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Velocity and magnetic fields within 1000 AU of a massive YSO*

A. Sanna¹, G. Surcis², L. Moscadelli³, R. Cesaroni³, C. Goddi⁴, W. H. T. Vlemmings⁵, and A. Caratti o Garatti⁶

1. Introduction

The role of magnetic fields in regulating the gas dynamics in the vicinity of growing, massive young stellar objects (YSOs) is still a matter of debate (e.g., Crutcher et al. 2010; Zhang et al. 2014). When simulating the build-up of massive protostars in the inner few 1000 AU, recent magneto-hydrodynamics (MHD) models have shown that magnetic fields may contribute significantly (1) to the degree of outflow collimation and (2) to stabilizing both Keplerian and sub-Keplerian disks against fragmentation (e.g., Seifried et al. 2011, 2012). In this context, Very Long Baseline Interferometry (VBL1) observations of maser emission, arising within a few 1000 AU of massive YSOs, allow us to determine both the velocity distribution and the magnetic field configuration close to the accreting protostar (e.g., Sanna et al. 2010a,b; Goddi et al. 2011; Moscadelli et al. 2011; Surcis et al. 2015). This gives us the unique opportunity to investigate, on a 10–100 AU scale, whether the magnetic field influences the gas kinematics.

G023.01−00.41 is a luminous star-forming region of about 4 × 10^4 L☉ (Sanna et al. 2014), located at a trigonometric distance of 4.6 kpc (Brunthaler et al. 2009). This star-forming site harbors a flattened, hot molecular core (HMC) that is centered on an active site of strong maser and radio continuum emission (Sanna et al. 2010b, their Fig. 4). The kinematics of warm (200 K) gas in the inner 3000 AU, as traced with CH₃CN and thermal CH₃OH lines, shows the composition of two orthogonal velocity fields (Sanna et al. 2014, their Fig. 3). The velocity component that dominates on larger scales is aligned with the axis of a collimated bipolar outflow, which is traced progressively away from the HMC center with SiO and CO gas emission. Since the outflow emission is almost perpendicular to the line of sight, any associated disk should be seen edge-on, which makes this object an excellent target for studying the gas dynamics in the vicinity of an O-type YSO. Furthermore, the 3D gas kinematics revealed by the CH₃OH masers shows a funnel-like morphology (Sanna et al. 2010b, their Fig. 6), which was best interpreted as the base of the outflow cavity (or the surface of a flared disk) with a size between 1000 AU and 2000 AU.

With this in mind, we decided to use the synergy between maser proper motions and polarization measurements, targeting the rich CH₃OH maser spectrum observed in G023.01−00.41, to investigate whether magnetic fields may be actively driving the circumstellar gas motion around a massive YSO. That can be assessed by quantifying whether a correlation exists between the orientation of the velocity and polarization vectors.
locally, as measured for individual CH$_3$OH masing cloudlets on scales of a few AU. To compare the magnetic field orientation with the velocity field previously measured by Sanna et al. (2010b), we conducted polarimetric observations of the 6.7 GHz CH$_3$OH masers toward G023.01−00.41 with the European VLBI Network (EVN$^1$).

2. Observations and calibration

We employed the EVN to observe in full polarization mode the $5_1$−$6_0$ A$^+$ CH$_3$OH maser transition at the rest frequency of 6668.519 MHz toward G023.01−00.41. The observations were conducted under program ES067 on 2011 May 29. We made use of a single frequency setup to obtain both a high spectral sampling (0.98 kHz) of the maser lines and a bandwidth large enough (2 MHz) to accurately measure the continuum emission of the calibrator, J 2202+4216. This calibrator served both as a fringe finder and a polarization calibrator and was observed every 45 min to properly calibrate the polarization leakage. Since many maser features are expected to be linearly polarized at a level of about 1%, to reach a conservative detection above 5σ over half of the maser cloudlets previously detected (with peak intensities $>3$ Jy beam$^{-1}$), we spent about 4.5 h on-source. The EVN data were processed with the SFXC software correlator (Keimpema et al. 2015) at the Joint Institute for VLBI in Europe by using an averaging time of 2 s. The single-dish spectrum of the CH$_3$OH maser emission toward G023.01−00.41 is plotted in Fig. 1.

