Massive Star Birth: A Crossroads of Astrophysics
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Uncovering the earliest stages of massive star formation

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Abstract. Massive stars begin their lives in cold, dense cores which are much more massive than the stars which form in them. We summarise the results of a program to find the earliest examples of massive star formation, and to examine the evolutionary sequence of events that occurs as such a star begins to form and heat its surroundings. Methanol maser emission has proved to be a particularly potent tool to locate such cores, though there are also clearly many massive cores which do not exhibit such maser emission. Our program began with a survey for 6.6 GHz methanol maser emission, but expanded to include dust continuum surveys in the mm and sub–mm, a survey for hot molecular cores associated with 'isolated' masers through mm-line CH_3CN emission, and follow-up probing of some cores through sub-arcsecond, diffraction limited observations in the mid–IR. This program is outlined below.

Keywords. stars: formation, masers, HII regions, ISM: molecules, astrochemistry

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1. Introduction

Rapidity, obscuration, rarity and overlapping evolutionary phenomena all serve to make the study of the earliest stages of massive star formation both intriguing as well as challenging. We report on a program at UNSW to investigate the earliest stages of the MSF process using a variety of infrared and millimetre-wave techniques. Our study has focussed on prospective sites of massive star formation selected through the signature of methanol maser emission, both isolated and when accompanied by radio UC HII region emission (Walsh *et al.* 1997, 1998). Millimetre dust emission always accompanies such maser sites, arising from cores whose mass ranges from a few hundred to a few thousand solar masses (Walsh *et al.* 2003, Hill *et al.* 2005). These cores likely represent a massive protostellar cluster. Accompanying them are many others in the same GMC–complexes that are only evident through their mm dust emission. In general, these latter cores are less massive than cores associated with other tracers of MSF. Whether these represent cores which are forming lower mass stars, or cores in which massive star formation has not (yet) occurred, remains to be determined. A survey for hot core molecular lines from a selection of the methanol-maser emitting cores shows that CH_3CN line emission from gas at a few tens of Kelvin is common, indicating internal heating sources when the core is isolated (Purcell *et al.* 2005). CH_3CN emission is, however, more prevalent in the cores also associated with UC HII regions than those without, suggesting an evolutionary sequence as the core warms up when a protostellar source switches on in its interior and begins to evaporate ices from the mantles of grains. Examination of selected cores at sub-arcsecond resolution in the mid–IR, to identify possible protostellar sources, not only finds such sources (Longmore *et al.* 2005), but also shows a multiplicity of the massive sources present, at projected separations of a few thousand AU. These most-luminous members of the proto-clusters also cannot be distributed with a Salpeter-like IMF — there are too many massive sources present in the core. In this paper we discuss this work through illustrative figures taken from the afore-mentioned papers.

