Cosmic Masers - from OH to H_0
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The W51 Main/South SFR complex seen through 6-GHz OH and methanol masers

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Abstract. W51 Main/South is one of the brightest and richest high-mass star-forming regions (SFR) in the complex W51. It is known to host many ultra-compact HII (UCHII) regions thought to be the site of massive young stellar objects. Maser emission from various species is also found in the region. We have performed MERLIN astrometric observations of excited-OH maser emission at 6.035 GHz and Class II methanol maser emission at 6.668 GHz towards W51 to investigate the relationship between the maser emission and the compact continuum sources in this SFR complex. Here we present the astrometric distributions of both 6.668-GHz methanol and 6.035-GHz excited-OH maser emission in the W51 Main/South region. The location of maser emission in the two lines is compared with that of previously published OH groundstate emission. The interesting coherent velocity and spatial structure observed in the methanol maser distribution as well as the relationship of the masers to infall or outflow in the region are discussed. It appears that the masers are excited by multiple objects potentially at different stages of evolution.

Keywords. astrometry, circumstellar matter, masers, magnetic fields, polarization, stars: formation, ISM: individual objects: W51, radio lines: ISM

1. Introduction

W51 is one of the most massive Giant Molecular Clouds (GMCs) in the Galaxy. This very rich high-mass star-forming region (SFR) environment is located in the Sagittarius spiral arm at 5.4 ± 0.3 kpc (Sato *et al.* 2010). W51 Main/South, one of the brightest regions of the W51 complex, is known to host many ultra-compact (UC) HII regions thought to contain massive young stellar objects at various stages of evolution. The UCHII regions are labelled W51e1, e2, e3 and e4 (Gaume, Johnston & Wilson 1993) and W51e8 (Zhang & Ho 1997). Of these, W51e2 was found to be composed of four more compact continuum sources labelled W51e2-W, e2-E, e2-NW and e2-N (Shi, Zhao & Han 2010a). Zhang, Ho, & Ohashi (1998) found evidence of gravitational infall towards W51e2 and W51e8 and, a CO outflow, oriented NW-SE, has been found associated to W51e2 (Keto & Klaassen 2008, Shi, Zhao & Han 2010b). W51 Main/South has been studied at a wide range of wavelengths both in continuum and molecular (thermal and maser) transitions. In particular, H_2O, OH, NH_3, CH_3OH maser emission has been found in the region (Genzel *et al.* 1981; Menten *et al.* 1990; Imai *et al.* 2002; Fish & Reid 2007; Phillips & van Langevelde 2005).

We have performed MERLIN astrometric observations of excited-OH maser emission at 6.035, 6.030 and 6.049 GHz and Class II methanol maser emission at 6.668 GHz towards W51 to investigate the relationship between the maser emission and the compact continuum sources in this SFR complex (Etoka, Gray & Fuller, 2012). Here we present the results regarding W51 Main/South. Association with the UCHII regions in the W51

Main/South complex and relationship of the masers to infall or outflow in the region are discussed.

2. Results

Overall the bulk of the methanol maser emission, both in terms of flux and number of components, is associated with W51 Main. Only two weak, isolated areas separated by ~ 2.5" are found to be producing methanol maser emission in W51 South, most likely associated with the e3 and e8 sources. Although the work of Fish & Reid (2007) shows that there is significant ground state OH emission from both Main and South, with indeed the brightest OH component being in South, excited OH emission is only detected towards Main (Fig. 1).

