PROCEEDINGS OF SCIENCE

High resolution magnetic field measurements in high-mass star-forming regions using masers

Gabriele SURCIS[*]
Joint Institute for VLBI in Europe
E-mail: `surcis@jive.nl`

Wouter H.T. VLEMMINGS
Chalmers University of Technology, Onsala Space Observatory
E-mail: `wouter.vlemmings@chalmers.se`

Huib J. VAN LANGEVELDE
Joint Institute for VLBI in Europe
E-mail: `langevelde@jive.nl`

Busaba HUTAWARAKORN KRAMER
Max-Planck Institut für Radioastronomie
E-mail: `bkramer@mpifr-bonn.mpg.de`

Three different scenarios have been proposed to explain the formation of high-mass stars (M>8 $M_{\odot}$). In the most popular scenario, core accretion, massive stars form similarly to the low-mass stars (M<8 $M_{\odot}$). In low-mass star-formation magnetic fields are thought to play an important role by removing excess angular momentum, by slowing down the collapse, and by powering bipolar outflows. However, the role of magnetic fields during the protostellar phase of high-mass star-formation is still undetermined. In particular, it is unclear how magnetic fields influence the formation and dynamics of disks and outflows. Most current information on magnetic fields close to high-mass protostars (10s-1000s AU) comes from polarized 6.7-GHz methanol maser emission. By using European VLBI Network observations we have investigated the magnetic field around eleven massive star-forming regions. Here we present the results achieved so far.

11th European VLBI Network Symposium Users Meeting
9-12 October 2012
Bordeaux (France)

---

[*] Speaker.

1. Introduction

Magnetic fields play an important role in the formation of low-mass stars (M $<$ 8 $M_{\odot}$). Indeed, the gravitational collapse of molecular clouds proceeds preferentially along the magnetic field lines, giving rise to large rotating disc or torus structures orthogonal to the magnetic field (e.g., [1]). Consequently, the molecular bipolar outflows, which originate from the protostar, are driven parallel to the magnetic field (e.g., [2]). Although the high-mass stars (M $>$ 8 $M_{\odot}$) are thought to form in a similar way as the low-mass stars [3], the role of magnetic fields in their formation is still under debate. The debate is due to the observational difficulties in measuring the magnetic fields close to the massive protostars, which are rare and typically at fairly large distance. Until now, the observations of magnetic fields have often been limited to low density regions at scales of several thousands astronomical units (AU) (e.g., [4]). By observing the polarized emission of 6.7-GHz methanol masers with radio-interferometers it is now possible to measure the orientation of magnetic fields at scale of hundreds and tens AU (e.g., [5]). Moreover, this maser species is also ideal for measuring the Zeeman-splitting even though the exact proportionality between the measured splitting and the magnetic field strength is still uncertain [6].

Furthermore, only recently the magnetic fields have been included in theoretical simulations of massive star formation (e.g., [7], [8], [9]). The simulations show that magnetic fields coupled to the prestellar discs are the possible driving power for early outflows [7], and their strength can influence the collimation and the velocity of the outflows ([8], [9]). Besides contributing to the formation of outflows, the simulations show that magnetic fields prevent fragmentation, reduce angular momentum via magnetic braking, and only marginally influences the accretion rate ([7], [8], [10], [11]). For weak magnetic fields Keplerian discs with sizes of a few 100 AU are easily formed, while for strong magnetic fields the Keplerian discs are formed only if turbulent velocity field is introduced in the simulations [11]. At last, magnetic fields determine also the size of H II regions that in the presence of strong magnetic field are generally smaller than without magnetic field [8].

Therefore, providing new measurements of magnetic fields orientation and strength at milliarcsecond (mas) resolution close to the massive protostars by using 6.7-GHz methanol maser is fundamental to verify and/or improve the numerical simulations of massive star formation. In the last five years we have observed with the European VLBI Network (EVN) 11 massive star-forming regions at 6.7-GHz in spectral mode and in full polarization (we refer to it as the EVN sample). The results are reported in several papers ([12], [13], [14]) and here we summarize them by focusing on three cases.

2. Magnetic field along outflows. The case of W75N-VLA 1

In five sources of the EVN sample (~50%) we have found that the magnetic field is oriented along the molecular outflows. The sources are W75N-VLA 1, W51-e2, IRAS06058+2138-NIRS 1, IRAS22272+6358A, and S231. In one case, IRAS18556+0138, the magnetic field is probably along the outflows but additional observations are necessary (see [14]). Here, we focus on the case of W75N-VLA 1.