Data were reduced with the NRAO Astronomical Image Processing System (AIPS). We mapped the CH$_3$OH maser distribution with a (robust 0) beam size of 11 mas $\times$ 4 mas, achieving a thermal noise of 5 mJy beam$^{-1}$. To calibrate the systematic rotation of the linear polarization angle ($\chi_{\text{pol}}$) in the EVN dataset, we compared the EVN measurement of $\chi_{\text{pol}}$ obtained on J 2202+4216, with two consecutive VLA polarimetric observations of the same calibrator$^2$ bracketing our VLBI observations (on 2011 April 30 and 2012 February 3). The linear polarization angle of J 2202+4216 estimated with the VLA remained nearly constant with an average value of $-31^\circ \pm 1^\circ$ (position angles, e.g., $\chi_{\text{pol}}$ are measured east of north, unless otherwise stated). The $\chi_{\text{pol}}$ measurements obtained with the EVN dataset are therefore affected by a systematic uncertainty of no more than a few degrees. The uncertainty of $\chi_{\text{pol}}$ due to thermal noise was obtained from the relative error of the polarization intensity measurement, following Wardle & Kronberg (1974). Details about the polarization calibration can be found in Surcis et al. (2013).

3. Results

In the HMC center of G023.01−00.41, the milliarcsecond distribution of the 6.7 GHz CH$_3$OH maser cloudlets has not changed over the five years covered by our observations. Although at some maser velocities the overall flux density has changed smoothly in time (Fig. 1), this variation affects the flux density of individual cloudlets, whereas the overall maser distribution is preserved. Among the eighty maser cloudlets detected by Sanna et al. (2010b), only about one third of them show linearly polarized emission, and their properties are listed in Table 1. Given that we know only the orientation of the linear polarization vectors ($\chi_{\text{pol}}$), while their direction is undefined, we folded these values in the range $-90^\circ < \chi_{\text{pol}} < 90^\circ$. The linear polarization fraction detected among the maser cloudlets ranges between 0.6% and 9.2% with an average value of 2%. The orientation of the linear polarization vectors is superposed on the CH$_3$OH maser distribution in Fig. 2. For cloudlets with detected linear polarization, we also draw the direction ($\chi_{\text{vel}}$) of the velocity vectors for comparison.

In Fig. 3, we study the distribution of the polarization vectors orientation with respect to the position of the CH$_3$OH maser

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$^1$ The European VLBI Network is a joint facility of European, Chinese, South African, and other radio astronomy institutes funded by their national research councils.

$^2$ http://www.aoc.nrao.edu/~smyers/evlapolcal/polcal_master.html
cloudlets. In Fig. 3a, we plot the minimum difference (\(\chi_{\text{pol}} - \chi_{\text{vel}}\)) between the orientation of the polarization and velocity vectors as a function of the sky position angle of each cloudlet. This position angle is measured east of north with respect to the HMC center (star symbol in Fig. 2), which is defined as the peak position of the high-excitation CH\(_2\)OH thermal line detected by Sanna et al. (2014), which is the origin of the reference system (e.g., upper right corner) used in Figs. 3 and 4. The star marks the peak position of the high-excitation CH\(_2\)OH thermal line detected by Sanna et al. (2014), which is the origin of the reference system (e.g., upper right corner) used in Figs. 3 and 4. The uncertainty of the position angle is ±20\(^\circ\), assuming that cloudlets that are close in space would respond to cloudlets with the shortest projected distances, and the uncertainty of \(\chi_{\text{pol}}\) values is of the same order as the marker size. The different regions identified in Sect. 3 are also indicated. c) Similar to panel b) with projected distances along the outflow axis (58\(^\circ\)). Data points plotted in panel b) are not drawn.