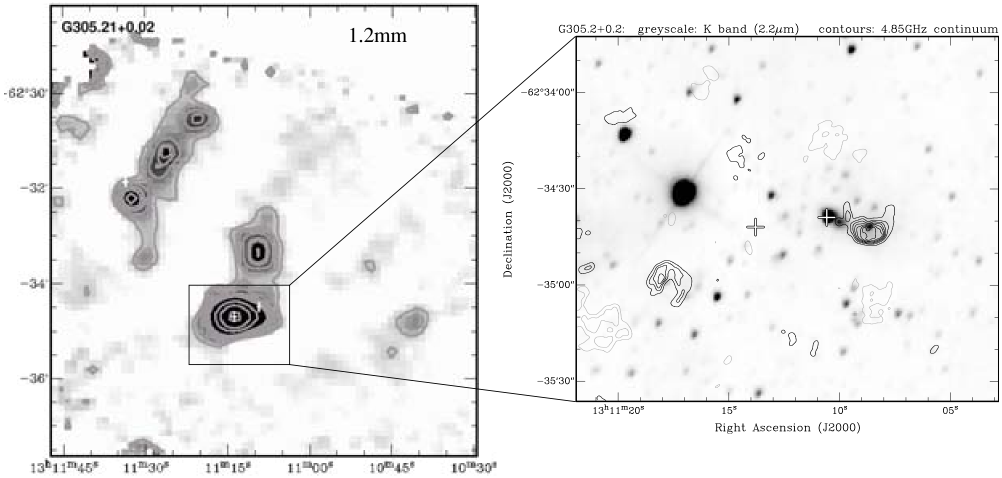

Figure 1. These images of the massive star formation region G305.2+0.2 illustrate both the sequence our observational program has taken and the range of star formation cores existing within a typical GMC–complex. The region in the right image was initially targeted for a class II 6.6 GHz methanol masers, based on IRAS far–IR colours indicating the presence of a UC HII region (Walsh *et al.* 1997, 1998). While indeed two UC HII regions were found (the contours show 4.85 GHz radio continuum from Phillips *et al.* 1998), neither coincides with the two (isolated) methanol masers also found there (crosses). Infrared imaging of the region shows a near–IR (2.2μm) source coinciding with the western maser (G305B), but nothing associated with the eastern maser (G305A; Walsh *et al.* 1999). This IR source has a steeply rising energy distribution, being bright in the mid–IR (Walsh *et al.* 2001). Deeper mid–IR observations also show a weak source that may be associated with the eastern maser (De Buizer 2003), however there is no clear sign of an exciting source for the maser. Millimetre observations, however, reveal a different picture (left image), with the eastern maser being associated with a bright 1.2 mm source with a dust + gas mass of $\sim$3000M$_\odot$ (Hill *et al.* 2005). Furthermore, mm continuum emission is seen from at least eight other cores spread over a $\sim$3 pc-sized region, with masses ranging from a few tens to a few hundred solar masses, and with sizes of a few tenths of a parsec. One of these additional mm cores may also be associated with a methanol maser (crosses), but for the other cores there are no signposts to the presence of star formation aside from the millimetre continuum itself. Many of these cores are clearly cold, not being associated with any mid–IR emission in the MSX satellite survey. Finally, N_2H^+ observations (see Walsh & Burton 2005) suggest there may be a massive, cold, quiescent core to the SW of the western maser (G305B) that is not evident in the mm continuum image. The inference is that the G305.2+0.2 region contains a number of massive star forming cores, all at different evolutionary stages: from cold pre-stellar cores, to cores where an internal heating source has just turned on and started exciting methanol masers, to warmer cores visible in the mid–IR, to cores where the ionized bubble of a UC HII region has formed and is expanding, leading to the termination of the maser emission.

2. The Observational Program

Our work initially centred on identifying methanol masers associated with the presumed UC HII regions around IRAS sources that met the colour criteria identified by Wood & Churchwell (1989). To our surprise, while some methanol masers clearly were associated with UC HII regions, the majority were not (Walsh *et al.* 1998). Furthermore, the larger the size of the UC HII region, the less likely it was that a maser would also be present, suggesting an evolutionary sequence of events where the maser switches on before the UC HII region forms, and is eventually destroyed after it does. As shown in Figure 1, many of the masers had no apparent source associated with them, which led to our beginning a program to search for such sources. Sub–mm observations at 450