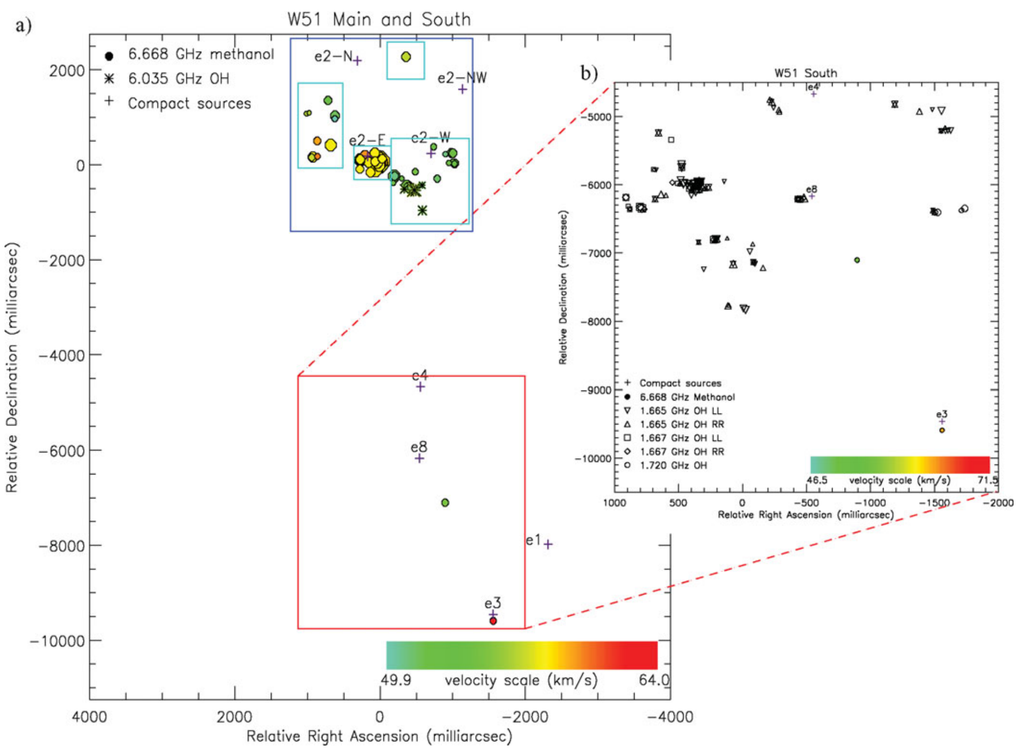

Figure 1. a) Maser components in the methanol 6.668-GHz and the excited OH 6.035-GHz transitions for the overall W51 Main/South region. The velocity colour-code covers the W51 Main and South methanol maser emission velocity range. The size of the symbols is proportional to the log of the intensity. The crosses indicate the positions of the compact continuum sources in the region. **b)** 6.668-GHz methanol Stokes I components from this work with all the ground-state OH maser components at 1.665, 1.667 and 1.720 GHz detected by Fish & Reid (2007) in W51 South. Note the change in the velocity range and hence colour-code.

In W51 Main, there seem to be 4 distinct regions of emission on the plane of the sky (Fig. 1a). Fig 2a presents an expanded view of the 3 most extended structures observed and Fig. 2b presents the velocity distribution of these methanol maser components versus radial distance (excluding the northern component likely associated to e-N/e-NW). The latter figure shows that the red- and blue-shifted maser components are diverging from a common point with an expansion velocity of $\simeq$5 km s^{-1}. This, added to the general

