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Methanol masers and the earliest stages of massive star formation

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Abstract. 6.7 and 12.2 GHz methanol masers were originally detected toward active star-forming regions. Since their discovery a decade ago, their role and their location have been better understood using high resolution interferometers. Observations with the EVN and the VLBA have shown that methanol masers are clearly associated with the earliest stages of massive star formation. They arise in hot molecular cores, in hyper compact regions of ionised gas, in ionised jets/outflows, in ultra-compact H II region and in H II region. Interestingly, the overall dimensions of the structures traced by the methanol masers increase during the evolution of the massive young stellar object. Our data suggest that they remain small and compact when associated with the massive protostar phase, and expand in sources associated with outflows. The methanol masers gradually disappear as the UC H II region develops. Based on these results, an evolutionary sequence for massive star formation is presented in connection with the evolution of methanol masers.

1. Introduction

Massive (> 8 M$_\odot$, OB) stars, from infancy to death, are the most important sources of energy in the Galaxy. At the early stages of their evolution, they first heat the surrounding dust, then ionise their H_2 environment and finally develop an H II region (i.e. a bubble of ionised gas) around them. Young massive stars are thus indirectly detectable in far-infrared (warm dust) and in radio (ultra-compact H II region) surveys (Wood & Churchwell 1989). However, these phases are already relatively evolved in the process of massive star formation (MSF), $\sim 10^5 - 10^6$ years in comparison with the $\sim 10^6 - 10^7$ year lifetime of OB stars. How massive stars exactly form remains poorly understood. This lack of knowledge has stimulated the search for precursors of ultra-compact H II region, i.e. *massive protostars* (Kurtz et al. 2000 for a review). The massive protostars are expected to be fainter infrared objects than UC H II regions, but strong emitters of millimetre emission (cooler dust). They would also be embedded in hot molecular cores (~ 200 K, $> 10^7$ cm^{-3}) and would be detected with high density molecular tracers (e.g. NH_3, CH_3OH, CH_3CN and $C^{18}O$).

The first targeted surveys, using single dish observations, toward star-forming regions have suggested a close association between the 6.7 and 12.2 GHz methanol masers and the traditional signposts of massive star formation. However, the large beam of a single dish ($\sim 2-7'$ i.e. 0.6-2.1 pc at a distance of 1 kpc) would never be sufficient to clearly identify the maser sources in densely populated, massive star-forming regions (e.g. ~ 8 OB stars within 0.5 pc in the Orion Nebula Cluster). In the present paper, we investigate the nature of the relationship between methanol masers and the regions of massive star formation. The 16 star-forming regions considered here have been extensively studied at other wavelengths (e.g. Minier et al. 2002a and 2002b). By comparing all the existing images of selected sources with the VLBI maps of the associated methanol masers, it should be possible to better understand the role of these masers in the evolution of massive young stellar objects (YSOs).

An extensive VLBI study of methanol masers was carried by Minier et al. (2000, 2001). We discuss in the present paper the implications of this VLBI work. The 6.7 GHz EVN observations were conducted in May 1997, November 1998, November 1999 and September 2000. The VLBA observations at 12.2 GHz were conducted in July 1997, November 1998, and January 1999. The observations as well as the data analysis were fully described in Minier et al. (2000). Standard amplitude, delay, rate and phase-referenced calibration and imaging procedures to analyse spectral line VLBI data were used.

2. Summary of the results

We have compared our VLBI maps of 16 methanol masers with observations in the optical, infrared, millimetre and centimetre regimes of the associated star-forming regions published in the last ten years and available online (the *Aladin* interactive software sky atlas and the MSX catalogue). The methanol maser sources can be classified in two groups: those coincident with a radio continuum source; and those *isolated* from any radio source. A detailed description of 13 out of these 16 sources is given in Minier et al. (2001).

Among the first group, methanol masers are associated with radio emission from hyper-compact or unresolved ionised regions (S255-IR, W51-North/D2), from ionised

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jets and outflows (NGC 7538, W75N, Cep A, G9.62+0.20), from a UC H II region (W48), and from an H II region (S269). W51-North is the least developed ionised region with a diameter less than 300 AU (∼ 1 mpc) and unresolved with the VLA at 22 GHz (Minier et al. 2001 and references therein). In contrast, S269 is an optically visible H II region of size ∼ 3.9×2.8 pc (Godbout et al. 1997). The methanol maser source in S269 was originally identified as a massive protostar site by Minier et al. (2001) because Kurtz et al. (1994) reported a non radio detection with the VLA at 8.6 and 15 GHz. That was because the VLA resolved out the emission from such a large region. S269 is probably older than 10^6 years, and the methanol masers are associated with S269-IRS2, classified as a young O star (Godbout et al. 1997).