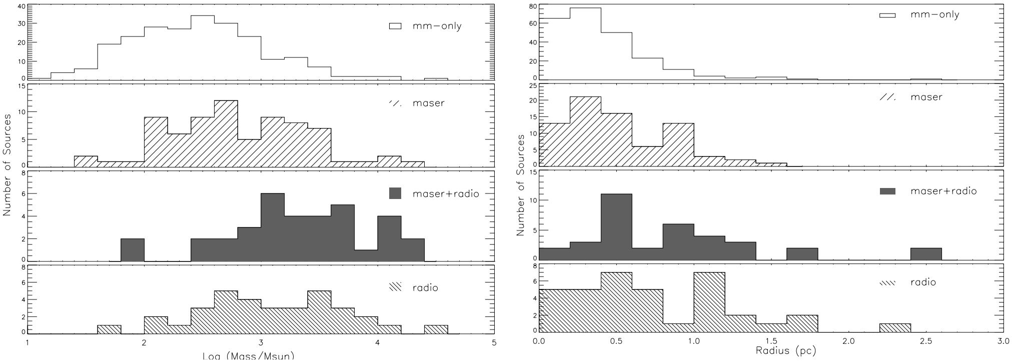

Figure 2. These two figures (from Hill *et al.* 2005) illustrate the masses (left) and sizes (right) for the mm-continuum cores found in the GMC-complexes originally targeted for their methanol maser emission. The histograms show the distribution of these quantities for four different categories of source: (i) those only identified by their mm-continuum emission, (ii) sources which in addition have methanol maser emission, (iii) sources which also have methanol maser emission and radio continuum emission from a UC HII region and (iv) mm-cores which have radio continuum emission but no methanol masers. The mm-only cores are clearly less massive, on average, than the other categories (although they extend over a similar mass range). The cores without radio emission are also, on average, smaller than those with radio emission. These results suggest that the mm-only cores are likely to consist of two classes of protostellar clusters. Firstly, there may be cold cores in the sample at an earlier evolutionary stage of massive star formation than those cores that have masers and/or UC HII regions, prior to the formation of the first massive stars in them. Secondly, there may also be cores in the sample which are not destined to form massive stars, even though they have sufficient mass to do so. If this latter case holds, it suggests that the maximum mass of a star is related to the mass of the core from which it forms.

and 850μm with JCMT/SCUBA (Walsh *et al.* 2003) found that a dust core was always associated with the methanol masers, and mapping around these cores at 1.2 mm with SEST/SIMBA (Hill *et al.* 2005) showed this often was just one (though also often the brightest) of several mm-emitting cores in a GMC–complex.

These cores were massive (many tens to a few thousand solar masses), and intriguingly those cores only identified in the mm continuum were, on average, less massive than those associated with other tracers of MSF, such as masers and UC HII regions (see Figure 2). Are the “mm-only” cores those which will form lower mass stars, or do they represent cores at an earlier evolutionary stage? Perhaps both categories of cores are present in the sample?

Few hot molecular cores had been identified when we began our investigation, and those that were known were invariably near UC HII regions (e.g. Kurtz *et al.* 2000), suggesting they may be externally heated. However, the isolated methanol masers we had identified called into question this interpretation, and so we began a survey with the Mopra telescope to search for evidence for hot molecular cores associated with these isolated masers (see Figure 3). Clear evidence for CH_3CN emission associated with many of these sources was found (though not for all), suggesting that indeed internal heating sources were present (Purcell *et al.* 2005), presumably in the dust cores that the millimetre continuum observations found. Our molecular line survey sought to also find chemical clocks, in order to identify the stage of star formation a particular core may be at. As Figure 3 shows, CH_3CN emission appears to switch on during the HMC phase, and grow in intensity after the UC HII region forms. The cores themselves have typical gas temperatures of a few tens of Kelvin, and are generally luminous enough for HII regions