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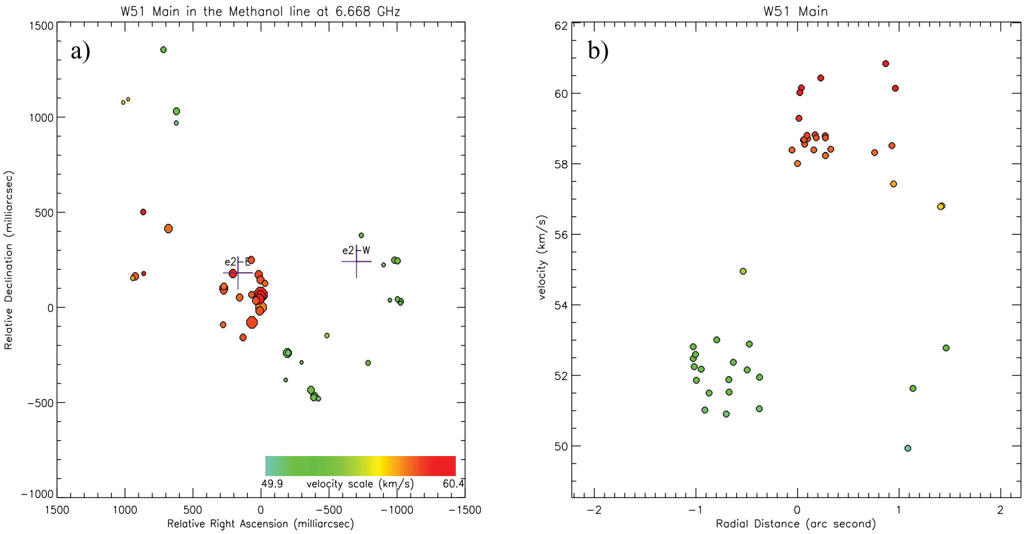

Figure 2. a) Maser components in the methanol 6.668-GHz line towards W51 Main, excluding the northern component. The velocity colour-code is restricted to the W51 Main methanol maser emission velocity range. **b)** The velocity distribution of the maser components versus radial distance. The central position is taken to be [0,+80 mas], inferred from the convergent point of the SW blue-shifted maser components.

distribution of the methanol maser components in the plane of the sky, indicates the presence of a structure with a wide opening angle associated with W51e2.

3. Discussion

As noted by Etoka *et al.* (2005) in the case of the SFR W3(OH), the present astrometric study towards W51 Main/South confirms that associations of individual OH and methanol maser components are rare. Despite all the components identified in the rich maser environment of W51 Main, no overlapping methanol and OH maser components are found, suggesting local variations in the abundance of the species and that both species are found in closely associated, but distinct, pockets. Similarly, even though 6.035-GHz excited-OH and ground-state OH maser components are in similar areas in W51 Main with similar magnetic field strength, they too do not show any overlap when observed at high spatial resolution. The total absence of 6.035-GHz emission and the scarcity of 1.720 GHz emission in W51 South, is suggestive of a lower density in W51 South than in W51 Main (Gray *et al.* 1992, Cragg *et al.* 2002).

Clearly, there are several distinct spatial-kinematic components in the region. These have been identified in Fig 3. The most extreme velocity maser components, which are all ground state OH masers, lie close to a line through W51e2-E at a P.A. $\sim 150°$ with the red-shifted components north of the source and blue-shifted components offset by a similar angular distance (~ 400 mas) south of the source. The location of these components as well as their velocities indicate that they are associated with the outflow from the source which has been imaged by Shi *et al.* (2010b).

There are two possible interpretations for the wide-opening angle structure observed in Fig. 2 which are discussed here below:

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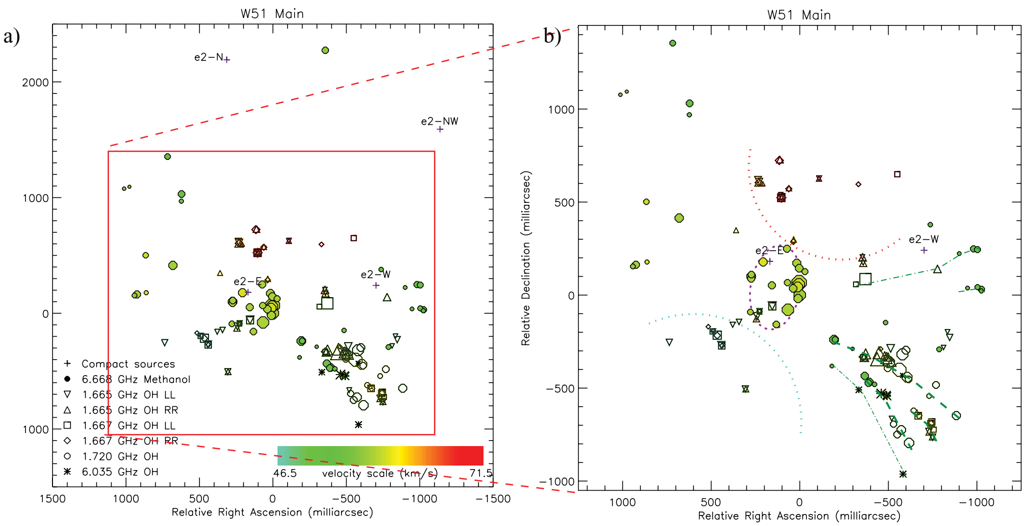

