.3	[1]			
7	6035	UCHII-OH2-2a	0.523	-1.130	-8.63	-3.8	[2]	0.05 arcsec × 0.015 arcsec	0.1	±1.3
	6030	Z ₂₅	0.559	-0.402	-8.63	-3.4	[0]			
	6030	no. 26	0.559	-0.401	-8.58	-3.7	[1]			
	6030	UCHII-OH3-1	0.560	-0.400	-8.58	-3.7	[2]			
	6035	Z ₃₅	0.558	-0.403	-8.66	-3.2	[0]			

Table 6 – *continued*

Group no.	Transition (MHz)	Zeeman pair	RA ^g (arcsec)	Dec. ^g (arcsec)	Avg. vel. (km s ⁻¹)	B (mG)	Ref.	$\Delta\Theta^h$	ΔV^i (km s ⁻¹)	ΔB^e (mG)
	6035	no. 15	0.558	−0.402	−8.61	−3.2	[1]			
	6035	UCHII-OH3-1	0.560	−0.390	−8.62	−3.4	[2]			

Notes. ^gThe average positions between LHCP and RHCP features for each Zeeman pair as listed in Tables 2–5.

^hAngular resolution.

ⁱVelocity resolution.

^eThe maximum uncertainty of **B** measurement as explained in the footnote of Tables 2–5.

^{e,h,i}The values are mentioned only once for each transition and each work.

^jThis Zeeman pair is not coincident with the other Zeeman pairs from our results, it is included in this group due to its corresponding average velocity and magnetic field strength.

^kThe reported value in their work.

[?]This is probably the blended Zeeman pair of our 6035-MHz Z₃₂ and Z₁₂ Zeeman pairs in our Groups 1 and 2, respectively.

*The position is shifted so that their brightest 1665-LHCP feature is the same as our result.

[0] This work (LBA: ATCA, Ho, Cd, Mp, Pa).

[1] Caswell et al. (2011) (LBA: ATCA, Mo, Pa).

[2] Hunter et al. (2018) (VLA).

[3] Gaume & Mutel (1987) (VLA).

[4] Argon et al. (2000) and Fish et al. (2003) (VLA).

[5] Zheng (1989) (VLBI MK III: VLA, NRAO, HRAS).

the brightest Zeeman pairs at 1665 and 1667 MHz are −5.0 and −5.1 mG, respectively. At 1665 MHz, our magnetic field value and Fish et al. (2003)’s agree within each other’s measurement errors and we resolve their ambiguous magnetic field value measurement at 1667 MHz. In addition, a Zeeman pair at 1720 MHz was also established in Fish et al. (2003)’s work, but they calculated a magnetic field strength of −3.1 mG by using the Zeeman coefficient of 0.236 km s⁻¹ mG⁻¹. However, using the Zeeman coefficient adopted for the current work for this transition (i.e. 0.113 km s⁻¹ mG⁻¹) leads to a magnetic field strength of −6.5 mG for this Zeeman pair which is in good agreement with our value of −6.3 mG from our brightest Zeeman pair. Besides, there are VLA observations of Gaume & Mutel (1987) (with poorer velocity resolution and absolute position uncertainty of 1.1 km s⁻¹ and 0.3 arcsec, respectively) that estimated the magnetic field value to be −5.6 mG from matched Zeeman pair of the brightest features at 1665 MHz (while there is not any matched Zeeman pair at 1667 MHz). At 1720 MHz, they reported a magnetic field value of −6.4 mG from the brightest Zeeman pair. This shows that much lower velocity resolution observations from Gaume & Mutel (1987) still provide corresponding magnetic field values compared to ours and Argon et al. (2000)’s.

There are also previous VLBI observations of Zheng (1989) with high spatial resolution but low velocity resolution (~0.015 arcsec and ~0.2 km s⁻¹, respectively). They found 4 and 1 matched Zeeman pairs at 1665 and 1667 MHz, respectively, and provided magnetic field values ranging from −5 to −7 mG. At 1665 and 1667 MHz, they reported magnetic field values of −6 and −5 mG, respectively, near our reference centre as listed in Table 6. Compared with our results at the centre, their magnetic field values are ~1 mG higher at 1665 MHz and correspondent at 1667 MHz.

The recent work of Hunter et al. (2018) also measured the spatial gradient magnetic fields in this source using the VLA with comparable velocity resolution of 0.1 km s⁻¹ but lower spatial resolution of 0.79 arcsec × 0.25 arcsec. Their results show corresponding magnetic field strengths and demagnetized velocities for all associated Zeeman pairs; some of them are demonstrated in our Table 6 (their brightest 6035-MHz LHCP feature is set as reference centre). Their 6035-MHz Zeeman pair UCHII-OH5-1 is located between our two

6035-MHz Zeeman pairs in Group 1 and Group 2; it is possible that our two Zeeman pairs are blended in UCHII-OH5-1. We can spatially resolve their blended Zeeman pairs reported at the same position at both 6030- and 6035-MHz transitions by considering the magnetic field strengths and demagnetized velocities. At 6030 MHz, their UCHII-OH2-2a, UCHII-OH2-2b, and UCHII-OH2-2c match with our Z₂₄, Z₂₃, and Z₂₂ in our Groups 6, 5 and 4, respectively. In the same way, at 6035 MHz, their UCHII-OH2-2a, UCHII-OH2-2b, and UCHII-OH2-2c are coincident with our Z₃₄, Z₃₁, and Z₂₉ in our Groups 6, 5 and 4, respectively. In addition, in Group 3 at 6035 MHz their brightest Zeeman pair UCHII-OH4-1a and the weaker coincident Zeeman pair UCHII-OH4-1b also match with our Z₄₃ and Z₄₅ that are also our brightest and weaker coincident Zeeman pairs, respectively.