W75N-VLA 1 is a H II region in the active high-mass star-forming region W75N(B) located at a distance of 1.30 ± 0.07 kpc [15]. A large-scale high-velocity outflow, with an extension greater

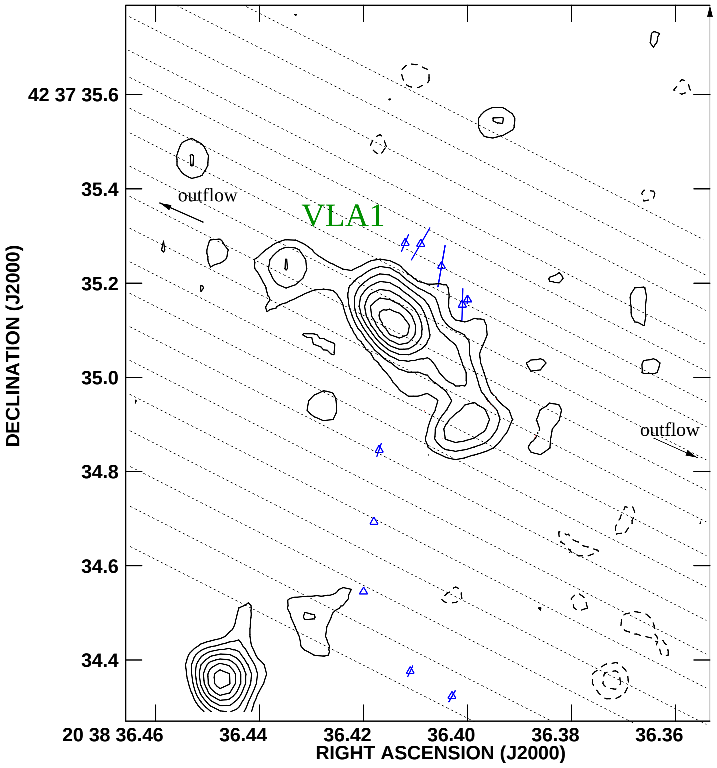

Figure 1: Modified version of Fig.1 of [12]. The linear polarization vectors are also reported (20 mas correspond to a linear polarization fraction of 1%). The dashed lines indicate the large-scale direction of the magnetic field.

than 3 pc and a total molecular mass greater than 255 $M_\odot$, was detected from the region [16]. We have detected linear polarized emission in 8 (out of 10) CH_3OH masers with a flux weighted orientation of the linear polarization vectors of $\langle\chi\rangle = -14^\circ \pm 8^\circ$. Because the angle between the maser propagation direction and the magnetic field (θ) is greater than $\theta_{\rm crit} = 55^\circ$, which is the Van Vleck angle ([17]), the magnetic field appears to be perpendicular to the linear polarization vectors, that is $\langle\Phi_{\rm B}\rangle = +76^\circ \pm 8^\circ$ (Fig. 1). Therefore, because the position angle (PA) of the outflows is 66°, the magnetic field is oriented along the outflow. This is also confirmed from H_2O maser polarization observations that indicate an orientation of the magnetic field very close to that derived from the CH_3OH masers ([18]), suggesting that VLA 1 is the driving source of the large-scale molecular bipolar outflows. For more details see [12] and [18].

3. Magnetic field on surfaces of torus/discs. The case of NGC7538-IRS 1

In about 40% of the massive star-forming regions of the EVN sample, magnetic fields have been measured on the surfaces of tori/discs (NGC7538-IRS 1, W3(OH)-group II, S255-IR, and IRAS20126+4104). The best example is NGC7538-IRS 1. IRS 1 is the brightest protostar of the complex region NGC7538 located at 2.65 kpc from us [19]. The protostar has been suggested to be an O6 star of about 30 $M_\odot$ (e.g., [20]) surrounded by a molecular torus (PA = 50°) and from which

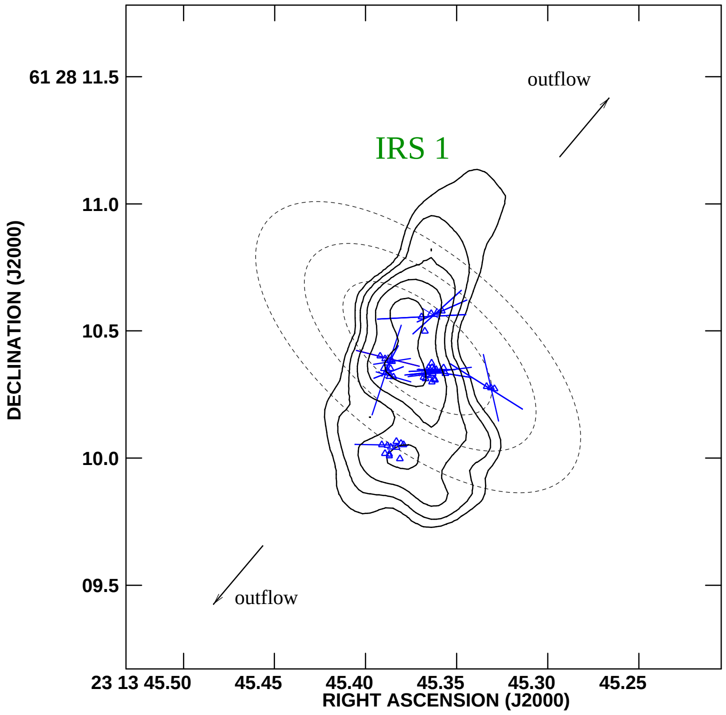

Figure 2: Modified version of Fig.1 of [13]. The linear polarization vectors are also reported (60 mas correspond to a linear polarization fraction of 1%). The dashed ellipses indicate the direction of the magnetic field.