Assuming a perfect symmetry of the gas dynamics with respect to these two axes, we produced a mirror image of the linear polarization vectors at each cloudlet on a single quadrant (\(\chi_{\text{pol}}\)). For the \(\chi_{\text{pol}}\) values, we also tried to solve the ambiguity of ±180\(^\circ\), assuming that cloudlets that are close in space would show a smooth change in the polarization (and magnetic) field with position. A posteriori, this criterion was found to minimize the difference between the direction of the linear polarization vectors and that of the corresponding velocity vectors. In Figs. 3b and c, we identify two regions, labeled Regs. 1 and 2, where \(\chi_{\text{pol}}\) changes smoothly with the projected distance of the maser cloudlets. These regions are fit by a linear slope of about 18\(^\circ\), and they correspond to nearby cloudlets, which also show a smooth variation in the velocity field (Fig. 4). A third region, labeled Reg. 3, shows a variation in \(\chi_{\text{pol}}\) by more than 100\(^\circ\) over a narrow range of projected distances. This region corresponds to cloudlets with the shortest projected distances, and is discussed further in Sect. 4.

4. Discussion
To infer the local magnetic field orientation, we ran the radiative transfer model by Vlemmings et al. (2010) for each cloudlet with detected linearly polarized emission (last columns of Table 1). According to the output parameters of this modeling (\(\theta \gg 55\)^\(\circ\)),...
the magnetic field orientation is perpendicular to the polarization vectors for all maser components. This information is used in Fig. 4 to plot the local magnetic field orientation by rotating the $\chi_{\text{pol}}$ values by $90^\circ$. More details about the radiative transfer modeling used can be found in Surcis et al. (2013).

In Fig. 4, we make use of the outflow/disk geometry described in Sanna et al. (2014) to give a complete picture of the velocity and magnetic fields within 1000 AU of the HMC center. In this plot, we produce a mirror image of all the measurements of the velocity and magnetic field vectors obtained from the 6.7 GHz CH$_3$OH maser cloudlets, as if they were sampling a single quadrant defined by the outflow direction and the disk plane. This picture holds under the assumption that the gas dynamics shows a symmetric behavior with respect to the outflow axis and the disk plane. Given the uncertainty of $30^\circ$ on the disk inclination (Sanna et al. 2014), one should keep in mind that the maser cloudlets might be closer to the disk plane than they appear. The high-density molecular tracers observed toward G023.01−00.41 show a fairly constant ratio of $\sim 2$ between the major and minor axes of the HMC. In Fig. 4, this ratio is interpreted as if it was due to a flared disk with a semi-opening angle of $30^\circ$ (dark gray area). We also indicate a central region along the outflow axis that is devoid of CH$_3$OH maser emission (light gray area).

In an attempt to derive a continuous magnetic field morphology, which reproduces the local maser measurements, we considered those regions (Regs. 1 and 2) that show a smooth change in the polarization vector (and magnetic field) orientation with the maser cloudlets’ positions. To first order, these slopes have been approximated by a linear fit as shown in Fig. 3 ($\chi_{\text{pol}} = f(x)$). We can then integrate the tangent of $f'(x) + 90^\circ$, in order to derive the families of curves that best fit the local magnetic field orientation at the maser cloudlet position. These curves give a first-order representation of the local morphology of the magnetic field lines (black dotted lines in Fig. 4).

The velocity field traced by maser cloudlets belonging to Regs. 1 and 2 provides a consistent picture of gas flowing out from the HMC center along the magnetic field lines. In Reg. 1, for small heights over the disk plane ($<400$ AU), the velocity field accommodates the magnetic field lines well, starting from projected distances of 600 AU up to about 1100 AU. Farther away, the velocity field mainly expands parallel to the disk plane and shows the highest maser velocities ($\sim 10$ km s$^{-1}$). On the other hand, maser cloudlets belonging to Reg. 2 and upward expand and get collimated in the direction of the outflow axis. In particular, as one proceeds upward along the magnetic field lines and closer to the outflow axis, both the velocity and magnetic field vectors independently undergo a turn of $90^\circ$. This feature may be interpreted as the result of the complex gas dynamics where a slow and a fast velocity component both exist (e.g., Sieffried et al. 2012, their Fig. 12). Indeed, at about 2000 AU along the outflow axis (not shown in Fig. 4), a shock front of dense gas traced by H$_2$O masers shows gas velocities of $20$ km s$^{-1}$ (Sanna et al. 2010b, their Fig. 5b), which is three times higher than those traced by the CH$_3$OH gas in Reg. 2.