Magnetic fields in this region were also studied using Parkes single dish observations with compatible velocity resolution of ~0.1 km s⁻¹. Caswell (2004) observed 1720-MHz OH maser emission and estimated the magnetic field value to be −6.4 mG from LHCP and RHCP spectrum splitting that is in good agreement with our value. Caswell (2003) and Caswell & Vaile (1995) observed OH maser emission at 6030 and 6035 MHz and derived the magnetic field of −4.0 mG from LHCP and RHCP spectrum splitting. The lower magnetic field possibly come from the blending of all the Zeeman pairs inside the velocity range of the LHCP and RHCP spectrum peaks. However, we confirm the agreement of the magnetic field from previous single dish observations with our results if considering the maximum measurement uncertainties at 6.0 GHz (i.e. ±1.3 and ±1.8 mG at 6030 and 6035 MHz, respectively).

These magnetic field comparisons allow us to prove the reliability of the magnetic field measurements from previous lower resolution observations. We confirm that magnetic field values from previous lower resolution measurements are still in good agreement with those from higher resolution measurements. However, higher resolution observation can provide more details of spatial gradient magnetic fields.

Furthermore, comparable LBA observations of Caswell et al. (2011) found 28 Zeeman pairs at both 6030 and 6035 MHz as listed in their table 1, providing magnetic field strengths ranging from −5.4 to +6.4 mG. However, our magnetic fields at 6.0 GHz range

from -5.4 to $+4.4$ mG as listed in Tables 2–5; a narrower magnetic field range is due to the vanishing of two Zeeman pairs (Z_3 and Z_4) from Caswell et al. (2011)’s work with magnetic fields of $+6.4$ and $+5.2$ mG. There are the same 21 Zeeman pairs from both 6030 and 6035 MHz from two epochs. The magnetic field variations are within 1 mG (which is less than the maximum uncertainties of magnetic field measurement) for all the same Zeeman pairs and the directions of magnetic field are the same. A very good agreement between magnetic field strengths and directions and demagnetized velocities (within 0.1 km s^{-1}) estimated at these two epochs as well as the trend of spatial distributions imply quite stable environmental conditions over an 11-yr time.

4.3.1 Interpretation of the reversal of magnetic field

The assumptions of reversal of magnetic fields were attributed in Caswell et al. (2011)’s analysis to the variation of magnetic field lines (along Galactic longitude) of clockwise Galactic magnetic field perpendicular to the line of sight. In this work, we propose a possible cause for the alteration of the direction of the magnetic field lines in this region.

Fig. 3 shows the spatial gradient magnetic fields along the north-west boundary of the dust clump MM3 (black contours) and the UCHII region NGC 6334F (red contours) as described in Fig. 2. It can be seen that the positive magnetic field positions (yellow to red features) are distributed in the overlapping region from two internal fragmented dust clumps inside MM3 or NGC 6334F that is also connected to the external clump MM1 above the NGC 6334F as shown in the top image of Fig. 2.

Recent FIR polarimetry observations of Dotson et al. (2010), Zhang et al. (2014) that are summarized in Li et al. (2015) provide the basis for a clearer picture of the observed changes of the magnetic field lines from large to smaller scales. Zhang et al. (2014) provide the polarization image and the magnetic field lines in the sky plane direction in the region NGC 6334I from their $870 \mu\text{m}$ polarimetric observation in their fig. 1(d) showing the magnetic field lines passing through the dust clumps MM1 and MM2 located in the north and north-west of MM3, while, unfortunately, they did not detect MM3 in $870 \mu\text{m}$. Additionally, the CH_3OH polarization observations of Dodson & Moriarty (2012) show the corresponding trend of magnetic field lines to those of Zhang et al. (2014)’s near the overlapping region where magnetic field values are positive implying there should be some significant influence from MM1 clump to smaller scale magnetic field lines in the north of MM3 clump (related to maser emission, i.e. CH_3OH and OH). To clarify this, the dust polarimetric observation and maser polarimetric study of both MM1 and MM3 together are necessary.

Based on Li et al. (2015), in the smaller scale, the large-scale magnetic field permeating the region can be compressed and subsequently bent by the fragmented dust clumps, resulting in different directions of magnetic field lines between clumps. As a result, for the two overlapping clumps in MM3 (supported by two peaks of the NGC 6334F contours) magnetic field lines can be distorted in the overlapping region providing the observed reversal of magnetic field direction in our 2D perspective.

This assumption supports the idea of Caswell et al. (2011) that for a predominantly perpendicular magnetic field lines to the line of sight, a variation of $\pm 20^\circ$ can provide the opposite magnetic field directions in Zeeman splitting effect.