a molecular bipolar outflow (PA $= 140^\circ$) with a mass of 82.8 $M_\odot$ has been launched ([21],[22]). We detected linear polarization emission towards 20 (out of 49) 6.7-GHz CH_3OH masers. Considering the velocities of the CH_3OH masers we suggest that the masers are associated with the torus structure and, in particular, are tracing the interface between the infall and the torus. From the linear polarization vectors of the CH_3OH masers (Fig. 2) we determined that the magnetic field is on the surfaces of the torus with a counterclockwise direction on the top surface. The direction of the magnetic field can be estimated from the sign of the Zeeman-splitting measurements, see [13] for more details.

4. Magnetic fields at different scales

In few cases we were also able to compare the morphology of the magnetic field determined from the CH_3OH masers with that measured by using the dust polarized emission (W51-North, W51-e2, W48). The best example is shown in Fig. 3. W51-e2 is located in the eastern edge of the massive star-forming region W51 at a distance of $5.41^{+0.31}_{-0.28}$ kpc [23]. Tang et al. [24] determined a hourglass-morphology of the magnetic field near the collapsing core of W51-e2 by observing the dust polarization emission at 870 μm (red segments in Fig. 3). The morphology determined from the linearly polarized emission of 6.7-GHz CH_3OH masers (green segments in Fig. 3) is consistent with the hourglass morphology.

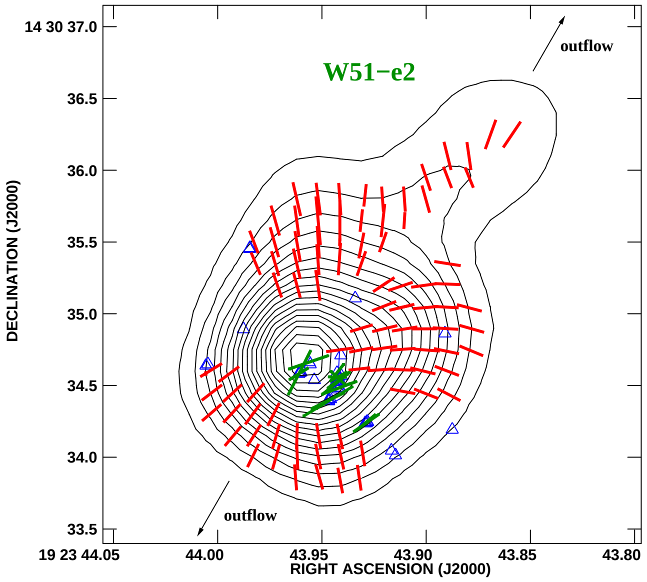

Figure 3: Modified version of Fig.5a of [24]. The magnetic field (red segments) detected with the SMA (angular resolution $0''.7$ that corresponds to $\sim$4000 AU) is superimposed on the 870 μm continuum contour map of W51–e2. The green segments mark the direction of the magnetic fields as derived from the CH_3OH masers (angular resolution $0''.001$ corresponding to $\sim$ 5 AU).

5. Conclusion

In the EVN sample we measured magnetic fields both along outflows ($\sim$ 50% of the sources of the EVN sample) and on the surfaces of torus/discs ($\sim$ 40%). In the remaining 10% of the sources (actually only W48) the association of the magnetic field was impossible because of the poor information about the structure of the source, consequently more observations are necessary. In general we found a good agreement with the theoretical simulations, and in particular with the importance of the magnetic fields in the build-up of early outflows (e.g., [7]). In conclusion we have demonstrated the power of 6.7-GHz CH_3OH maser polarization observations in deducing the magnetic field morphology around massive protostars at scales between 10s and 1000s AU. Furthermore, we showed the great importance of the EVN in this research field and its role is even more important now that the software correlator (SFXC) at the Joint Institutes for VLBI in Europe (JIVE) is available. Indeed the SFXC allowed us to increase the spectral resolution of our observations implying a more precise measurements of the Zeeman-splitting.

References

[1] T. Matsumoto & K. Tomisaka, *Directions of Outflows, Disks, Magnetic Fields, and Rotation of Young Stellar Objects in Collapsing Molecular Cloud Cores*, *ApJ* **616** (2004) 266.