The second group, that of the *isolated* methanol maser sources, consists of AFGL 5180, S231, G29.95-0.02, G31.28+0.06, G31.41+0.31, Mon R2, G59.78+0.06 and IRAS 20126+4104. They were classified by Minier et al. (2001) as *massive protostar* sites. An illustrative case is AFGL 5180 whose observational properties are seen in the seven other candidates for massive protostar sites.

Figure 1 gives an overview of the properties of AFGL 5180. Low resolution observations demonstrate that AFGL 5180 is embedded in cold dust (Fig. 1c) and in molecular gas, rich in NH_3 and CH_3OH (Fig. 1e & f). From the 1.2 mm flux, an estimate of 650 $M_\odot$ for the core mass is derived assuming that the dust emits black body radiation with a temperature ∼ 30 K (peak emission in FIR) and the optical depth of the dust is $\tau_\lambda = 1.3 \times 10^{-20}\, N_{\rm H}\, \lambda_{\mu m}^{-2}$ (Mezger et al. 1990). Dust emission is also observed in the infrared with strong emission (1600 Jy) at 100 μm. Using the flux densities measured from 2 to 1200 μm with 2MASS, MSX, IRAS and SIMBA, the spectral energy distribution of the dust emission in AFGL 5180 gives a total luminosity of $\sim 10^4$ $L_\odot$. These physical quantities are typical of massive star-forming regions. More interestingly, high resolution observations of AFGL 5180 reveal bipolar outflows seen in the NIR (Fig. 1b and Davis et al. 1998 and references therein) with a NIR source at the centre, AFGL 5180-NIRS1. The EVN and VLBA observations position the methanol masers on AFGL 5180-NIRS1 with a linear distribution nearly perpendicular to the bipolar outflows (Fig. 1b and 1d). The masers might trace the inner dense (n_{H_2}∼10^7 cm^{-3}, T_d=150 K) part of a proto-stellar disk.

AFGL 5180 is a prototypical example of the *isolated* methanol maser sources discussed in this paper. They exhibit millimetre dust emission and molecular line emission from high density tracers. They are faint in infrared, especially at 2 μm in J and H bands, and show infrared excess in the K band. They were not detected in various radio survey with the VLA down to 1 mJy beam^{-1} (e.g. Kurtz et al. 1994), suggesting that the ignition of a massive star has not started yet. All these observational facts characterise the expected environment of massive protostars. In conclusion, the *isolated* methanol masers do trace massive star-forming regions that are still in a very early phase.

3. An evolutionary sequence for MSF

In the previous section, the methanol maser sources have been found in various stages, from massive protostars to optically observable H II region. Interestingly, the overall dimensions of the structures traced by the methanol masers increases during the evolution of the massive YSO (Fig. 2). The total extent of the maser distribution increases with the number of maser features. The wider is the velocity range (Δv), the larger is the total extent (Fig. 2a). More precisely, the massive protostar sites are generally characterised by a total extent lower than 400 AU and Δv lower than 4 km s^{-1}. In contrast, maser sites associated with well developed ionised regions have a larger extent (> 600 AU) and span over a wider velocity range. Finally, the distribution of methanol masers in S269 remains compact, suggesting that the ionising radiation in the H II region progressively quenches the masers. In summary, our data suggest that the spatial distribution of methanol masers is small and compact when associated with the massive protostar phase, and expands in sources associated with outflows. The methanol masers gradually disappear as the UC H II region expands (Fig. 2b).

Based on these results, we propose an evolutionary sequence for massive star formation in connection with methanol masers:

1. Collapsing phase: A protostar forms within a collapsing, cold core of condensed gas and dust, increases in mass and heats up the proto-stellar envelope. This phase has not been identified yet;
2. Massive protostar phase: An accretion disk forms around the massive protostar with bipolar outflows. Methanol maser commences in the warm (> 60 K) part of the disk, where methanol evaporates from the icy dust grain mantles. This phase is characterised by a rich proto-stellar chemistry and spectral line emission (hot molecular core) as well as by (sub)millimetre emission from the external cold dust layer ;
3. Hyper-compact H II region phase: The young massive star is hot enough and ionises the molecular gas. An hyper-compact H II region forms around the newly born star and expands, gradually ionising the nearby molecular environment;
4. Ionised jets and outflows phase: Methanol masers spread and occur in the outflows that are also ionised by the intense UV radiation from the OB star;
5. Ultra-compact H II region phase: The ionised region turns to a UC H II region, gradually destroying the methanol molecules via photodissociation and chemical reaction with ions. The methanol masers are slowly quenched.
6. H II region phase: The UC H II region evolves into a conventional HII region, methanol masers, if they still exist, remain marginal.