In a general sense, it is also possible for other multiclump regions, similar to NGC 6334F, to exhibit reversal of magnetic fields. For example, the nearby G351.775-0.536 containing two overlapping

Figure 4. The spatial gradient radial velocities of OH maser features at 1.7 and 6.0 GHz calculated by averaging the velocities of LHCP and RHCP features of each matched Zeeman pair and the internal proper motions of 6.0-MHz OH maser features relative to the brightest 6035-MHz LHCP. The black features are our incomplete Zeeman pair Z_{44} ; this is the same Zeeman pair as Z_2 from Caswell et al. (2011) with demagnetized velocity -10.75 km s^{-1} of and magnetic field strength of -4.8 mG .

clumps defined by $8 \mu\text{m}$ contours as shown in fig. 15 of Goedhart, van der Walt & Gaylard (2002) shows a reversal of magnetic fields from ground-state OH maser observations as shown in fig. 38 of Fish et al. (2005) with positive magnetic fields in lower Dec. near the overlapping region.

4.4 Kinematics

We calculated the demagnetized radial velocity of OH maser features at 1.7 and 6.0 GHz by averaging the velocities of LHCP and RHCP OH maser features of each Zeeman pairs. Fig. 4 shows the spatial radial velocity gradient from 21 and 24 Zeeman pairs at 1.7 and 6.0 GHz, respectively, with velocity range between -11.7 and -5.2 km s^{-1} as listed in column 9 of Tables 2–5. This range does not much differ from the systemic velocity of -10 km s^{-1} . There are two OH maser features at the highest and lowest positions in Dec. showing clearly high red shift with radial velocities of -5.2 and -6.8 km s^{-1} (i.e. Z_{27} and Z_{28} , respectively). However, it is still insufficient for interpreting any kinematic property. In comparison with Caswell et al. (2011)’s results, there are no significant changes in radial velocities for the same matched Zeeman pair (the differences are less than a velocity resolution of $\sim 0.1 \text{ km s}^{-1}$). This infers that all OH maser features at 6.0 GHz have been moving at apparently constant velocity along the line of sight direction in an 11-yr period.

We also tried to calculate the internal proper motion⁶ by considering the position shifts of the same 42 OH maser features from Caswell et al. (2011)’s (2001 epoch) and our observations (2012 epoch). The actual internal proper motion is defined by using the

⁶The internal proper motion is based on the assumption that the brightest LHCP features from 2 epochs (i.e. the features 119 and e of ours and Caswell et al. (2011)’s, respectively) are at the same position at the centre: this represents the actual proper motion relative to the brightest features at the reference centre rather than absolute proper motion.

criteria that the angular displacement of the same feature has to be larger than the position uncertainties.⁷ We assume the position errors are the same for Caswell et al. (2011)'s features. Based on this criteria, 21 OH maser features of all the same 42 features (50 per cent) are defined as actual internal proper motion. The proper motion vectors showing the translational velocities and directions are overlaid on the Fig. 4. The features 105 (or s of Caswell et al. 2011) shows the largest actual proper motion of ~ 21 mas corresponding to the maximum transverse velocity of ~ 11 km s⁻¹. It is shown that they generally tend to move downward to both south-east and south-west directions relative to the reference centre.

4.5 Physical conditions

Inside HMSFRs, there are many possible pumping mechanisms producing OH maser emissions: collisions, local line overlap, non-local line overlap and external IR radiation (Pavlidis & Kylafis 1996a,b). However, various physical conditions inside HMSFRs can allow such mechanisms to happen including the dust temperature (T_d), the gas kinetic temperature (T_k), the H₂ gas density (n_{H_2}) and the OH specific column density ($N_{OH}/\Delta V$) (Cragg, Sobolev & Godfrey 2002). As a result, OH maser modellings are very necessary for inferring specific physical conditions for different types of masers or coincidences of masers. In this work, we classify 12 types of coincidence (TOC) of masers from A–L as follows: A (only 1665 MHz), B (only 1667 MHz), C (only 1720 MHz), D (only 6030 MHz), E (only 6035 MHz), F (1665 & 1667 MHz), G (1665 & 6035 MHz), H (1667 & 6035 MHz), I (6030 & 6035 MHz), J (1665 & 1667 & 6035 MHz), K (1665 & 6030 & 6035 MHz), and L (1665 & 1667 & 6030 & 6035 MHz). We list the TOC associated with each OH maser feature in column 12 of Tables 2–5 and summarize the number of OH maser feature for each TOC as listed in Table 7. From 142 OH maser features detected in this work, most of the OH maser features or 23.2 per cent (33 features) are in TOC A. For the second most abundant TOCs, i.e. TOC J and L have equivalent number of OH maser features holding totally 24.0 per cent (17 features each). Besides, in decreasing order, TOC E, G, I, B, C, F, and K share 10.6 per cent (15 features), 9.9 per cent (14 features), 8.5 per cent (12 features), 7.7 per cent (11 features), 7.0 per cent (10 features), 5.6 per cent (8 features), and 3.5 per cent (5 features) of the total number, respectively. Note that there is not any OH maser feature in TOC D and H is found in this work.

To investigate the physical conditions in this region, we compare our results with the OH maser modellings of Cragg et al. (2002) that was developed from previous models of Sobolev & Deguchi (1994) to obtain better agreement with the observational data. Note that Cragg et al. (2002)'s OH modellings include only local line overlap; however, their modellings consider the collision rate constants for 48 OH energy levels to obtain more reliable results for the 6.0-GHz transitions compared to previous work of Pavlidis & Kylafis (2000) that uses only 28 levels. Our criteria for defining physical conditions are mainly based on the TOCs. Fig. 5 shows the distribution of OH maser features in different colour-coded TOCs. The physical conditions associated to each TOC adopted from Cragg et al. (2002)'s paper are shown in Fig. 6. The area delimitations correspond to the coincidence of the transitions presented in the

⁷For internal proper motion, only relative positions to the reference centre are considered, so for the position errors, we use standard deviations (σ) for the 6030- and 6035-MHz transitions and the intraband astrometric errors ignoring the effects from thermal noise and interband astrometric errors.

