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Magnetic Fields and Massive Star Formation

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Magnetic fields potentially play an important role during massive star-formation, especially in stabilizing disks and launching outflows. Currently, the only information on the magnetic field in the dense regions close to protostars comes from maser observations. Much of the work has been focused on OH and water maser observations. Recently it has been shown that methanol masers, the most abundant of the maser species in massive star-forming regions, are also excellent probes of the magnetic field. This paper present the results of recent Effelsberg and MERLIN observations that indicate energetically dominant and large scale ordered fields in the majority of massive star-forming regions. This includes the detection of magnetic field regulated infall on the massive protostellar disk of Cepheus A HW2. With the advent of new and improved instruments such as e-MERLIN and the SKA pathfinders, maser polarization observations will be able to provide important constraints on the role of magnetic fields during massive star formation.

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1. Introduction

Massive stars typically form in distant, dense clusters. In such regions, graviational, radiation and turbulent energies are different from those in the regions that form lower mass stars like the Sun. For example, young stars more massive than 8 $M_\odot$ have a radiation pressure that would be sufficient to halt infall and prevent the accretion of additional mass. Still, stars more massive than 200 $M_\odot$ have been observed. This shows that our knowledge of the processes governing massive star-formation are yet poorly understood, even though massive stars play an important role in the chemical and energetic evolution of their host galaxies. This problem is the topic of extensive observational and theoretical efforts (for a review, see e.g. [16]). Even though few of the current simulations include magnetic fields, the influence of magnetism on the star formation processes is extensive as it can support a molecular cloud against collapse, affect core fragmentation and change the feedback processes.

Most current high-mass star formation magnetic field information comes from H_2O and OH maser polarization observations [13] (and references therein). The observations of the H_2O maser Zeeman effect using Very Long Baseline Interferometry (VLBI) reveal field strengths between 10 and 600 mG, while the linear polarization measurements reveal a complex but often ordered magnetic field morphology (e.g. [10]). Aside from H_2O masers, tracing high density regions ($n_{\rm H_2} \approx 10^8 - 10^{11}$ cm^{-3}), the magnetic field in the less dense surrounding regions is typically probed by polarimetric OH maser observations (e.g. [1]). These observations reveal fields of a few mG as well as ordered structure in the magnetic field. However, the strongest and most abundant of the high-mass star formation region masers arises from the 6.7 GHz $5_1 - 6_0A^+$ methanol transition, and for this maser hitherto only very few polarization observations exist. Like H_2O, methanol is a non-paramagnetic molecule, and thus both the linear and circular polarization fractions are small. The first polarization measurements were made with the Australia Telescope Compact Array (ATCA) on the 6.7 GHz maser toward a handful of southern massive star forming regions and linear polarization between few and 10% was detected [5]. The first high angular resolution linear polarization maps were made using MERLIN [11] and the Long Baseline Array [4]. These proceedings provide the current state of the art of massive star formation maser polarization observations, and in particular those using methanol masers. MERLIN observations and the three-dimensional reconstruction of the magnetic field around the massive protostar Cepheus A HW2 are discussed in §.2, and serve as an illustration our upcoming e-MERLIN legacy project. In addition to the linear polarization observations, observations with the Effelsberg telescope that have for the first time revealed the Zeeman splitting of the 6.7 GHz methanol masers [14]. These observations are shortly discussed in §.3. Finally, even higher resolution European VLBI Network (EVN) observations are discussed in Surcis et al. (these proceedings; [9]).

2. MERLIN observations

The 6.7 GHz methanol masers of the nearby massive star forming region Cepheus A were observed on 2006 December 2-4 using 6 of the MERLIN telescopes. The resulting beam-size was 40×30 mas. We used a 250 kHz bandwidth with 256 channels for a total velocity coverage of ~ 11 km s^{-1} centered on the source velocity $V_{\rm LSR} = -3$ km s^{-1}. This provided a velocity