In this scenario methanol maser is the first prominent signature of massive star formation. Methanol masers can then signpost clusters of OB stars in a younger stage than

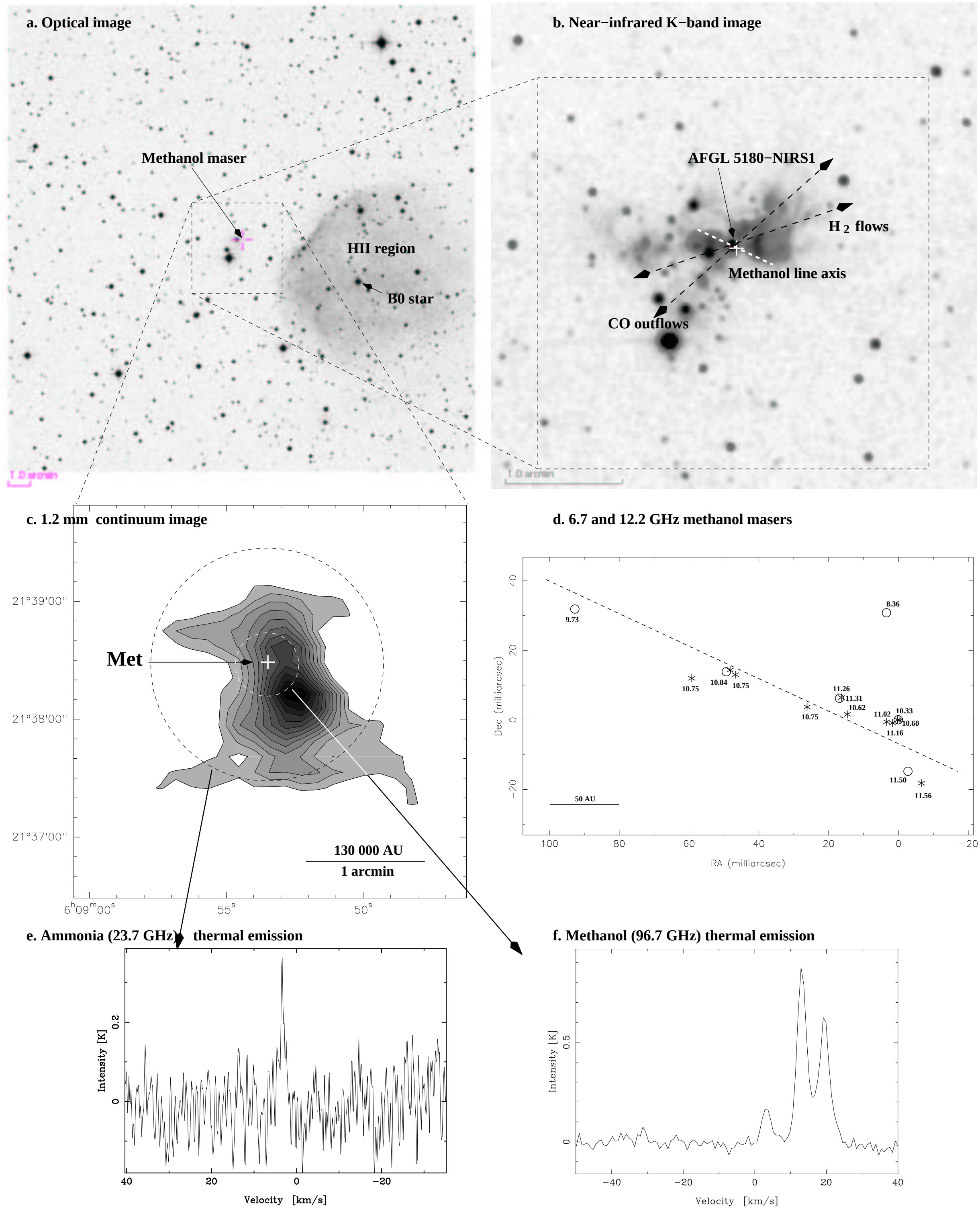

Fig. 1. AFGL 5180 - a proto-cluster of very young massive stars. The cross represents the position of the methanol masers **a.** Optical image of the neighbourhood of AFGL 5180. The methanol maser source is not coincident with any visible object. It is, however, nearby an optically visible H II region around the B0 star ALS 8736. **b.** Near-infrared image of AFGL 5180 taken in the K-band with 2MASS. The methanol masers coincide with the AFGL 5180-NIRS1. This NIR source is located at the centre of an infrared nebula and CO outflows, oriented South-East/North-West. An H_2 flow has also been detected by Davis et al. (1998). **c.** 1.2 mm image taken with SIMBA (Minier et al., in prep.). The millimetre continuum emission arises from cold dust surrounding AFGL 5180-NIRS1. SIMBA partially resolves the mm emission in two cores. The methanol maser source is located in between the two mm cores. Moreover, the mm sources is elongated North/South and roughly perpendicular to the NIR nebula orientation. **d.** Methanol maser distribution at 6.7 GHz and 12.2 GHz imaged by the EVN and VLBA. The masers form a line of $\sim$ 300 AU in extent with a position angle of 70°. The maser line is perpendicular to the outflow axis. The methanol masers might trace an outflow/disk system around AFGL 5180-NIRS1, and seen nearly edge-on. **e. & f** Thermal NH_3(23.7 GHz) and CH_3OH(96.7 GHz) emission detected toward AFGL 5180-NIRS1 with the Onsala-20m telescope (Minier et al. 2002a). The dashed black and white circles represent the size of the OSO-20m beams at 23.7 and 96.7 GHz, respectively.