Table 7. The summary of OH maser feature numbers for each TOC from Tables 2 to 5.

Transitions (MHz)	Feature number	A	B	C	D	E	F	G	H	I	J	K	L
1665	56	33	–	–	–	–	5	5	–	–	6	1	6
1667	24	–	11	–	–	–	3	–	0	–	5	–	5
1720	10	–	–	10	–	–	–	–	–	–	–	–	–
6030	10	–	–	–	0	–	–	–	–	6	–	2	2
6035	42	–	–	–	–	15	–	9	0	6	6	2	4
Total	142	33	11	10	0	15	8	14	0	12	17	5	17
	(100 per cent)	(23.2 per cent)	(7.7 per cent)	(7.0 per cent)	(0.0 per cent)	(10.6 per cent)	(5.6 per cent)	(9.9 per cent)	(0.0 per cent)	(8.5 per cent)	(12.0 per cent)	(3.5 per cent)	(12.0 per cent)

Figure 5. The physical conditions at different positions in these regions based on different TOC as listed in column 12 in Tables 2–5. The OH maser features are from both LHCP and RHCP. Different colours represent the different TOC as follows: A (dark-green), B (brown), C (grey), E (blue), F (violet), G (black), I (red), J (cyan), K (yellow-green), L (orange) (there is not any TOC D and H found in this work).

Figure 6. The physical conditions exciting OH maser emission for different TOC as a function of H_2 density and OH specific column density at $T_d = 175$ K and $T_k = 30$ K (left) and 150 K (right) adapted from the OH maser modellings of Cragg et al. (2002). Note that we excluded the 4765-MHz line from the interpretation, as it was not observed in this work. The contours trace where the brightness temperature is equal to 10^4 K. Different colour-coded regions represent the physical conditions corresponding to TOC colours of OH maser features in Fig. 5.

current work (i.e. hence excluding the 4765-MHz transition appearing in the figure). The contours in Fig. 6 trace the boundary where the brightness temperature is equal to 10^4 K⁸ that rapidly increases after those boundaries up to 10^{10} – 10^{11} K and 10^9 – 10^{10} K for 1.7- and 6.0-GHz transitions, respectively. Note that Cragg et al. (2002)’s modellings in Fig. 6 do not consider UCHII background radiation. However, their simulations show that brightness temperature decreases with increasing UCHII background radiation as shown in their fig. 7. Only the 1720-MHz OH maser features are not coincident with OH maser features from other transitions. From Fig. 6, it is obvious that excluding the 1720-MHz emission region from those of other transitions can more precisely identify the possible condition region for each TOC. Based on this criteria, the physical condition of each TOC can be described and ordered by their significances of interpretation as follows.

TOC L (1665 & 1667 & 6030 & 6035 MHz; orange colour): A TOC L cluster is only present near the reference centre as shown in Fig. 5. As illustrated in Fig. 6 where T_d is fixed at 175 K, at low T_k (30 K) only a narrow region in the parameter space leads to the required conditions for the coincidence of all four transitions: $N_{OH}/\Delta V$ range of $\sim 10^{10.6}$ to 10^{11} cm^{-3}s and n_{H_2} range of $\sim 10^{7.5}$

to $10^{8.2}$ cm^{-3} . In particular too high T_k leads to the disappearance of the 6030- & 6035-MHz transitions.

TOC A (only 1665 MHz; dark-green colour): A TOC A cluster is observed near the reference centre close to the TOC L cluster but slightly shifted to higher RA as shown in Fig. 5. Besides, some of the isolated 1665-MHz maser features are found along the UCHII region boundary. Fig. 6 shows that at $T_k = 30$ K this TOC can be present in very specific $N_{OH}/\Delta V$ of $\sim 10^{9.7}$ cm^{-3}s but in a much wider n_{H_2} range of $<10^4$ to $10^{6.5}$ cm^{-3} . However, the region for this TOC increases with increasing T_k providing a much larger region with a $N_{OH}/\Delta V$ range of $\sim 10^{9.7}$ to 10^{12} cm^{-3}s and a n_{H_2} range of $<10^4$ to $10^{6.9}$ cm^{-3} at $T_k = 150$ K. Therefore, this TOC is more likely to be present for high T_k . Moreover, fig. 6 of Cragg et al. (2002) suggests that this TOC can be obtained for a T_k ranging from ~ 90 to 125 K at $T_d = 175$ K with $N_{OH}/\Delta V = 10^{11.2}$ cm^{-3}s and $n_{H_2} = 10^7$ cm^{-3} . Besides, for the same $N_{OH}/\Delta V$ and n_{H_2} values, considered at $T_k = 150$ K, this TOC can also be present when T_d is >200 K as shown in fig. 5 of Cragg et al. (2002). Therefore, if this TOC is generated in high T_k and T_d conditions, it is expected to be found in distinctively separated location than TOC L clusters which require low T_k .

