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# Massive star-formation studies with GLIMPSE

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**Abstract.** The infrared counterparts (IRC) of high mass protostellar objects are studied primarily with the Spitzer Space Telescope (SST), and also, with other infrared observations. The IRCs are examined for clustering to investigate the sequence of low and high mass star formation. The spectral energy distributions of the IRCs are modelled using a grid of radiative transfer models to obtain physical parameters of the putative massive protostars. We review the above studies and present some new findings of the relation between source properties and outflow properties.

*Keywords* : stars: formation – infrared: stars, ISM

## 1. Introduction

The formation of massive stars (Zinnecker & Yorke 2007) is not a well understood phenomenon because of observational limitations to examine the distantly located, highly extinct, and rapidly forming, massive stars. The Kelvin-Helmholtz timescale is comparable or shorter than the nuclear burning time scale for a massive protostar, making it a complicated theoretical problem. Consequently, multiple scenarios have been suggested; such as the formation of massive stars on the zero-age-main-sequence (Bernasconi & Maeder 1996), through coalescence of lower mass stars (Bonnell, Bate & Zinnecker 1998) or via rapid accretion (Krumholz, McKee & Klein 2005). Observational evidences are crucial in evaluating these scenarios, thus making the studies of massive star-formation an important goal of much of modern day ground and space based observational facilities.

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High-mass protostellar object (HMPO) candidates are identified by choosing luminous far-infrared sources (IRAS sources) with colours similar to the colours of ultra-compact HII regions (Palla et al. 1991), and using various other sign-posts of massive star-formation such as association of masers and dense molecular gas (Molinari et al. 1996). A subset of such sources without significant radio-continuum emission (indicative of ionized gas) have been targets of many studies in the past decade (Sridharan et al. 2002; Beuther et al. 2002a). HMPOs have been studied by making use of far-infrared and millimeter observations, that, in general, lack the spatial resolution to resolve single cores or central stars (Beuther et al. 2002a; Fontani et al. 2002; Faúndez et al. 2004; Fuller, Williams & Sridharan 2005). The Spitzer Space Telescope (SST) provides an excellent spatial resolution of $\sim 1''$in the $3.6\,\mu$m–$8.0\,\mu$m bands and a sensitivity that is superior to most previous ground and space missions. This is an excellent opportunity to probe in detail the HMPO candidates and pinpoint the massive protostars. In this article, we will review some of our recent and on-going studies of the massive protostellar candidates using the SST, in particular, exploiting the GLIMPSE legacy survey data. We have extensively used the 2MASS, IRAS and MSX point source catalogs and millimeter surveys from literature to supplement the Spitzer observations.

## 2. Clustering around massive protostars

The HMPO candidates selected by FIR and radio surveys are luminous point-like sources as detected by the relatively large FIR and millimeter beams of $10''$–$60''$. At the typical distances of 3–5 kpc at which they are located, they represent dense cores with spatial dimensions of 0.1–1 pc. Star-formation in such dense cores can not only give rise to massive stars but also a cluster of low-mass stars, as we know from well-studied near-by examples such as the Orion nebula cluster. Using the 2MASS point-source catalogs, Kumar, Keto & Clerkin (2006) examined the HMPO candidates for the presence of clustering. Embedded clusters were identified as density enhancements of near-infrared excess stars associated with the HMPO targets. 54 embedded clusters were found associated with 217 HMPO targets, of which, 34 were new detections. Most of the identified clusters are associated with HMPO targets that are located away from the Galactic mid-plane. The detection rate of roughly 25% is attributed to the insensitivity of the 2MASS data to probe into the densest HMPO cores located in the Galactic mid-plane. Nevertheless, the discovery of embedded clusters associated with the HMPO candidate sources suggested a sequence for the formation of low and high mass stars in a clustered environment. Assuming that low-mass star formation lasts for about 1 Myr which is roughly ten times the time-scale of massive star-formation, the above result implied that at least one generation of low-mass stars had formed prior to the formation of a massive star.