Figure 3. a) 6.668-GHz methanol and 6.035-GHz maser components from this work with all the ground-state OH maser components at 1.665, 1.667 and 1.720 GHz detected by Fish & Reid (2007) in W51 Main. **b)**Magnification on the masers around e2-E and e2-W presenting the various spatial-kinematic components identified.

3.1. **Scenario 1: Outflow**

According to Churchwell (2002), typically an outflow from a high-mass young stellar object (HMYSO; i.e., $L_{bol} > 10^3$ $L_\odot$) lives $\sim 10^4$ yr with a mass outflow rate of $\sim 10^{-3}$ $M_\odot$ yr^{-1}. With an expansion velocity of 5 km s^{-1}, only $\sim 5 \times 10^3$ year would be needed to reach 1", corresponding to the extent of the red- and blue-shifted lobe observed in Fig. 2b.

In this scenario, the 2 gaps observed in the distribution of the masers could be explained by 2 episodic events. The ring-like structure closest to e2-E, well defined by an ellipse of long-axis ~ 220 mas, would trace an outflow event $\sim 1.1 \times 10^3$ yr old, assuming no acceleration or deceleration.

3.2. **Scenario 2: Accreting flow**

The northeast-southwest distribution of the masers is close to perpendicular to the axis of the well collimated outflow of material imaged in CO by Shi *et al.* (2010b). This suggests that alternatively the masers could be tracing material which is part of the static or infalling envelope around the forming star.

In this scenario, the methanol masers closest to e2-E, forming a compact ring-like structure is likely to trace a distinct physical component. Similar structures are seen by Bartkiewicz *et al.* (2009) towards some 29% of the 6.7-GHz methanol maser sources they studied. They interpreted these as a result of the masers being associated with a dense disk or torus around the central source, an interpretation which could also be applied to the masers seen here.

4. Conclusion

We have presented MERLIN astrometric observations towards W51 Main and South of the Class II methanol maser emission at 6.668 GHz and the excited OH maser emission at

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6.035 GHz. The 6-GHz maser distributions have been aligned with those of the ground-state OH maser transitions at 1.665, 1.667 and 1.720 GHz from Fish & Reid (2007). Although Main and South have similar number of OH ground-state maser components with the strongest component in South, the bulk of the methanol 6.668 GHz maser emission, and all of the excited OH 6.035 GHz maser emission are found to be associated with e2 in W51 Main.

The methanol masers revealed a wide-opening angle structure centred on e2-E, roughly aligned on a P.A. $\sim 150°$, that is roughly perpendicular to the CO outflow, and showing a clear velocity coherence. The two possible interpretations of this structure are the signature of **(1)** an outflow showing episodic events of $\sim 5 \times 10^3$ yr for the older event and $\sim 1 \times 10^3$ yr for the younger one, assuming an outflow velocity of ~ 5 km s^{-1} or; **(2)** an accretion flow in which two physical components are present: an infalling envelope with the central ring-like structure probing a compact and dense disk or torus around the central object.

Although e2-W is the only continuum source in W51e2 clearly associated with a UCHII region, currently e2-E seems to be the most active source in the region. The presence of methanol masers and the lack of a UCHII region point at a massive central object at an early stage of the star forming process.

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