TOC E (only 6035 MHz; blue colour): The isolated 6035-MHz maser features are distributed in a strip RA offset = $[0.3 \text{ arcsec}; 1.0 \text{ arcsec}]$ and Dec. offset = $[-2.0 \text{ arcsec}; 1.5 \text{ arcsec}]$ as shown in Fig. 5. As illustrated in Fig. 6, there are two possible separate regions in the parameter space for this TOC at low T_k (i.e. $T_k = 30$ K). The first region requires n_{H_2} to be in the range of $\sim 10^{8.1}$ to $10^{8.7}$ cm^{-3} and $N_{OH}/\Delta V$ to be in the range of $\sim 10^{10.5}$ to $10^{12.4}$ cm^{-3}s . The second region occurs at much higher $N_{OH}/\Delta V$ ranging from $\sim 10^{12.9}$ to $>10^{14}$ cm^{-3}s and wider n_{H_2} range of $<10^{6.2}$ to $10^{8.1}$ cm^{-3} .

⁸This corresponds to flux densities of ~ 0.02 mJy beam⁻¹ for 1665 and 1667 MHz, ~ 0.4 mJy beam⁻¹ for 1720 MHz and ~ 0.7 mJy beam⁻¹ for 6030 and 6035 MHz. These are calculated from the relation $T = 1.36\lambda^2 S/\theta^2$ derived from the Rayleigh-Jeans law where T is brightness temperature (K), λ is wavelength (cm), and θ is HPBW (arcsecond). Note that we used HPBW of 0.03 for 1665 and 1667 MHz, 0.13 for 1720 MHz, and 0.05 for 6030 and 6035 MHz. All of our OH maser features have higher flux densities than those at the boundaries confirming the possible physical conditions are within the contour boundaries.

TOC I (6030 & 6035 MHz; red colour): This TOC is present in a wide range of both $N_{\text{OH}}/\Delta V$ and n_{H_2} conditions at $T_k = 30$ K: $\sim 10^{10.9}$ to $10^{13.8}$ cm^{-3}s and $\sim 10^{6.5}$ to $10^{8.6}$ cm^{-3} , respectively, and absent at particularly high T_k as shown Fig. 6. There is a very good agreement between our results and Cragg et al. (2002)'s models: all the 6030-MHz OH maser features are coincident with a 6035-MHz feature. However, we notice that only 10 in 42 of the 6035-MHz features are coincident with a 6030-MHz feature, which is quite unexpected due to the very large region in the parameter space for this TOC.

TOC K (1665 & 6030 & 6035 MHz; yellow-green colour): TOC K is only present at position ~ 0.530 arcsec and -1.125 arcsec in RA and Dec. offsets as shown in Fig. 5(c). Its scarcity is in agreement with the very small region it occupies in the parameter space (at the far bottom of the TOC-I region) with $N_{\text{OH}}/\Delta V$ and n_{H_2} of $\sim 10^{11}$ cm^{-3}s and $10^{8.2}$ cm^{-3} , respectively, at $T_k = 30$ K as illustrated in Fig. 6. A slight increase in n_{H_2} density can alter the TOC from K to I and the other way around which we assume to be the reason why we found TOC-I clusters close to the TOC-K one (cf. Fig. 5c).

TOC J (1665 & 1667 & 6035 MHz; cyan colour): TOC J, compared to TOC L at $T_k = 30$ K, requires lower $N_{\text{OH}}/\Delta V$ in the range of $\sim 10^{10.4}$ – $10^{10.6}$ cm^{-3}s with nearly the same n_{H_2} range of $\sim 10^{7.2}$ – $10^{8.1}$ cm^{-3} as shown in Fig. 6. This TOC is also absent at particularly high T_k not favourable for the 6035-MHz line. From Fig. 5, we found three separate locations where this TOC occurs. One of them is located near the TOC E and G clusters that possibly comes from slightly lower $N_{\text{OH}}/\Delta V$ and n_{H_2} comparing to TOC E as shown in Fig. 6, while the other two clusters are close to a TOC A feature that are from obviously different physical conditions.

TOC B (only 1667 MHz; brown colour): TOC B features are found in a very narrow range of RA offset but a much wider range of Dec. offset along the H II region boundary ranging from -1.5 to 0.75 arcsec as shown in Fig. 5. In comparison with TOC J at $T_k = 30$ K, this TOC requires slightly lower $N_{\text{OH}}/\Delta V$ in the range of $\sim 10^{9.9}$ to $10^{10.5}$ cm^{-3}s but comparable n_{H_2} in the range of $\sim 10^{7.0}$ to $10^{7.9}$ cm^{-3} as illustrated in Fig. 6. This TOC is also absent in higher T_k .

TOC F (1665 & 1667 MHz; purple colour): TOC F clusters are observed in three separate locations as shown in Fig. 5. As illustrated in Fig. 6, at $T_k = 30$ K, this TOC is present in a large possible n_{H_2} range of $<10^4$ to $10^{7.8}$ cm^{-3} but a much narrower $N_{\text{OH}}/\Delta V$ range of $\sim 10^{9.8}$ to $10^{10.1}$ cm^{-3}s . This TOC can also be observed at high T_k with a comparable $N_{\text{OH}}/\Delta V$ range but decreased possible maximum n_{H_2} of $10^{5.9}$ cm^{-3} at $T_k = 150$ K. In two locations, this TOC is observed close to TOC E and TOC L clusters, though TOC F requires lower $N_{\text{OH}}/\Delta V$ and n_{H_2} at low T_k . In the third location, this TOC is close to both a TOC A feature and a TOC G cluster; if we ignore TOC G here, it appears that TOC F can be present in a wide possible T_k range similar to that of TOC A.