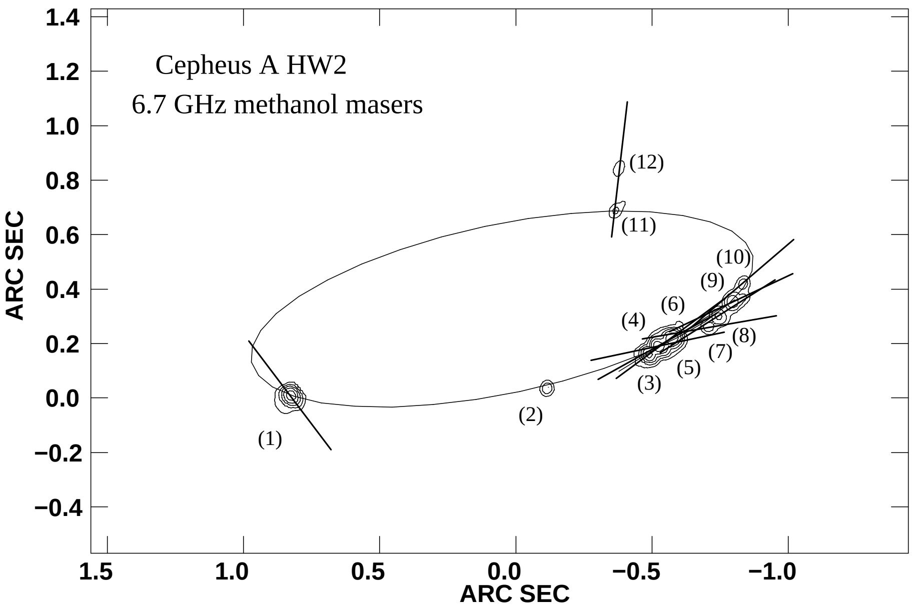

Figure 1: The methanol masers of Cepheus A (contours) including the polarization vectors (black). The 3-dimensional magnetic field derived from these observations is illustrated in the movie uploaded with the paper (or found at http://www.astro.uni-bonn.de/ wouter/papers/cepheusa/).

resolution of 0.044 km s^{-1}. The details of the calibration are described further in [12]. A map of the strongest 6.7 GHz maser features together with their polarization vectors is shown in Fig. 1.

Cepheus A is one of the closest regions of active massive star-formation. Located in the Cepheus OB3 complex, it hosts a powerful extended bipolar molecular outflow that likely originates from HW2, the brightest radio continuum source in the region. HW2 is thought to be a young protostar of spectral type B0.5 with a mass of $\sim$20 $M_\odot$ [7]. The extended outflow appears to be driven by a small scale ($\sim$700 AU) thermal radio jet.

The full 3-dimensional magnetic field orientation shown in the accompanying movie, was inferred using maser radiative transfer models described in [12]. The inferred magnetic field in the plane of the sky is perpendicular to the molecular ($R = 580$ AU, $\phi = -56^\circ$ and $i = 68^\circ$, [7]) and dust disk ($R = 330$ AU, $\phi = -59^\circ$ and $i = 56^\circ$, [8]) with a rms weighted average angle $\phi_B = 26 \pm 12^\circ$. Moreover, the error weighted average angle between the magnetic field and the line of sight $\theta = 73 \pm 5^\circ$ is consistent with the inclination of the molecular disk and the outflow. The overall magnetic field orientation angle corresponds closely to the magnetic field direction observed in the encompassing dust envelope [3].

Since we have obtained the angle between the magnetic field and the line of sight, we can directly determine the total magnetic field strength around the protostellar disk in the methanol maser region. For $B_{||} = 8.1 \pm 0.2 \pm 2$ mG [14] and $\theta = 73 \pm 5^\circ$, the absolute field strength $|B| = 23^{+9}_{-7}$ mG. From this, we can calculate a number of parameters to asses the role of the magnetic field during the massive protostellar collapse. For example, we find the ratio between thermal and magnetic energy $\beta = 2(m_a/m_s)^2 = 0.27$. The magnetic field dominates the energies in the high density protostellar environment probed by the masers. We can also calculate the mass to magnetic flux ratio M/Φ compared to the critical value of this ratio $\lambda = (M/\Phi)/(M/\Phi)_{\rm crit}$. When

