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The role of magnetic fields in massive star-formation

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We discuss the important role of magnetic fields in the formation of massive stars and present some recent observational evidence of magnetic fields in these regions. W3(OH) is the exemplar of the use of multi-transitional maser studies to determine the physical, kinematical and magnetic properties of an ultra-compact HII region. The recent publication of linear polarization maps of methanol masers in W3(OH) gives hope of a new and independent probe of the magnetic field direction in these regions, particularly in the earliest stages of the star-formation process. We discuss future strategies involving high-resolution observations of polarized OH and methanol maser emission.

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1. Introduction

A great deal of work is currently underway to observe and model the environments around regions of massive star-formation. Massive stars have a profound effect on the chemical enrichment of the surrounding environment and provide the vast majority of the radiation and turbulent energy that is fed back to the interstellar medium. Due to the cool and dusty nature of the protostellar environment, the observational emphasis for these regions is put on molecular tracers of cold dust and high-resolution (VLBI) studies of masers. Observations of masers in particular provide a high spatial-resolution probe of the gas kinematics and, in some cases, a measure of the strength and direction of the magnetic field in the region.

From observations of dust polarization and spectral line Zeeman splitting, it is clear that magnetic fields are widely present in star-forming regions (e.g. Vlemmings et al. 2006a [1]; Hutawarakorn & Cohen 2003 [2]). The degree to which turbulence and magnetic fields contribute to the support and ordered collapse of interstellar clouds is still under scrutiny, with evidence in different regions suggesting the dominance of either one or the other process. Recent observational studies point to the magnetic energy density being comparable to the turbulent energy density in star-forming clouds (e.g. Li et al. 2006 [3]). Recently, Girart et al. (2006) [4] reported evidence of cloud collapse by ambipolar diffusion in NGC1333. The typical 'hourglass' shape of the magnetic field in the collapsing cloud is seen as evidence that magnetically-coupled material is able to collapse in the direction parallel to the magnetic field lines to form a dense core. This cloud-collapse paradigm is also supported by the conclusions of Mouschovias et al. (2006) [5] that were based on the statistical study of existing observational evidence of linewidths and magnetic fields in regions of star-formation.

In order to test such models, it is necessary to observe the strength and direction of the magnetic fields within individual star-formation cores at high angular resolution. To understand the precise role of magnetic fields in the collapse of a molecular cloud to form hot cores and circumstellar discs, it is also necessary to observe a sample of star-forming regions at a wide range of ages in the star-forming process. This is where observations of interstellar masers – in particular methanol masers – prove invaluable.

There is evidence suggesting that class II methanol masers (characterised by the bright 6.7- and 12.2-GHz transitions) are tracers of the earliest stages of massive star-formation. They are observed at sites of massive star-formation, often prior to the creation of ionised HII regions (Walsh et al. 1999 [6]; Pestalozzi et al. 2002 [7]; Ellingsen 2006 [8]). They are often associated with OH (hydroxyl) masers which, along with the class II methanol masers, allow us to test the models of maser pumping and constrain the physical conditions surrounding star-forming cores. Hydroxyl masers are also useful because their spectral lines often exhibit Zeeman splitting in the presence of an external magnetic field. The measurement of the magnitude of Zeeman splitting, along with the linear polarization (characterised by the Stokes parameters U and V), allow us to measure the strength and direction of the magnetic field in the region at high spatial resolution.

Until recently, methanol masers were thought not to exhibit any measurable polarization. That notion changed when Ellingsen (2002) [9] reported the measurement of linear polarization of the 6.7-GHz methanol masers in a small sample of southern star-forming regions. The next section will describe how this observation has led to the first maps of the linear polarization being made in the massive star-forming region W3(OH) and how this ground-breaking result promises to greatly improve our ability to map the magnetic field structure throughout the earliest stages of massive star-formation.

2. First maps of polarized methanol maser emission in W3(OH)

W3(OH) is an extremely well-studied OH-HII region in the Perseus arm of our Galaxy, lying at an estimated kinematic distance of 1.95 kpc (Xu et al. 2006 [10]). A large number of maser transitions originating from several different molecules have been observed in the region (see Harvey-Smith & Cohen, 2005 [11] and references therein). The OH and methanol masers are often observed to follow both small-scale and large-scale ‘arcs’ in this and other star-forming regions (e.g. Cohen et al. 2006 [13]; Niezurawska et al. 2005 [14]; Wright et al. 2004 [12]; Baudry & Diamond 1998 [15]). The causes of these regular structures are still unknown, but they have been attributed to shocks or circumstellar disks.