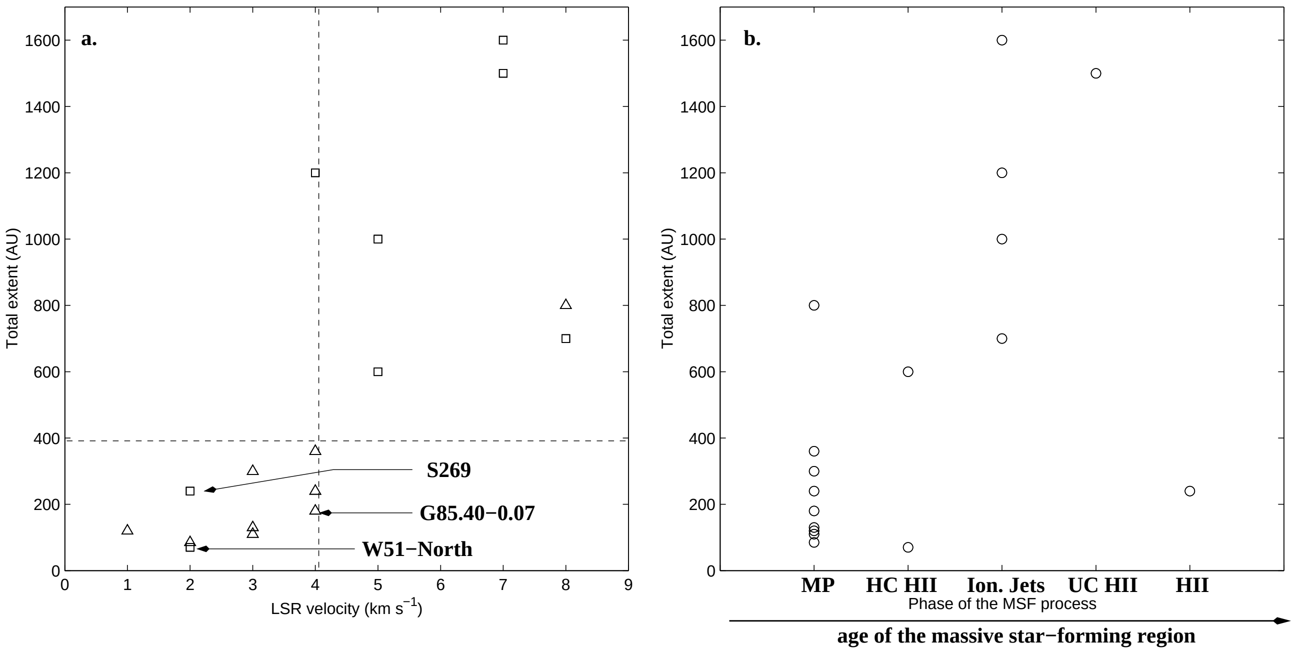

Fig. 2. a. Total extent of the spatial distribution of methanol masers across the VLBI map vs. the velocity range of the maser spectrum. The triangles represent the *isolated* methanol maser sources. The squares represent the methanol maser sites associated with a radio continuum source. With the exception of one case, the *isolated* methanol maser sources are grouped in the bottom left part of the diagram. The squares occupy the top right part of the diagram with the exception of W51-North (i.e. an HC H II region unresolved with the VLA), and S269 (i.e. an H II region). Two additional sources detected in the Onsala methanol survey (Pestalozzi et al., in prep.) are also plotted. They belong to the massive protostar group. **b.** Total extent of the spatial distribution of methanol masers vs. the phase of the massive YSO. The massive protostar (MP) candidates have generally an extent lower than 400 AU. The variation of the total extent from MP to HC H II is not very clear. It is likely that HC H II regions represent MPs that have just become detectable in radio. IRAS 20126+4104 is typical example of a MP with an extremely weak radio emission at a level of 10 μJy beam^{-1} at 8.6 GHz (Kurtz et al. 2000). The total extent increases during the ionised jets/outflows phase, and finally decreases as the HC H II evolves to reach a level of compactness similar to that in the MP phase.

those discovered using radio emission from UC HII regions.

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