$\lambda < 1$, the magnetic field prevents collapse, but when λ becomes larger than 1 gravity overwhelms the magnetic field. In the high-density region around Cepheus A HW2, we find $\lambda = 1.7^{+0.7}_{-0.5}$, indicating that the region is slightly super-critical, a condition needed for the collapse to proceed. Similar values for λ were found using large-scale Zeeman-splitting observations of an ensemble of molecular clouds [2]. However, as those observations lacked the 3-dimensional magnetic field information, the results were uncertain by of order a factor two, making it impossible to distinguish between sub- and super-critical cloud cores. Finally, using other magnetic field measurements in different density regions, we find that the field scales approximately as $B \propto n_{\mathrm{H}_2}^{0.5}$ [14]. This relation could be the consequence of ambipolar diffusion, but it also naturally occurs for the collapse of a spherical cloud with frozen in field lines, when the preferred infall direction is along the magnetic field. Such a collapse forms a flattened disk-like structure similar as observed around HW2.

3. Effelsberg observations

In addition to linear polarization, circular polarization due to Zeeman splitting was recently detected in a large sample of 6.7 GHz methanol masers using the Effelsberg telescope [14]. Where the linear polarization fraction is of order 2%, circular polarization is found to be of order 0.5%. An example of the observed circular polarization is shown in Fig.2.

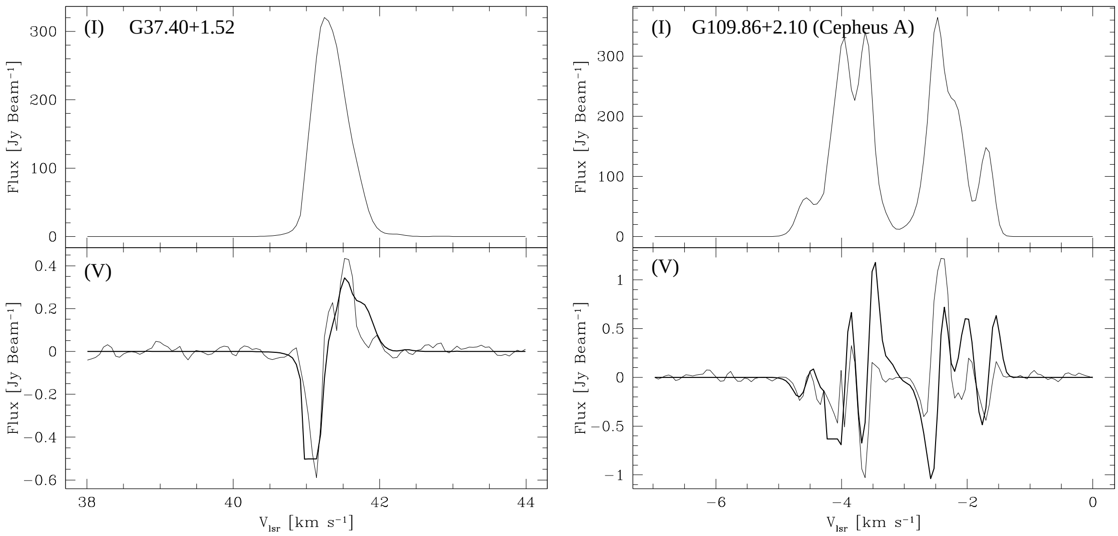

Figure 2: Total intensity and circular polarization spectrum for G37.40+1.52 (left) and G109.86+2.10 (Cepheus A; right). The thick solid line in the bottom panel is best fit fractional total power derivative to the circular polarization spectrum

Significant Zeeman splitting was detected for 35 out of 47 sources and indicates an absolute magnetic field strength component $|B_{||}|$ along the maser propagation direction between 2.8 and 42 mG (Fig.3). Weighing the field strength by measurement significance, the average magnetic field $\langle B_{||,\mathrm{meth}} \rangle = 12$ mG. This needs to be corrected for a random angle between magnetic field and