A larger sample of 380 HMPO targets, including those that are located in the Galactic mid-plane were examined for clustering using the GLIMPSE data by Kumar & Grave (2007). Contrary to the findings of Kumar, Keto & Clerkin (2006), this search only uncovered the infrared-counterparts (IRC) of the HMPO targets and did not find any embedded clusters. The non-detections are argued to be due to two reasons: a) low-mass young stars have relatively less emission at mid-infrared wavelengths as opposed to near-infrared wavelengths, and, b) the insensitivity of the shallow (2 sec exposure) GLIMPSE survey. These interpretations have been more rigorously substantiated by detailed studies of individual targets such as IRAS 19343+2026 (Ojha et al. 2010). Nevertheless, the identification of the IRCs to HMPO targets found in the Galactic mid-plane resulted in the first, large sample of such point-like sources at $1''$ spatial resolution.

## 3. Infrared-counterparts of massive protostars

The IRCs to HMPO candidates identified by the GLIMPSE survey constitute point-like sources detected in the Spitzer-IRAC bands at a spatial resolution of $\sim 1''$. At typical distances of 3–5 kpc these point sources represent physical dimensions of 3000-5000 AU. They typically represent single massive stars, or, in the worst case scenario doubles or a few multiple stars. However, they do not represent embedded clusters. The IRCs associated HMPO candidates displayed extremely red colours and high luminosities (Kumar & Grave 2007). The spectral indicies of the IRCs in the Spitzer-IRAC bands were found to be more steeper than many embedded sources in the Orion nebula or IC348, confirming that the identified IRCs are deeply embedded objects. Together with their central location on the FIR/MM cores, they constitute a unique sample of isolated young massive stars, to conduct detailed studies of their physical properties. In order to do so, it is essential to construct a fairly extended spectral energy distribution (SED) of the individual sources. For a total of 68 IRCs, it was possible to construct the SEDs extending from the near-infrared J, H, K bands (using 2MASS data) to the millimeter range (using surveys of HMPOs from literature: Beuther et al. 2002a; Fontani et al. 2002; Faúndez et al. 2004; Fuller, Williams & Sridharan 2005). A radiative transfer model grid is widely used in recent days (Robitaille et al. 2006) to characterise the SEDs of young stellar objects. This grid of models assumes an accretion scenario including a stellar photosphere, disk, envelope and a bipolar cavity, all under radiative equilibrium. The grid is thought to be effective in modelling the SEDs of young stellar objects upto $20 M_\odot$ and valid upto a range of $50 M_\odot$. A SED fitting tool (Robitaille et al. 2007), made available online can match the observed data to models in the grid by scaling them appropriately to the observed data. Using this tool, we conducted the radiative transfer modelling of the SEDs of 68 IRCs to obtain estimates of the physical properties of the star, disk and envelope (Grave & Kumar 2009; Grave 2009). Fig. 1 displays

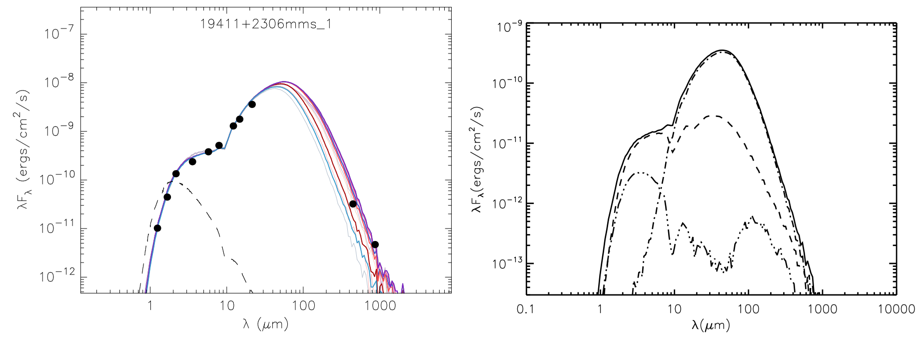


**Figure 1.** (*left*) An example of SED modelling. The solid line shows the best fit model of the target IRAS19411+2306mms_1 and the group of grey lines represent models with ${\chi^2}_{best} - \chi^2 < 3$. Filled circular symbols represent the data points. The dashed line corresponds to the stellar photosphere used in the best YSO model fit. (*right*) Decomposition of the best fit model for the source 19411+2306mms_1. The full line represents the total flux of the source, the disk flux is represented by the dashed line, the envelope flux by the dot-dashed line and the scattered flux by the three dot-dashed line.

