THE EARLIEST STAGES OF HIGH MASS STAR FORMATION – METHANOL MASER INSIGHTS

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We report on recent multi-scale observational studies of the earliest stages of high mass (>8 $M_\odot$) star formation using methanol MASERs as astronomical probes. Methanol masers can provide unique information about densely populated, embedded protoclusters in which precursors of O and B stars form.

Tracers of high mass star-forming complexes in the Galactic plane: The brightest methanol masers are detected in radio frequencies at 6.7 and 12.2 GHz and are not affected by extinction in high mass star-forming regions. They were originally detected in the environment of very active star-forming complexes of HII regions a decade ago [1]. Since their discovery, more than 500 methanol maser sites have been located in the Galactic plane through searches toward IRAS colour selected sources [2], OH and H_2O masers [3] as well as through unbiased full-sampling surveys [4,5]. Interestingly, 6.7-GHz methanol masers have not been detected toward low mass star-forming regions despite very sensitive searches [6]. All these results strongly suggest that 6.7-GHz methanol masers are exclusively associated with high mass star-forming complexes in the Galactic plane [5] (Fig. 1a).

Tracers of massive protoclusters: Several complementary studies have been undertaken to identify the nature of the relationship between the maser sites and the star-forming regions. Methanol masers arise from deeply embedded (>10 mag), massive (>50 $M_\odot$), cold (20-50 K) and luminous (>10^3 $L_\odot$) molecular clumps (~0.5 pc in diameter) [7,8,9]. Various classes of object can be identified among these molecular clumps based on their thermal dust emission in submillimetre and infrared. Methanol masers are associated with both mid-infrared dark and bright clumps, a combination often seen in a unique complex (e.g. Fig. 1b). The mid-IR dark clumps are characterised by a Spectral Energy Distribution of cold dust emission that peaks at longer wavelengths (~20-30 K) than that of bright IR clumps (~40-50 K). Mid-IR dark clumps might then represent early stages of the clustered star formation process. Many bright IR clumps are radio quiet in terms of free-free continuum emission. These results indicate that within high mass star-forming complexes methanol masers trace massive protoclusters of young stellar objects in earlier evolutionary phases than in HII regions.

Tracers of high mass protostars: High angular resolution observations have demonstrated that methanol masers are in fact generally not associated with strong radio continuum emission from ultra-compact HII regions [10]. However, methanol maser sites appear to coincide with hot molecular cores as well as with hyper compact and very weak radio sources in many cases [11]. They are also detected in mid-IR at sub-arcsec resolution and pinpoint bright objects with luminosities (~10^4 $L_\odot$), radius (~100 AU) and masses (~10 $M_\odot$) consistent with those expected for high mass young stellar objects [12,13] (e.g. Fig. 1c,d). VLBI observations of methanol masers have revealed that they often form lines with velocity gradients along them [14] which are interpreted as protostellar Keplerian disks seen edge-on [15] (e.g. Fig. 1e). Alignments with outflows are also observed [13,14]. These results strongly suggest that CH_3OH masers trace precursors of UC HII regions, i.e. sites of massive protostars.

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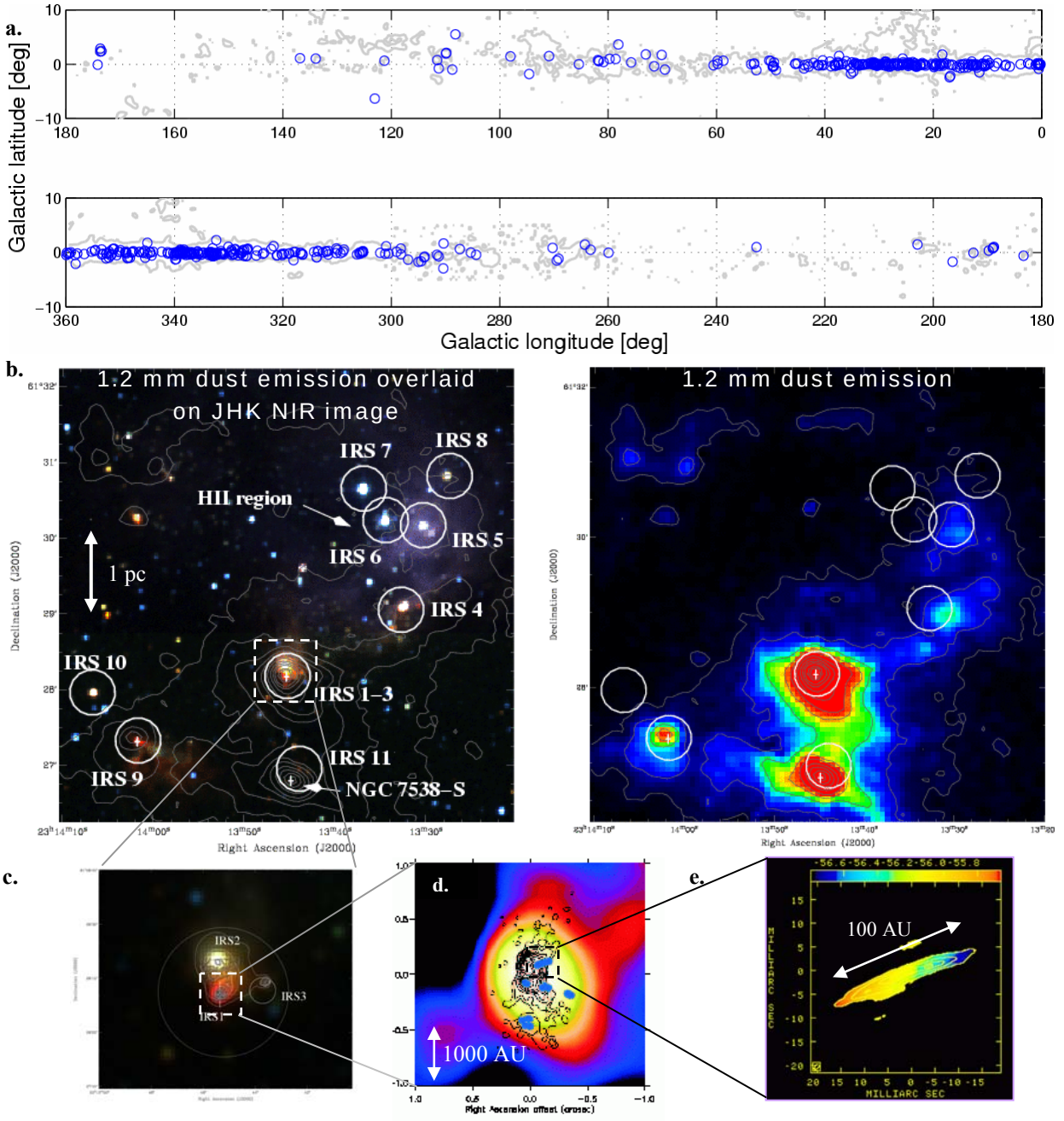

Figure 1: **a.** Distribution of methanol maser sites in the Galactic plane overlaid on the CO(1-0) map of molecular clouds. **b.** NGC 7538 – a complex of high mass star formation. Methanol masers (white crosses) are associated with the bright IR source IRS 1 in NGC 7538, as well as with the deeply embedded IRS 9 and the dark cloud NGC 7538 S. **c.** Close-up composite JHK image with 2MASS of IRS1-3. The contours represent 18-μm thermal dust emission detected with GEMINI/MICHELLE. **d.** Close-up of the mid-IR image. Black contours are radio continuum emission at 22 GHz. Blue symbols are methanol masers. **e.** Close-up of the maser line. Colours vary with velocities.