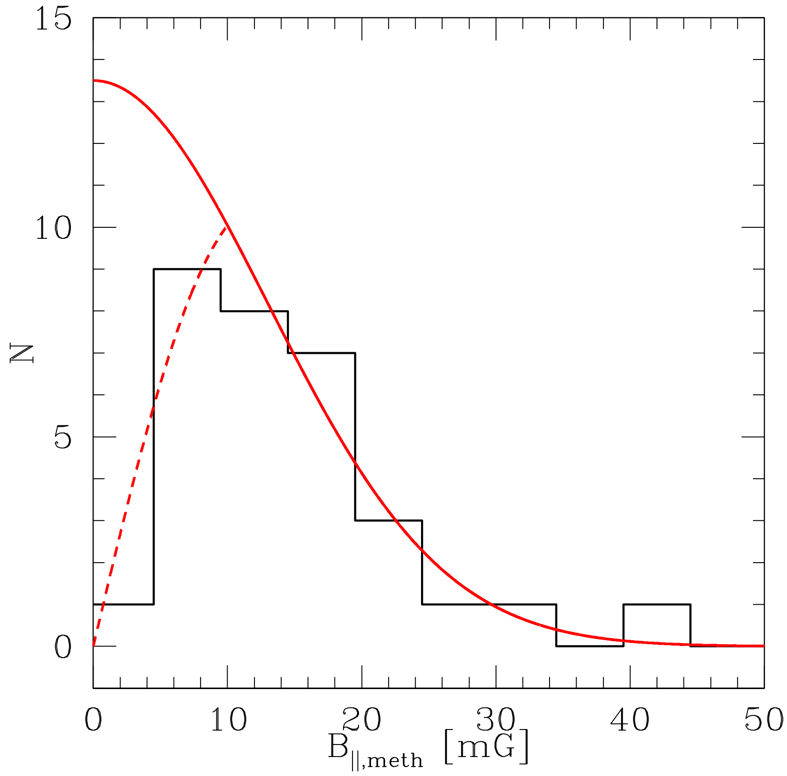

Figure 3: Distribution of the line-of-sight magnetic field strengths $B_{||}$ determined from Effelsberg 6.7 GHz methanol maser Zeeman measurements [14] and Vlemmings et al. (in prep.). The solid curve indicates the distribution expected from a randomly oriented magnetic field with $B_{||} = 12$ mG and the dashed line indicates the approximate completeness limit.

the line-of-sight, which implies for the absolute field strength $|B| = 2\langle B_{||}\rangle$. This gives $|B_{\rm meth}| = 23 \pm 5$ mG. The error on the absolute field strength is dominated by the estimated uncertainty in the Zeeman coefficient. This field strength is larger than that found in the OH maser regions, with the average OH maser determined field strength being ~ 4 mG.

The dynamical importance of the magnetic field can be quantified by defining a critical magnetic field strength $B_{\rm crit} = (8\pi\rho v^2)^{1/2}$ for which the dynamic and magnetic pressure are equal. Here ρ and v are the density and velocity of the maser medium respectively. The current observational limits suggest that the majority of the 6.7 GHz maser sources occur near the high-density limit that allows for maser emission ($n_{\rm H_2} = 10^7 - 10^9$ cm^{-3}), with a typical value of $n_{\rm H_2} = 10^8$ cm^{-3}. Taking this density and a typical gas velocity of $\lesssim 5$ km/s, $B_{\rm crit} \approx 12$ mG. The measured magnetic field vales are thus comparable to $B_{\rm crit}$ and hence dynamically important.

In addition to the large number of magnetic field detections, we also discovered an apparent magnetic field variability during the maser flares of G09.62+020 [15][6]. Monitoring of the circular polarization produced by this strongest of Galactic 6.7 GHz methanol masers revealed a fast decrease, and possible sign reversal, of the Zeeman splitting at the time when the periodic maser