Methanol maser cloudlets belonging to Reg. 3 have projected distances of less than about 500 AU (dashed box in Fig. 4), along both the disk plane and the outflow axis. In this inner region, the velocity field is composed of (at least) two different motions: 1) an inflowing motion closer to the disk plane ($y$-offset $<200$ AU) and 2) an upward motion for higher offsets. The magnetic field pattern of this region is more complex, so we did not attempt to reproduce the magnetic field lines. Still, nearby cloudlets show a similar orientation of the magnetic field vectors and confirm the accuracy of our measurements.

Interestingly, Reg. 3 corresponds to a diffuse halo emission from strong CH$_3$OH masers (Sanna et al. 2010b, see their Fig. 6b), which are probably saturated owing to the proximity of the central IR source. This ridge of extended emission is...
significantly elongated in the direction of the outflow axis, in agreement with the average orientation of the magnetic field vectors between y offsets of ~300 and 400 AU and the upward motions detected there. This evidence makes us speculate that Reg. 3 may trace the outer launching region of the primary outflow, in agreement with recent MHD simulations by Seifried et al. (2012, their Figs. 5 and 12). Furthermore, we make use of the inward stream of gas close to the disk plane, to obtain an estimate of the mass inflow rate, \( \dot{M}_{\text{in}} = (5.0 \times 10^{-5} M_\odot \text{yr}^{-1}) R_{100}^2 v_{10} n_8 \). In this formula, \( R_{100} \), \( v_{10} \), and \( n_8 \) are the mean radius of the inward stream in units of 100 AU, its velocity in units of 10 km s\(^{-1}\), and the volume density of molecular hydrogen in units of \( 10^8 \text{cm}^{-3} \), respectively. We take into account that the inward stream of gas is confined within an angle of 60\(^\circ\) either side of the YSO and allow for gas densities as high as \( 10^8 \text{cm}^{-3} \), above which the Class \( \text{II} \) CH\(_3\)OH masers start to be quenched (Cragg et al. 2005). Noticeably, we find no maser detection at closer distances to the HMC center. At an average distance of 300 AU, the inward stream of gas, flowing at a velocity of 5 km s\(^{-1}\), brings a mass inflow rate of 2 \( \times 10^{-4} M_\odot \text{yr}^{-1} \).

We finally consider the average misalignment of 60\(^\circ\) observed between the velocity and polarization vectors (Fig. 3a), which translates to 30\(^\circ\) between the velocity and magnetic field vectors (Fig. 4). If gas and magnetic field were fully coupled, we would observe gas flowing along the magnetic field lines and expect an average misalignment close to zero. Given that the observed misalignment appears randomly distributed (1\( \sigma = \pm 18^\circ \)) around 30\(^\circ\), we model this effect as if it were due to a random (turbulent) velocity component, which adds to ordered velocity vectors aligned with the magnetic field lines. By considering a velocity vector of 7 km s\(^{-1}\), as averaged across the whole region, we estimate this turbulent contribution to be on the order of 3.5 km s\(^{-1}\). This value is very similar to the velocity dispersion (4–5 km s\(^{-1}\)) derived from the CH\(_3\)CN linewidth in the inner 3000 AU from the HMC center (Sanna et al. 2014), which supports our estimate.

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References


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## Table 1. Parameters of 6.7 GHz methanol maser cloudlets with detected linear polarization.