an example of the SED modelling and the decomposition of the best fit model into individual contributions. See the figure caption for explanations. We find that the detected IRCs can be modelled as accreting massive stars in the mass range between 5-40$M_\odot$, and age between $10^3$–$10^6$ yr. However, the effective temperatures are low (in the range 4000-10 000 K) with correspondingly large radii (2–200$R_\odot$), thus, implying bloated protostars. The envelope accretion rates are found to be high with a mean value of $10^{-3}$ $M_\odot$/yr. The results indicate the presence of disks in most cases, but the envelope and disk emission can not be clearly separated, therefore making it impossible to ascertain the presence of disks. Nevertheless, other studies (Bik & Thi 2004) based on different type of observations have shown the presence of disks around massive stars.

## 4. Comparing the properties of massive protostars and their outflows

If massive stars form via rapid accretion as predicted by some theoretical scenarios, one of the important signatures of the accretion process are the molecular outflows. In the case of low-mass stars, it is known that the outflow mass increases with the luminosity of the driving source and decreases with the age of the driving source. Beuther et al. (2002b) mapped several massive molecular outflows from known HMPO candidates. We looked for the IRCs associated with the outflow targets using the SST data and found good driving

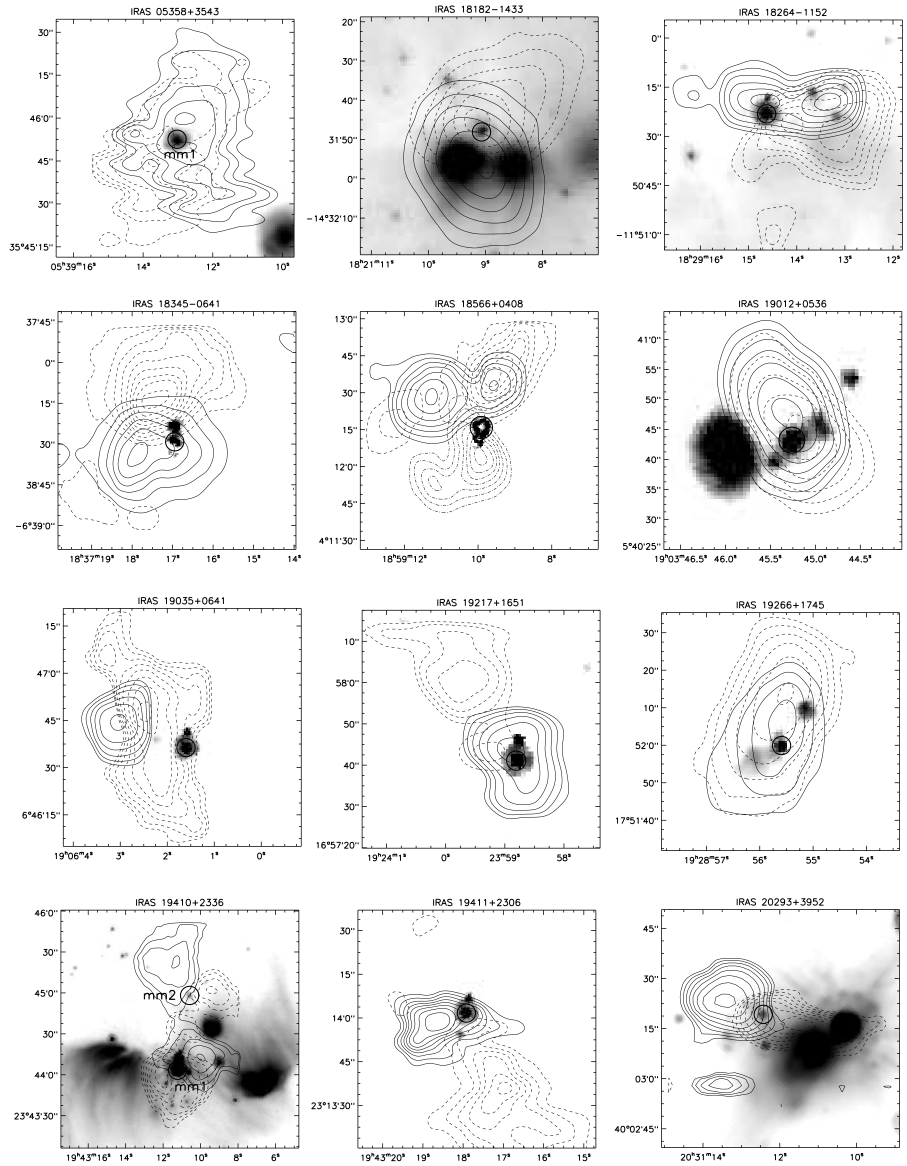


**Figure 2.** The driving engines of massive molecular outflows shown for a sample of 12 targets. Spitzer-IRAC 8 $\mu$m images are represented by grey scale. The CO outflow data from Beuther et al. (2002b) is shown using dashed (red-shifted lobe) and solid (blue-shifted lobe) contours. Black circles mark the IRC's modelled as driving engines.

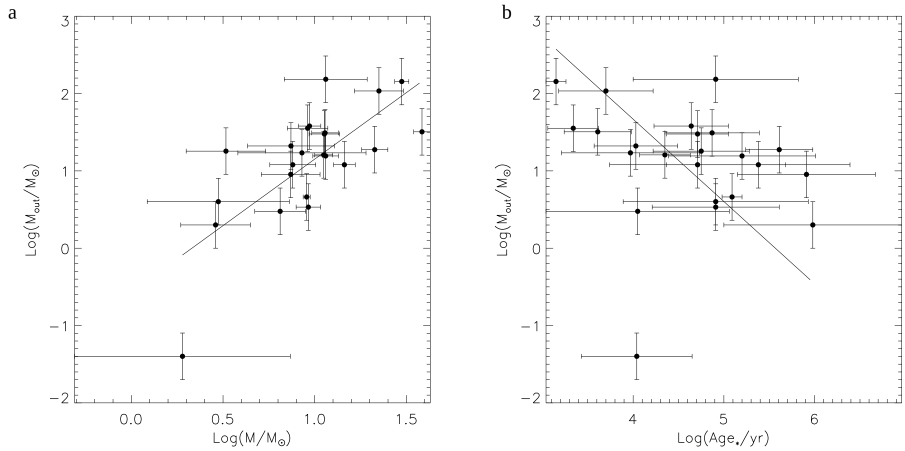