[2] C.F. McKee & E.C. Ostriker, *Theory of Star Formation*, *ARA&A*, **45** (2007) 565.

[3] C.F. McKee & J. Tan, *The Formation of Massive Stars from Turbulent Cores*, *ApJ* **585** (2003) 850.

[4] Y.-W. Tang, P.T.P. Ho, P.M. Koch et al., *High-angular Resolution Dust Polarization Measurements: Shaped B-field Lines in the Massive Star-forming Region Orion BN/KL*, *ApJ* **717**, (2010) 1262.

[5] W.H.T. Vlemmings, G. Surcis, K.J.E. Torstensson et al., *Magnetic field regulated infall on the disc around the massive protostar CepheusAHW2*, *MNRAS* **404** (2010) 134.

[6] W.H.T. Vlemmings, R.M. Torres & R. Dodson, *Zeeman splitting of 6.7 GHz methanol masers. On the uncertainty of magnetic field strength determinations*, *A&A* **529** (2011) A95.

[7] R. Banerjee & R.E. Pudritz, *Massive Star Formation via High Accretion Rates and Early Disk-driven Outflows*, *ApJ* **660** (2007) 479.

[8] T. Peters, R. Banerjee, R.S. Klessen et al., *The Interplay of Magnetic Fields, Fragmentation, and Ionization Feedback in High-mass Star Formation*, *ApJ* **729** (2011) 72.

[9] D. Seifried, R.E. Pudritz, R. Banerjee et al., *Magnetic fields during the early stages of massive star formation - II. A generalized outflow criterion*, **422** *MNRAS* (2012) 347.

[10] P. Hennebelle, B. Commerçon, M. Joos et al., *Collapse, outflows and fragmentation of massive, turbulent and magnetized prestellar barotropic cores*, *A&A* **528** (2011) A72.

[11] D. Seifried, R. Banerjee, R.S. Klessen et al., *Magnetic fields during the early stages of massive star formation - I. Accretion and disc evolution*, *MNRAS* **417** (2011) 1054.

[12] G. Surcis, W.H.T. Vlemmings, R. Dodson et al., *Methanol masers probing the ordered magnetic field of W75N*, *A&A* **506** (2009) 757.

[13] G. Surcis, W.H.T. Vlemmings, R.M. Torres et al., *The properties and polarization of the H2O and CH3OH maser environment of NGC 7538-IRS 1 A&A* **533A** (2011) 47.

[14] G. Surcis, W.H.T. Vlemmings, H.J. van Langevelde et al., *EVN observations of 6.7 GHz methanol maser polarization in massive star-forming regions A&A* **541A** (2012) 47.

[15] K.L.J. Rygl, A. Brunthaler, A. Sanna et al., *Parallaxes and proper motions of interstellar masers toward the Cygnus X star-forming complex. I. Membership of the Cygnus X region*, *A&A* **539** (2012) 79.

[16] D.S. Shepherd, L. Testi & D.P. Stark, *Clustered Star Formation in W75 N*, *ApJ* **584** (2003) 882.

[17] P. Goldreich, D.A. Keeley, & J.Y. Kwan, *Astrophysical Masers. 11. Polarization Properties*, *ApJ* **179** (1973) 111.

[18] G. Surcis, W.H.T. Vlemmings, S. Curiel et al., *The structure of the magnetic field in the massive star-forming region W75N*, *A&A* **527** (2011) A48.

[19] L. Moscadelli, M.J. Reid, K.M. Menten et al., *Trigonometric Parallaxes of Massive Star-Forming Regions. II. Cep A and NGC 7538*, *ApJ* **693** (2009) 406.

[20] G. Sandell, W.M. Goss, M. Wright et al., *NGC 7538 IRS 1: An Ionized Jet Powered by Accretion*, *ApJ* **699** (2009) L31.

[21] K. Qiu, Q. Zhang, & K.M. Menten, *Outflows, Accretion, and Clustered Protostellar Cores Around a Forming O Star*, *ApJ* **728** (2011) 6.

[22] P.D. Klaassen, C.D. Wilson, E.R. Keto et al., *Rotation of the Warm Molecular Gas Surrounding Ultracompact H II Regions ApJ* **703** (2009) 1308.

[23] M. Sato, M.J. Reid, A. Brunthaler et al., *Trigonometric Parallax of W51 Main/South ApJ* **720** (2010) 1055.

[24] Y.-W. Tang, P.T.P. Ho, P.M. Koch et al., *Evolution of Magnetic Fields in High-Mass Star Formation: Linking Field Geometry and Collapse for the W51 e2/e8 Cores*, *ApJ* **700** (2009) 251.

PoS(11th EVN Symposium)034