TOC G (1665 & 6035 MHz; black colour): We found a TOC G cluster in five different locations as shown Fig. 5. However, there is no possible region for this TOC in the parameter space of Cragg et al. (2002)'s OH models. As a result, OH models that can specifically describe the physical conditions for this cluster are needed. We noticed that these TOC G clusters are observed close to several TOCs including TOC A, B, C, E, F, and J. Therefore, we assume similar conditions to those needed for these TOCs to occur are also favourable for TOC G.

TOC H (1667 & 6035 MHz; pink colour): We do not detect any TOC H; the lack of this TOC is in agreement with the very small region in the parameter space, requiring very specific $N_{\text{OH}}/\Delta V$ and n_{H_2} of $10^{10.5}$ cm^{-3}s and 10^8 cm^{-3} , respectively, as shown in Fig. 6.

TOC C (1720 MHz; grey colour): TOC C is observed in westernmost locations near the UCHII region boundary. This TOC requires high $N_{\text{OH}}/\Delta V$ ranging from $\sim 10^{12.3}$ to $>10^{14}$ cm^{-3}s but low n_{H_2} ranging from $<10^4$ to $10^{5.9}$ cm^{-3} at $T_k = 30$ as shown in Fig. 6. Moreover, the region in the parameter space, favourable for this transition to occur in isolation, increase with increasing T_k with possible range of $N_{\text{OH}}/\Delta V = [10^{12}; >10^{14}]$ cm^{-3}s and $n_{\text{H}_2} = [<10^4; 10^{6.7}]$ cm^{-3} at $T_k = 150$ K. However, in Fig. 6, Cragg et al. (2002)'s OH models seem to provide overprediction of 1720-MHz OH maser emission suggesting a large range of conditions favouring coincidence with the other transitions. This contradicts our results since we do not find any 1720-MHz OH maser features in coincidence with another OH transition.

4.5.1 An example from previous study related to the association of 1.7-/6.0-GHz OH and 6.7-GHz CH_3OH lines in the source W3(OH)

The copropagation between different OH maser transitions (1665-, 1667-, 1720-, 6030-, and 6035-MHz lines) and between OH and CH_3OH (6668-MHz line) masers was also previously reported in Etoka et al. (2005)'s paper for the HMSFR W3(OH) as summarized in their fig. 3.

The strongest association is from 6.0- and 1.7-GHz transitions especially between 6035 and 1665 MHz. Our results also show the same trend as shown in our Table 7. The other interesting similarities are that all 6030-MHz features are coincident with 6035-MHz features and no 1720-MHz masers are associated with 6.0-GHz and the other ground-state transitions. In their work, weak association is found between 6.7-GHz CH_3OH masers and 1.7/6.0-GHz OH masers.

Additionally, Etoka et al. also simulated maser gains (negative optical depths) of several OH maser lines including 1.7- and 6.0-GHz transitions as a function of OH abundance and dust temperature using the accelerated lambda iteration method (Scharmer & Carlsson 1985). All 1665-, 1667-, 1720-, 6030-, and 6035-MHz transitions show similar gain surface; among them, 1720 MHz is of the lowest gain. As a result, based on their model, the obvious separation between 1720-MHz and the other transitions is reasonable.

5 CONCLUSIONS

With the high spatial and velocity resolutions afforded by new LBA observations, we provide well characterized spatial gradient magnetic fields and radial velocities at both ground- and excited-state OH transitions for the first time. In comparison with previous lower spatial and velocity resolution observations, we verify the reliability of the measured values of magnetic field strength, confirming that our measured magnetic fields are within the uncertainties of previous measurements. Moreover, we confirm the reversal of magnetic fields in this regions with evidence from both 1665- and 6035-MHz OH Zeeman pairs. This reversal of magnetic fields can be described by the cloud fragmentation inducing a twist of the dominant negative magnetic fields that turn to positive in the overlapping region.

Additionally, we found similar spatial distributions of OH maser features at both 1.7 and 6.0 GHz along the arc-shaped north-western boundary of UCHII region NGC 6334F.

We compared two epochs (2001 and 2012) of LBA high spatial and velocity resolution observations at 6.0 GHz. We found that in

the 11-yr time span, the spatial gradient magnetic field and radial velocities had no significant changes (within the velocity resolutions and magnetic field measurement uncertainties). Moreover, we estimated the internal proper motions over the 11-yr interval and found that 50 per cent of all the same OH maser features between those two epochs tended to move downward relative to the reference feature, while the other half were transversely stationary. This suggests that the environmental conditions in this region have been very stable during this period.

We also inferred the physical conditions in this region based on the types of coincidence of OH maser features from different transitions by comparing with models of OH maser emission mechanisms from previous work. We provide possible ranges of OH specific column density, H₂ density at particular gas and dust temperatures in different locations of this source.