**Figure 3.** a) Outflow mass plotted against the modelled stellar mass. b) Outflow mass against stellar age.

source candidates for 21 outflows. A sample of 12 targets are shown in Fig. 2 to demonstrate how well, the identified red-excess IRCs coincide with the 12CO outflow maps. The SEDs of these IRCs were modelled in the same ways as described in the previous section and physical parameters of the star, disk and envelopes were obtained. The resulting mass and age of the massive-star is compared with the mass of the outflow. In Fig. 3 we show these comparisions which show power-law relations those are similar to the relations obtained in the case of low-mass stars. Here, we compare the outflow mass with the stellar mass rather than stellar-luminosity. The results presented in Fig. 3 are a good indication that massive stars may form via accretion similar to low-mass stars. However, the exact nature of the accretion mechanism may be different in the two cases which can not be proven with the presented analysis.

## 5. Conclusions

Infrared observations from the Spitzer Space Telescope, 2MASS and other surveys were used to study high-mass-protostellar objects in some detail. Clustering is found around HMPO candidates leading to the suggestion that low-mass stars form prior to high-mass stars in a clustered environment. The GLIMPSE survey data was used to identify IRCs to HMPOs pin-pointing massive-stars in the formation process. These young stars were modelled using a grid of radiative transfer models in the frame-work of accretion. The observed infrared-millimeter SEDs of the IRCs are well represented by single massive stars with mass in the range 5-40$M_\odot$ . High accretion rates are deduced from modelling. Bloating of the (proto)-stars is suggested with low effective temperature photospheres. A subset of HMPOs, known to show massive molecular outflows were studied. Comparing the properties of the driving engines with that of the outflows indicate that massive stars should form via accretion, similar to the way low-mass stars form. The detailed mechanism, however, can be significantly different and warrants further studies.

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