<table>
<thead>
<tr>
<th>Feature #</th>
<th>V$_{LSR}$ (km s$^{-1}$)</th>
<th>$F_{peak}$ (Jy beam$^{-1}$)</th>
<th>$P_t$ (%)</th>
<th>$X_{pol}$ (°)</th>
<th>$X_{vol}$ (°)</th>
<th>$\Delta V_t$ (km s$^{-1}$)</th>
<th>$T_{b}\Delta\Omega$ (log K sr)</th>
<th>$\theta$ (°)</th>
</tr>
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<tr>
<td>1</td>
<td>74.76</td>
<td>105.50</td>
<td>4.0 ± 0.1</td>
<td>−61 ± 2</td>
<td>+22 ± 14</td>
<td>1.5$_{-0.5}^{+0.2}$</td>
<td>9.2$_{-0.1}^{+0.4}$</td>
<td>88$_{-27}^{+2}$</td>
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<td>2</td>
<td>75.55</td>
<td>34.52</td>
<td>1.1 ± 0.1</td>
<td>−14 ± 1</td>
<td>...</td>
<td>2.6$_{-0.3}^{+0.1}$</td>
<td>8.6$_{-0.2}^{+0.2}$</td>
<td>89$_{-23}^{+2}$</td>
</tr>
<tr>
<td>3</td>
<td>74.32</td>
<td>44.47</td>
<td>2.2 ± 0.3</td>
<td>−22 ± 4</td>
<td>+108 ± 19</td>
<td>1.4$_{-0.2}^{+0.0}$</td>
<td>9.0$_{-0.1}^{+0.5}$</td>
<td>79$_{-20}^{+10}$</td>
</tr>
<tr>
<td>4</td>
<td>74.54</td>
<td>97.84</td>
<td>1.1 ± 0.1</td>
<td>+51 ± 1</td>
<td>+5 ± 7</td>
<td>2.2$_{-0.3}^{+0.2}$</td>
<td>8.6$_{-0.1}^{+0.2}$</td>
<td>90$_{-25}^{+25}$</td>
</tr>
<tr>
<td>5</td>
<td>74.81</td>
<td>45.39</td>
<td>0.9 ± 0.2</td>
<td>+81 ± 2</td>
<td>...</td>
<td>2.1$_{-0.3}^{+0.2}$</td>
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<td>78$_{-12}^{+12}$</td>
</tr>
<tr>
<td>7</td>
<td>75.86</td>
<td>38.56</td>
<td>1.1 ± 0.1</td>
<td>+76 ± 1</td>
<td>...</td>
<td>2.3$_{-0.2}^{+0.2}$</td>
<td>8.6$_{-0.1}^{+0.1}$</td>
<td>84$_{-40}^{+26}$</td>
</tr>
<tr>
<td>11</td>
<td>72.70</td>
<td>30.90</td>
<td>2.2 ± 0.1</td>
<td>+36 ± 5</td>
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<td>2.1$_{-0.4}^{+0.4}$</td>
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</tr>
<tr>
<td>13</td>
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<td>0.9 ± 0.3</td>
<td>0 ± 9</td>
<td>+96 ± 8</td>
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<td>+75 ± 7</td>
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<tr>
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<td>10.69</td>
<td>1.4 ± 0.1</td>
<td>−17 ± 1</td>
<td>−160 ± 10</td>
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<td>84$_{-43}^{+26}$</td>
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<td>90$_{-23}^{+23}$</td>
</tr>
<tr>
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<td>73.93</td>
<td>4.03</td>
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<td>0 ± 12</td>
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<td>73.18</td>
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<td>0.6 ± 0.2</td>
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<td>80$_{-37}^{+10}$</td>
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### Notes: Column 1: cloudlets’ labels (same labels as for corresponding cloudlets identified in Table 4 of Sanna et al. 2010b). Columns 2 and 3: LSR velocity and brightness of the brightest spot of each cloudlet on 2011 May 29, respectively. Columns 4 and 5: measured linear polarization fraction and position angle (east of north) of the linear polarization vectors for each cloudlet, respectively. Column 6: position angle of the velocity vectors as measured from Sanna et al. (2010b), for comparison with Col. 5. Columns 7–9: model results for the emerging brightness temperature, the intrinsic thermal linewidth, and the angle between the magnetic field and the maser propagation direction for each cloudlet, respectively. New feature, see Fig. 2.