The mystery was deepened when Harvey-Smith & Cohen (2006) [16] reported the discovery of very large-scale ($\sim 10^3$ AU) extended masers that follow the same arcs and filaments as the individual VLBI-resolved maser ‘spots’ in W3(OH). These were found using MERLIN, in both 4765-MHz OH masers and 6.7-GHz methanol masers. In the case of the largest maser filament seen in W3(OH), the OH and methanol masers seem to be highly sensitive to the local conditions along the filament, as each species is seen to switch on and off in turn along its length. Figure 1 (left) shows the integrated OH and methanol emission contours in this region, superimposed on the VLBI-resolved OH 18-cm maser spots. Another interesting feature in the methanol maser images was a very compact but extremely bright region of linearly extended methanol maser emission. This region had a large velocity gradient (4990 km s^{-1} pc^{-1}) and was characterised by masers with an unusually large spectral linewidth. For this reason it was called the ‘broadline region’, to distinguish it from the many other small arcs of 6.7-GHz methanol masers in W3(OH). This unusual linear structure was identified as a possible circumstellar disc with a diameter of 400 AU. Assuming Keplerian rotation, the implied mass of the central star is >13 $M_\odot$, which is consistent with the estimation of Dreher & Welch (1981) [17] – based on the far infra-red and implied uv emission – of a 30$M_\odot$ ZAMS O7-type central star. A map of maser spots from several different transitions in the broadline region is shown in Figure 1 (right).

In order to investigate the magnetic field behaviour along these ordered masing structures, Vlemmings et al. (2006b) [18] made maps of the MERLIN data in all (*IQUV*) Stokes parameters to measure the degree of linear and circular polarization of the methanol 6.7-GHz masers. They found that several of the methanol maser spots exhibited linear polarization (of up to 8%) but there was no measurable circular polarization. They also searched for Zeeman splitting but none was found, although the search was limited by dynamic range effects. This non-detection indicating an upper limit on the magnetic field strength in W3(OH) of 22 mG. Figure 2 shows the polarization map of W3(OH) produced by Vlemmings et al. (2006a). This is the first 6.7-GHz methanol maser polarization map to be produced for any astronomical region.

Wright et al. (2004) found a large spread in the polarization angles of the OH masers. This has been attributed to Faraday rotation along the maser path (e.g. Fish & Reid 2006 [19]). The polarization angles of the methanol and OH masers are clearly systematically different. Vlemmings and

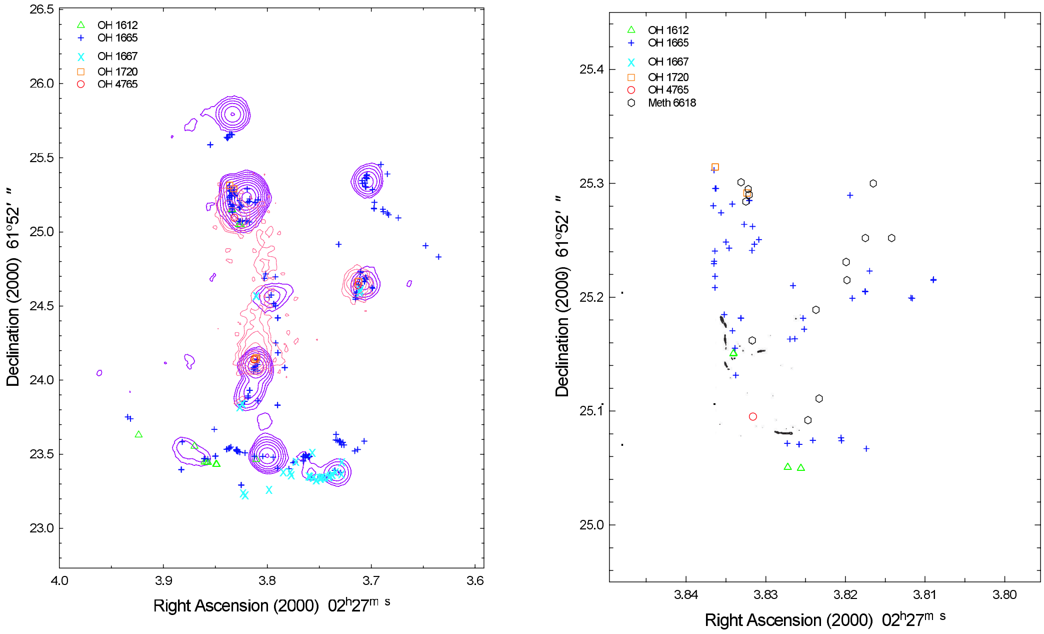

Figure 1: Left: The large-scale maser filaments in W3(OH). Purple contours show the integrated 6.7-GHz methanol maser flux and orange contours show the integrated 4765-MHz OH maser flux between –44.0 and –44.8 km s^{-1}. The symbols represent OH maser spots. **Right:** Map of the central (broadline) maser region in W3(OH). The linear maser structure with position angle 50° is traced by 6.7- and 12.2-GHz methanol masers and 1665-MHz OH mainline masers. This structure has an extraordinary linear velocity gradient and is the site of the brightest methanol masers and the continuum emission peak. Figures reproduced from Harvey-Smith & Cohen (2006).

co-workers attributed this to Faraday rotation of the polarization angle by electrons in the intervening medium between the source and the observer. The degree of Faraday rotation is dependent on the square of the frequency of the radiation, and this means that the 6.7-GHz methanol masers are much less affected by internal and external Faraday rotation than the lower frequency OH masers, making them excellent probes of the magnetic field direction in the maser region.