ACKNOWLEDGEMENTS

TC thanks the Science Achievement Scholarship of Thailand (SAST) and the International Centre for Radio Astronomy Research (ICRAR) for the financial support. KA acknowledges the financial support obtained from the National Astronomical Research Institute of Thailand (NARIT) for fiscal year 2016–2017. We thank many of the staffs at the CSIRO's Australia Telescope National Facility (ATNF) associated with the LBA project V452. We would also like to thank (1) Dr. Hiroshi Imai from Department of Physics and Astronomy, Graduate School of Science and Engineering, Kagoshima University for useful suggestion in analysis of OH internal proper motion, (2) Dr. Malcolm Gray and Dr. Sandra Etoke from Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, the University of Manchester, UK, for their beneficial ideas and suggestion on OH maser modelling works, (3) Dr. Crystal L. Brogan and Dr. Todd R. Hunter from National Radio Astronomy Observatory (NRAO), USA, for giving permission to use their 5-cm and 3-mm continuum images of the UCHII region NGC 6334F.

REFERENCES

Argon A. L., Reid M. J., Menten K. M., 2000, *ApJS*, 129, 159
 Argon A. L., Reid M. J., Menten K. M., 2003, *ApJ*, 593, 925
 Asaki Y. et al., 2007, *PASJ*, 59, 397
 Bartkiewicz A., van Langevelde H. J., 2012, in Booth R. S., Vlemmings W. H. T., Humphreys E. M. L., eds, Proc. IAU Symp. 287, Cosmic Masers – from OH to H₀. Cambridge Univ. Press, Cambridge, p. 117
 Beuther H., Sridharan T. K., Schilke P., Wyrowski F., Menten K. M., 2000, in Favata F., Kaas A., Wilson A., eds, ESA Special Publ. Vol. 445, Star Formation from the Small to the Large Scale. p. 331, ESA, Noordwijk
 Breen S. L., Ellingsen S. P., 2012, in Booth R. S., Vlemmings W. H. T., Humphreys E. M. L., eds, IAU Symp. Vol. 287, Cosmic Masers – from OH to H₀. Cambridge Univ. Press, Cambridge, p. 156
 Brogan C. L., Hunter T. R., Cyganowski C. J., Chandler C. J., Friesen R., Indebetouw R., 2016, *ApJ*, 832, 187
 Caswell J. L., 1997, *MNRAS*, 289, 203
 Caswell J. L., 2003, *MNRAS*, 341, 551
 Caswell J. L., 2004, *MNRAS*, 349, 99
 Caswell J. L., Vaile R. A., 1995, *MNRAS*, 273, 328
 Caswell J. L., Kramer B. H., Reynolds J. E., 2011, *MNRAS*, 414, 1914
 Caswell J. L., Green J. A., Phillips C. J., 2013, *MNRAS*, 431, 1180
 Cragg D. M., Sobolev A. M., Godfrey P. D., 2002, *MNRAS*, 331, 521

Davies R. D., 1974, in Kerr F. J., Simonson S. C., eds, Proc. IAU Symp. 60, Galactic Radio Astronomy. Springer, Dordrecht, p. 275
 De Buizer J. M., Pina R. K., Telesco C. M., 2000, in American Astronomical Society Meeting Abstracts. AAS, Washington, DC, p. 1469
 De Buizer J. M., Radomski J. T., Piña R. K., Telesco C. M., 2002, *ApJ*, 580, 305
 Dodson R., Moriarty C. D., 2012, *MNRAS*, 421, 2395
 Dotson J. L., Vaillancourt J. E., Kirby L., Dowell C. D., Hildebrand R. H., Davidson J. A., 2010, *ApJS*, 186, 406
 Ellingsen S. P., Voronkov M. A., Cragg D. M., Sobolev A. M., Breen S. L., Godfrey P. D., 2007, in Chapman J. M., Baan W. A., eds, Proc. IAU Symp. 242, Astrophysical Masers and Their Environments. Cambridge Univ. Press, Cambridge, p. 213
 Etoke S., Cohen R. J., Gray M. D., 2005, *MNRAS*, 360, 1162
 Fish V. L., 2007, in Chapman J. M., Baan W. A., eds, Proc. IAU Symp. 242, Astrophysical Masers and Their Environments. Cambridge Univ. Press, Cambridge, p. 71
 Fish V. L., Reid M. J., 2007, *ApJ*, 656, 952
 Fish V. L., Reid M. J., Argon A. L., Menten K. M., 2003, *ApJ*, 596, 328
 Fish V. L., Reid M. J., Argon A. L., Zheng X.-W., 2005, *ApJS*, 160, 220
 Forster J. R., Caswell J. L., 1989, *A&A*, 213, 339
 Gaume R. A., Mutel R. L., 1987, *ApJS*, 65, 193
 Goedhart S., van der Walt D. J., Gaylard M. J., 2002, *MNRAS*, 335, 125
 Green J. A., McClure-Griffiths N. M., Caswell J. L., Robishaw T., Harvey-Smith L., 2012, *MNRAS*, 425, 2530
 Greisen E. W., 2003, *Inf. Handl. Astron.–Historical Vistas*, 285, 109
 Harvey P. M., Gatley I., 1983, *ApJ*, 269, 613
 Hunter T. R., Brogan C. L., Megeath S. T., Menten K. M., Beuther H., Thorwirth S., 2006, *ApJ*, 649, 888
 Hunter T. R. et al., 2018, *ApJ*, 854, 170
 Hutawarakorn B., Cohen R. J., 2005, *MNRAS*, 357, 338
 Kent S. R., Mutel R. L., 1982, *ApJ*, 263, 145
 Kraemer K. E., Jackson J. M., 1999, *ApJS*, 124, 439
 Li H.-B. et al., 2015, *Nature*, 520, 518
 Lo K. Y., Walker R. C., Burke B. F., Moran J. M., Johnston K. J., Ewing M. S., 1975, *ApJ*, 202, 650
 Marseille M. G., van der Tak F. F. S., Herpin F., Jacq T., 2010, *A&A*, 522, A40
 McBreen B., Fazio G. G., Stier M., Wright E. L., 1979, *ApJ*, 232, L183
 Migenes V. et al., 1999, *ApJS*, 123, 487
 Pavlakis K. G., Kylafis N. D., 1996a, *ApJ*, 467, 300
 Pavlakis K. G., Kylafis N. D., 1996b, *ApJ*, 467, 309
 Pavlakis K. G., Kylafis N. D., 2000, *ApJ*, 534, 770
 Persi P., Roth M., Tapia M., Marenzi A. R., Felli M., Testi L., Ferrari-Toniolo M., 1996, *A&A*, 307, 591
 Persi P., Tapia M., Felli M., Lagage P. O., Ferrari-Toniolo M., 1998, *A&A*, 336, 1024
 Reid M. J. et al., 2014, *ApJ*, 783, 130
 Rodriguez L. F., Canto J., Moran J. M., 1982, *ApJ*, 255, 103
 Sakai T., Sakai N., Hirota T., Yamamoto S., 2010, *ApJ*, 714, 1658
 Scharmer G. B., Carlsson M., 1985, *J. Comput. Phys.*, 59, 56
 Schönrich R., Binney J., Dehnen W., 2010, *MNRAS*, 403, 1829
 Shepherd M. C., 1997, in Hunt G., Payne H., eds, ASP Conf. Ser. Vol. 125, Astronomical Data Analysis Software and Systems VI. Astron. Soc. Pac., San Francisco, p. 77
 Slysh V. I., Migenes V., Val'ts I. E., Lyubchenko S. Y., Horiuchi S., Altunin V. I., Fomalont E. B., Inoue M., 2002, *ApJ*, 564, 317
 Sobolev A. M., Deguchi S., 1994, *A&A*, 291, 569
 Trinidad M. A. et al., 2013, *MNRAS*, 430, 1309
 Walsh A. J., Burton M. G., Hyland A. R., Robinson G., 1998, *MNRAS*, 301, 640
 Zhang Q. et al., 2014, *ApJ*, 792, 116
 Zheng X.-W., 1989, *Chin. J. Space Sci.*, 9, 336

