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The SOFIA Massive (SOMA) Star Formation Survey and the open-source python package sedcreator.

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Abstract

Massive stars have dramatic impacts throughout the universe at different scales and are one of the reasons you are reading this abstract today. But their birth, deep within dusty molecular clouds, is literally shrouded in uncertainty. The formation of massive protostars is still an open question and there is still a lot to be understood. Theories range from Core Accretion, i.e., a scaled-up version of low-mass star formation, to Competitive Accretion at the crowed centres of forming star clusters, to Stellar Collisions. The SOMA survey aims at understanding the basic formation mechanisms governing massive stellar birth through multi-wavelength observations but also through radiative transfer (RT) modelling of their spectral energy distributions (SEDs).

Here I present the current status of the SOFIA Massive (SOMA) Star Formation Survey for which more than 40 sources have been observed in the mid-infrared with SOFIA/FORCAST and that have been combined with Spitzer and Herschel observations. These data were used to construct SEDs and to fit a grid of RT models. To do this, we used the open-source python package sedcreator which is also presented to the community. This package includes a number of convenient tools to measure fluxes on any astronomical image and to fit to a set of models. We find evidence that relatively massive protostars can form across a range of clump mass surface density environments, which contradicts some models for the required conditions of massive star formation. However, we see a trend that to form the most massive protostars, i.e., $m_* > 25\,M_\odot$, the mass surface density ($\Sigma_{\rm cl}$) needs to be $> 1\,{\rm g\,cm^{-2}}$. Our favoured explanation for this result is the Turbulent Core Accretion model prediction that the star formation efficiency of a core due to internal protostellar feedback is higher in higher $\Sigma_{\rm cl}$ environments.

1 Introduction

Massive stars are fundamental in driving the evolution of galaxies. Their strong radiation, winds, and supernovae impact their surrounding environments, including protoplanetary disks around lower-mass stars that are forming in the same protocluster. In spite of their importance, there are many open questions about the origins of massive stars, including the basic nature of their formation mechanism, e.g., whether it is a scaled-up version of the standard core accretion theory [1] or whether it requires a more chaotic, competitive accretion in the centre of a dense protocluster of low-mass protostars [2, 3].

The *SOFIA* Massive (SOMA) Star Formation Survey (PI: Tan) aims to characterise a sample of > 50 high- and intermediate-mass protostars over a range of evolutionary stages and environments with their ~ 10 to $40\,\mu$m emission observed with the *SOFIA*-Faint Object infraRed CAmera for the *SOFIA* Telescope (FORCAST) instrument [4]. These SOFIA observations have been complemented with Spitzer and Herschel archival data to have a wavelength coverage from ~ 3 to $\sim 500\,\mu$m. In Paper I of the survey [5], the first eight sources were presented, which were mostly massive protostars. In Paper II [6], seven additional high luminous sources were presented, corresponding to some of the most massive protostars in the survey. In Paper III [7], 14 intermediate-mass sources were presented and analysed. Here in Paper IV in the series [8], we present 10 regions that harbour a total of 11 sources, selected based on the nature of their environment, i.e., appearing to be relatively *isolated* in $37\,\mu$m imaging.

2 Methods

We have introduced a number of new and updated analysis methods to analyse efficiently the SOMA sources. The main update is the release of `sedcreator`, which is an open-source python package hosted in GitHub (https://github.com/fedriani/sedcreator) and the documentation can be accessed at this URL https://sedcreator.readthedocs.io/. The main two sets of tools of `sedcreator` are encapsulated into *SedFluxer* and *SedFitter*. *SedFluxer* helps one construct an SED by providing tools to measure fluxes on a given image. *SedFitter* fits an SED with massive star formation radiation transfer model grid by [9].

Figure 1: Logo for sedcreator python package.

3 Main results

We used sedcreator/SedFluxer to measure the fluxes at wavelengths 3.6, 4.5, 5.8, and $8.0\,\mu$m from Spitzer/IRAC; at 7.7, 19.7, and 31.5, and $37.1\,\mu$m from SOFIA/FORCAST; and at 70, 160, 250, 350, and 500 μm from Herschel /PACS and SPIRE. We note that not all bands were available for all sources. We then used sedcreator/SedFitter to fit the measured fluxes to the [9] model grid. In this section, we highlight the main findings.