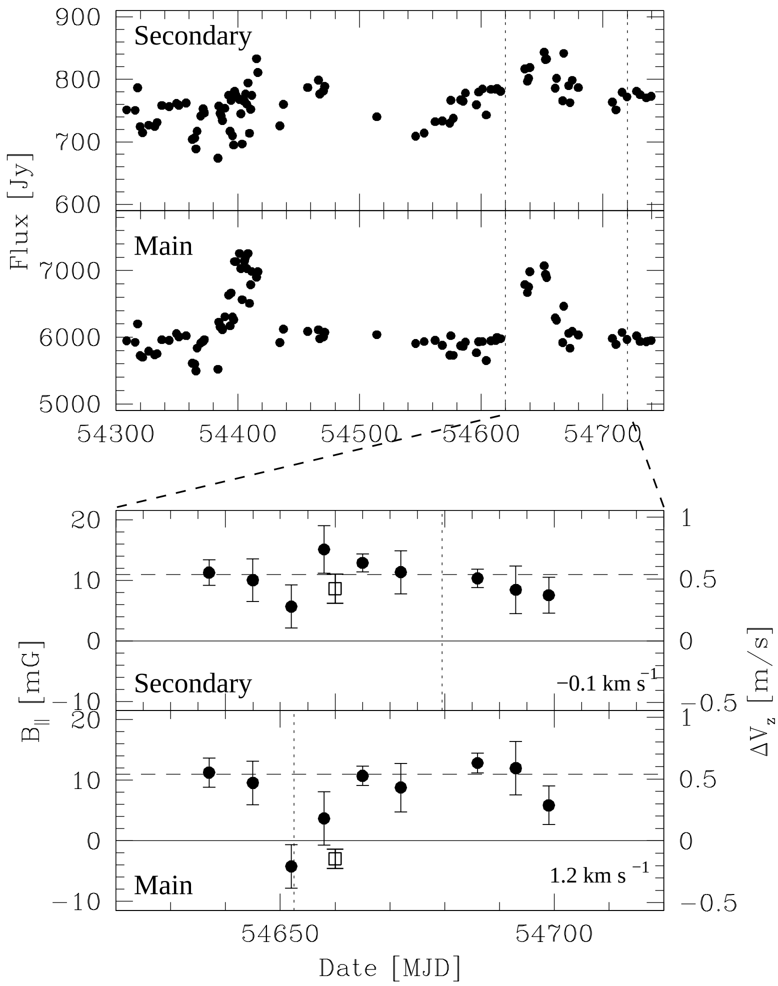

Figure 4: (bottom panels) The Zeeman-splitting ΔV_Z (in m s^{-1}) and derived line-of-sight magnetic field strength $B_{||}$ (in mG) for the two strongest 6.7 GHz methanol maser features of G09.62+0.20 at the 9 successful monitoring epochs (filled dots). The previous observations of Nov 11th 2007 (open square; [14]) has been folded into the new observations. The vertical short-dashed lines indicate the predicted date of the emission peak. The horizontal dashed lines indicate the weighted average magnetic field strength (see text). (top panels) HartRAO telescope observations of the two maser features for two flaring periods. The period of the Effelsberg observations is indicated by the vertical short-dashed lines.

flare peaks. However, the origin of the decrease, either related to the maser amplification process or external (magnetic field) effects is still unclear.

4. Summary

Methanol masers have been shown to be able to probe magnetic field strength and structure in dense regions of massive starformation. Around Cepheus A HW2, the full three-dimensional magnetic field is reconstructed and shown to be perpendicular to the molecular and dust disks. The magnetic field strength indicates that the accretion onto the massive protostellar disk is governed by magnetic forces.

Often, a large difference is found between methanol and OH maser polarization angles due to external Faraday rotation. This highlights the limits of OH maser polarimetry in studying the intrinsic large scale structure of magnetic fields. As methanol masers are much less affected by Faraday rotation, they are a more promising tool to study magnetic field morphology, despite their much lower fractional linear polarization of $\sim 2\%$. Using the Effelsberg 100-m telescope, the first Zeeman splitting observations were made in a sample of 24 massive starforming regions, indicating a magnetic field strength of $|B_{\rm meth}| = 23 \pm 6$ mG.

5. Outlook

With the e-MERLIN upgrade, it will soon be possible to map multiple maser transitions simultaneously with the radio-continuum. By observing in full polarization mode, this will allow for a direct comparison between the magnetic field structure determined from the masers and the continuum morphology. This is the goal of our e-MERLIN legacy project 'Feedback during massive star formation'. Similary, though with other maser species, MeerKAT will also be able to contribute to answering the question of the role of magnetic fields during massive star formation, and the high-spatial resolution maser observations will provide essential complementary data to future ALMA dust and line polarization measurements.

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