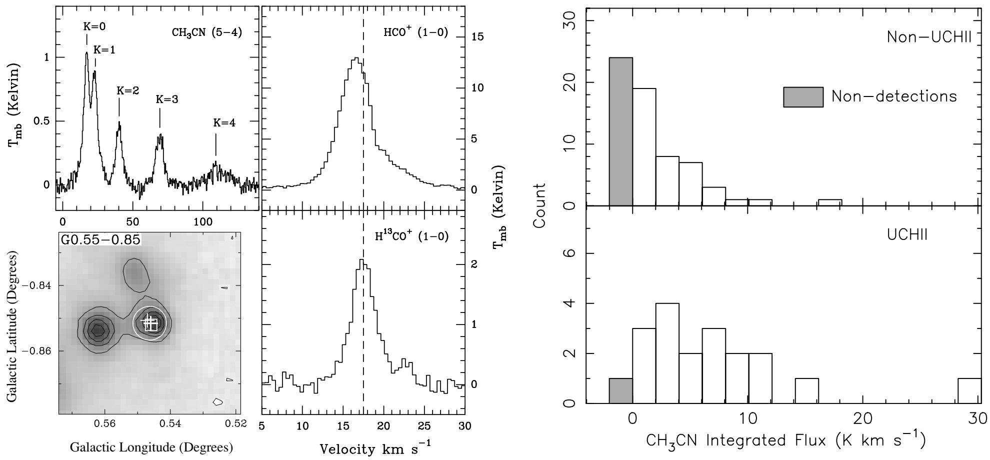

Figure 3. In order to understand the nature of the isolated methanol masers (i.e. those devoid of radio continuum emission in the Walsh *et al.* survey), we undertook a molecular line survey with the Mopra 22 m mm-telescope to search for evidence of an associated hot molecular core, through the presence of CH_3CN line emission at 92 GHz (Purcell *et al.* 2005). This molecule, thought to be formed following the evaporation of ices from grain mantles, was found associated ∼70% of the maser sources examined. The survey is illustrated in the figures here. The left hand figure is for a representative source, G0.55+0.85, with the image showing 21μm MSX emission arising from three cores, the central one also containing a methanol maser (cross) and UC HII region (square). We targeted this core with the Mopra telescope for our molecular line survey. The spectra for three lines, CH_3CN, HCO^+ and $H^{13}CO^+$, are shown. The CH_3CN rotational spectrum arises from gas at ∼60 K. However, such hot core emission was found to be more common and brighter in the presence of an UC HII region than when one was absent, as the figure to right illustrates. This is a histogram of the flux of the CH_3CN emission for sources without, and with, UC HII regions (it is also not biased by the distance of the sources, though this is not apparent from this figure alone). Other molecular lines measured did not show any obvious distinction between maser sources with and without UC HII regions. While CH_3CN emission almost certainly begins before the UC HII region has turned on, and indeed will be terminated by the expansion of the UC HII region, the larger emitting volume of warm gas outside the UC HII region likely results in the stronger CH_3CN emission from these sources. CH_3CN is also showing its utility as a chemical clock, signposting a part of the hot core phase of star formation.

to be expected to form within them at some stage if they do harbour natal protostars (see Figure 4).

It is of great interest to probe the mass function of the protoclusters that are presumably forming within many of the cores, and this is now possible through mid–IR imaging on 8 m class telescopes such as Gemini. This provides both the sensitivity to find the brightest sources and the spatial resolution to probe scales down to ∼1000 AU. In Figure 5 we illustrate the first results of such a study (from Longmore *et al.* 2005). A few sources dominate the mid–IR flux, whose SEDs rise steeply to longer wavelengths. Close to the peak of the dust emission and the methanol masers there invariably seem to be multiple sources, with separations on the order a few thousand AU (though it is not clear whether they are gravitationally bound). The mass distribution in the centre of these protoclusters clearly cannot be Salpeter-like.

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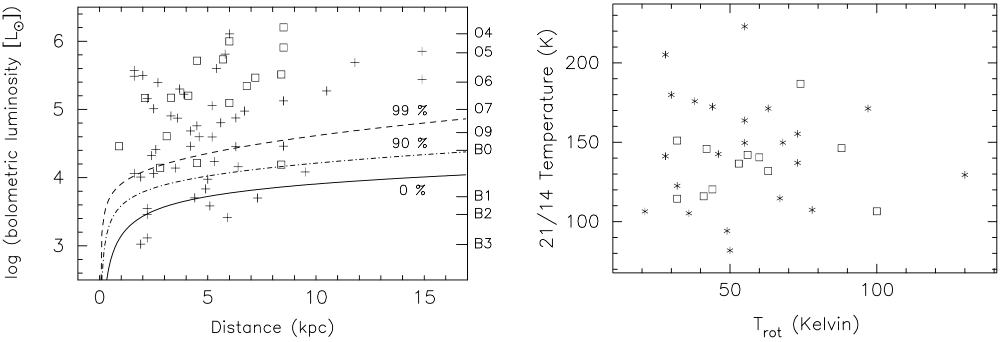

Figure 4. The figure to left illustrates that the hot core sources examined by Purcell *et al.* almost certainly are harbouring massive stars that will produce HII regions, even though many do not show evidence of radio continuum emission as yet (it remains to be examined whether they may harbour HCHII regions). Plotted is the estimated bolometric luminosity (and spectral type if assumed to come from a single star) of the cores, as a function of their distance. Crosses show sources where only methanol maser emission was detected in the Walsh *et al.* survey, and squares sources where 8.67 GHz radio continuum was also seen. Overlaid are the thresholds for the latest type of star that could have been detected, as a function of distance, derived from the 8.67 GHz detections limits, and assuming none, 50% and 99% of the Lyman-continuum photons are absorbed by dust within the source. The majority of sources with methanol masers clearly are luminous enough to be expected to produce HII regions. The figure to right illustrates the range in temperatures for the hot cores found, from 30–130 K, based on the CH_3CN rotational temperature. It is plotted against the mid–IR colour temperature. The colour temperatures (∼100–200 K) are generally somewhat warmer than the gas temperatures, but no correlation between these two temperature indicators is evident (the colour temperature, however, is also likely to reflect the optical depth at 14 and 21μm). Nor do sources with masers only (stars) distinguish themselves from sources that also have UC HII regions (squares) in this plot.