In order to understand the reason for this systematic difference in polarization angle between the OH and methanol masers, Vlemmings and co-workers attempted to calculate the degree of Faraday rotation expected by the two masers. They assumed typical values of the interstellar electron density 0.04 cm^{-3} and magnetic field 1.5 μG, and assumed a distance to W3(OH) of 1.95 kpc. Using these values, the calculated Faraday rotation angle at 6.7 GHz is 11°. The Faraday rotation at 1.6 GHz, on the other hand, is 190°. Therefore, they concluded that the difference between the median polarization angles at 6.7 GHz and 1.6 GHz, 171° ± 28°, is probably solely caused by external Faraday rotation.

Taking Faraday rotation into account, and assuming that the magnetic field is perpendicular to the OH (and therefore the methanol) polarization vectors, led to the conclusion that the magnetic field in W3(OH) runs parallel to the large-scale OH and maser filament shown in Figure 1. The polarization angle of one particular methanol maser region is clearly quite different to the general

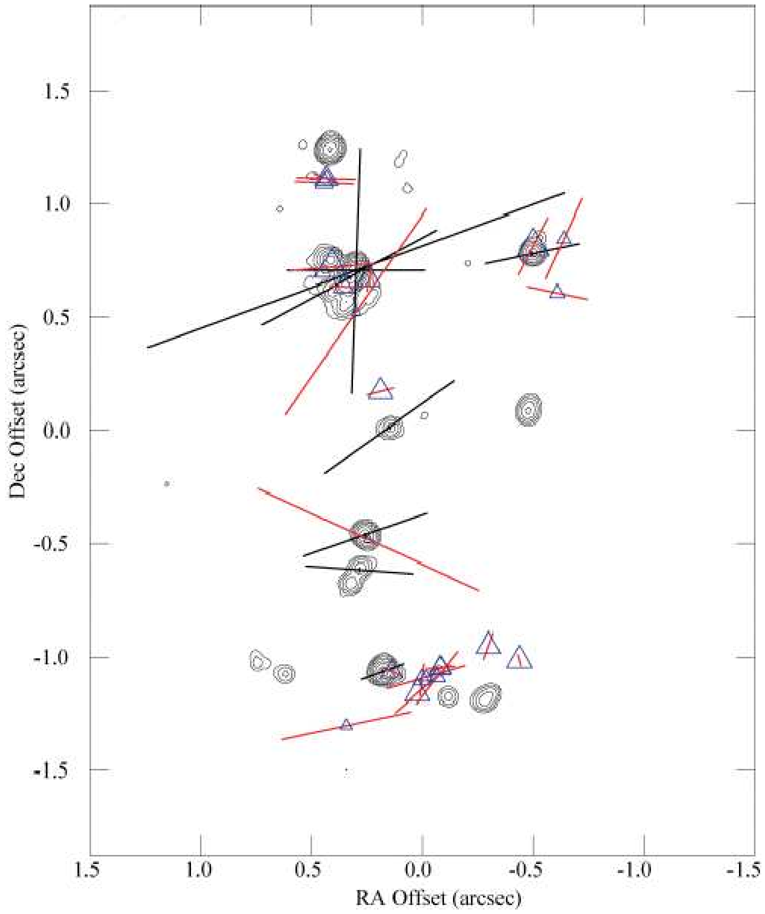

Figure 2: Methanol polarization map of W3(OH). Contours show the methanol maser flux integrated between –44.0 and –44.8 km s^{-1} and the black vectors are the linearly scaled polarization vectors. The blue triangles denote the main line OH masers from Wright et al. (2004) for which polarized intensity was detected at 5σ significance. The red vectors are their linearly scaled polarization vectors. The main line OH maser polarization vectors lengths are scaled down by a factor of 5 with respect to the lengths of the methanol maser polarization vectors. Figure reproduced from Vlemmings et al. (2006a).

case. This unusual polarization feature appears in the broadline region (Figure 1, right) at the same position as the possible circumstellar disc seen by Harvey-Smith & Cohen (2006). The magnetic field direction also varies within the broadline region, supporting the notion that there is some unusual physical significance to this particular region.

3. On-going work

We are following up the results described above with a MERLIN study of the size, distribution and polarization properties of excited OH masers at 6.0 GHz in W3(OH). Preliminary maps show a complex magnetic field structure close to the broadline region, which will add to the existing data. The polarization angles of the 6.0-GHz OH masers are expected to be much closer to those of the 6.7-GHz methanol masers. This comparison will provide an extremely rigorous test as to whether external Faraday rotation is entirely responsible for the relative rotation of the OH and methanol vectors. It will also provide further evidence to test the model of the broadline region as the centre of a circumstellar disc, addressing one of the current hot topics in massive star-formation research.

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