The 11 *isolated* protostars analysed in this work span a wide range in bolometric luminosity, i.e., $\sim 10^2 - 10^5\, L_\odot$. Fitting the SEDs with the RT models, we obtain protostellar masses ranging from $m_* \sim 3 - 50\, M_\odot$, which are accreting at rates of $\dot{m}_{\rm disk} \sim 10^{-5} - 10^{-3}\, M_\odot\, {\rm yr}^{-1}$ from cores with initial masses $M_c \sim 20 - 430\, M_\odot$ and in clump environments with mass surface densities ranging $\Sigma_{\rm cl} \sim 0.3 - 1.7\, {\rm g\, cm}^{-2}$. The SOMA IV sub-sample complements the full SOMA sample and adds some of the most massive protostars in the survey. Figure 2 left panel summarises the three main physical parameters in the SED fit, i.e., core mass, mass surface density of the clump, and protostellar mass ($M_{\rm c} - \Sigma_{\rm cl} - m_*$) for all SOMA sources analysed so far. Figure 2 right panel shows the values of m_* versus $\Sigma_{\rm cl}$ for the SOMA survey sample to date. One can see how the most massive protostars, i.e., with $m_* > 25\, M_\odot$, tend to be concentrated in the higher $\Sigma_{\rm cl}$ region of parameter space. The fiducial condition for massive star formation from [10] is that one needs $\Sigma_{\rm cl} \sim 1\, {\rm g\, cm}^{-2}$ to form stars with $> 10\, M_\odot$ (red line). The prediction is that massive protostars should only be found on the right of this line, i.e., which defines a minimum $\Sigma_{\rm cl}$ for high-mass star formation. We see that the SOMA results are inconsistent with this, i.e., there are numerous massive protostars that appear to be forming in conditions with $\Sigma_{\rm cl} \ll 1\, {\rm g\, cm}^{-2}$.

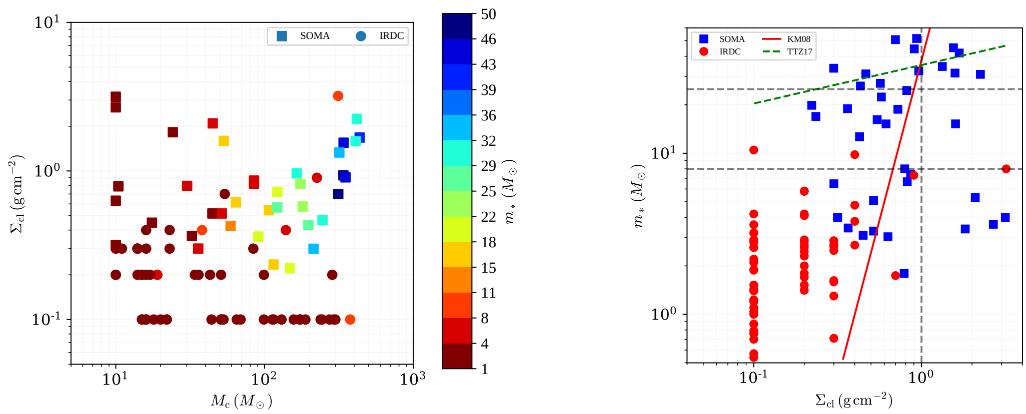

Figure 2: Left: Mass surface density of the clump environment ($\Sigma_{\rm cl}$) versus initial mass of the core ($M_{\rm c}$) for the full SOMA sample to date and the IRDC samples. Each data point is the average of good model fits. Each point is also colour coded with current mass of the protostar (m_*). Right: m_* versus $\Sigma_{\rm cl}$ for the 40 SOMA sources of Papers I to IV and IRDC sources. The red solid line shows the fiducial prediction of [10] for the minimum $\Sigma_{\rm cl}$ needed to form a star of given mass m_*. The green dashed line is results for the final stellar mass formed from 100 $M_\odot$ prestellar cores as a function of $\Sigma_{\rm cl}$ [11].

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