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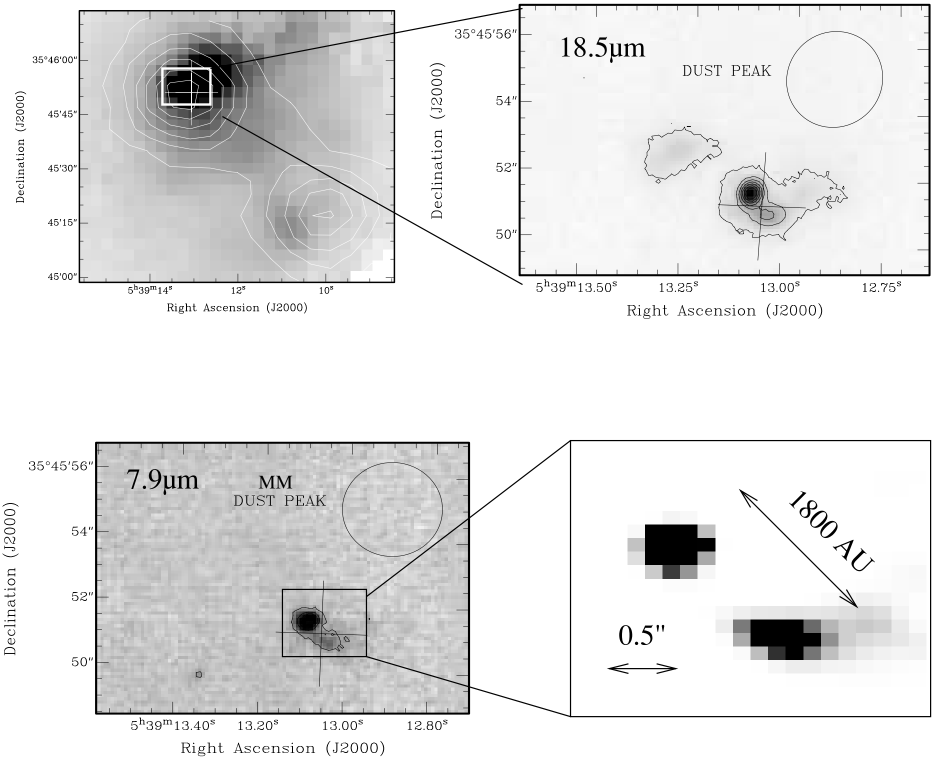

Figure 5. This series of figures illustrates how high spatial resolution imaging in the mid–IR is allowing the protostellar content of the mm-dust cores to be assessed. The figures show the source S231–IR (G173.49+2.42), which featured as the cover illustration of the last IAU Symposium in this field (IAU Symposium 221 *Star Formation at High Angular Resolution*). At top left, the 450μm image (JCMT/SCUBA) is overlaid by 21μm contours (MSX) (from Minier et al. 2005), showing a dust core centred on a methanol maser (cross). This core, 1.8 kpc away, has a mass of $\sim$120 $M_\odot$ and luminosity of $\sim 5 \times 10^4$ $L_\odot$, coming from a 0.1 pc diameter mm-emitting region at $T_{\rm dust} \sim 50$ K. Diffraction limited images in the mid–IR from Gemini at 18.5 and 7.9μm are shown in the next two panels (Longmore *et al.* 2005), achieving 0.4″ resolution. The infrared emission predominantly arises from a few, barely resolved and extremely red sources (whose SEDs peak at longer wavelengths). The final panel is a deconvolved image of the brightest source, close to the methanol maser position, showing three sources with a projected separation for the brightest two of just 1,800 AU. Each of these sources is estimated to have luminosities of $\sim$300 $L_\odot$ and masses $\sim$4 $M_\odot$, based on their colour temperatures. In the three methanol maser-selected sites we have so far studied in this way, protostellar multiplicity similar to this is evident. Massive, multiple sources, close to both the dust emission peak and to the methanol masers, are found. It cannot yet be determined, though, whether the individual sources are themselves gravitationally bound. By considering the likelihood that these stars could have arisen from a standard initial mass function, it is clear that the top-end of the mass distribution in these protoclusters cannot follow a Salpeter-like law.