APPENDIX: ASTROMETRIC ERROR ANALYSIS

This section concerns the estimate of astrometric errors that are used through this paper arising from different contributions and analysis. These are relevant for the studies based on comparisons between the morphology of the emission from a given transition at multiple epochs, between transitions within the same frequency band, or intraband, (i.e. 1665, 1667, and 1720 MHz; 6030 and 6035 MHz), and between bands (i.e. 1.7 and 6.0 GHz), or interband. When more than one error contribution is relevant for the comparison, the errors are added in quadrature.

A1 Thermal-noise position errors in an image

The relative position errors for emission in the images from a same transition can be calculated using the formula for the thermal noise contribution, as $0.5 \times \text{FWHM}/\text{SNR}$. The estimated astrometric errors for the brightest features are ~ 1.6 and ~ 1.0 mas, in the images at 1.7 and 6.0 GHz, respectively, using typical values for the beamwidths (38 and 15 mas, at 1.7 and 6.0 GHz, respectively). Weaker features will have larger errors.

A2 Interband astrometric errors

We have used phase referencing techniques, with respect to a reference quasar, for the analysis of target emission at both 1665 and 6035 MHz transitions. This allows to astrometrically register the target emission at both transitions. Note that this, combined with the intraband astrometry, results in a bona fide astrometric registration of the five maser transitions observed. Here, we estimate the propagation of astrometric errors in the phase referencing with respect to 1729 – 373, which is $\sim 3^\circ$ away from the target source G351.417+0.645.

We use the formulae in (Asaki et al. 2007) to estimate the error budget for our observations, using nominal values for the errors in the total electron content. The dominant contribution to the phase errors arises from the static component of the ionosphere, and is larger at lower frequencies, that is, 108° and 30° , at 1.7 and 6.0 GHz, respectively, using nominal values for the error in the total electron content. These propagate into astrometric errors equal to 11.4 and 1.3 mas, at 1665 and 6035 MHz, respectively, using beamwidths 38 and 15 mas.

A3 Intraband astrometric errors

We have used phase referencing techniques to astrometrically register the emission from the multiple transitions within each of the two bands, 1.7 and 6.0 GHz with respect to 1665 and 6035 MHz, respectively. We calculate the propagation of astrometric errors in this case attending to the formula:

$$\text{Intraband astrometric error} = \left(\frac{\Delta \nu}{\nu} \right) \times \Delta s, \quad (\text{A1})$$

where Δs is the errors in the source position used at the correlator, which we measured from the phase referenced maps with respect to the external reference source to be ~ 400 mas. The largest error is for the registration between 1665 MHz $\rightarrow$ 1720 MHz, which is 13.2 mas. The estimated errors for 1665 MHz $\rightarrow$ 1667 MHz and 6035 MHz $\rightarrow$ 6030 MHz are 0.5 and 0.3 mas, respectively.

This paper has been typeset from a $\text{\LaTeX}$ file prepared by the author.