Massive star formation remains an important unsolved problem in astrophysics. A detailed multi-wavelength comparison between theoretical models and observations of massive protostars will help advance our understanding of the massive star formation process. Here we present results of the SOFIA Massive (SOMA) star formation survey, which aims to build up a sample of ~50 massive and intermediate-mass protostars in a range of different environments that are observed across MIR and FIR bands to test theoretical models of massive star formation. We build the spectral energy distributions (SEDs) of massive and intermediate-mass protostars observed with SOFIA-FORCAST from ~10 to 40 μm together with archival Spitzer and Herschel data and other ground-based IR data. Radiation transfer (RT) models of Zhang & Tan (ZT, in prep.), which are based on the Core Accretion scenario, including outflow cavities driven by MHD disk winds, are then fit to the SEDs. As a comparison, we also fit the SEDs with the widely used Robitaille et al. (2007) models. We examine to what extent these simple, symmetric core accretion models can fit these protostellar sources and the different results that are obtained by using different model grids.

1. Introduction

Massive stars impact many areas of astrophysics, yet there is still no consensus on how they form. One possible scenario is the Turbulent Core Accretion model (McKee & Tan 2002, 2003), which may involve relatively ordered, monolithic accretion via a central disk and the driving of collimated bipolar outflows. Outflows may limit the formation efficiency since they expel material along polar directions. The results from outflow cavities have been proposed to significantly affect the appearance of the protostar in the mid-IR (MIR) (De Buizer 2006) and this is seen in the RT calculations using the RT code.

2. SOFIA Massive (SOMA) Star Formation Survey

The SOFIA Massive (SOMA) star formation survey aims to obtain ~10 to 40 μm images of a statistically significant sample of about 50 high- and intermediate-mass protostars over a range of evolutionary stages and then compare the observed SEDs and image intensity profiles with theoretical models. MIR to FIR SOFIA-FORCAST observations have been carried out in Basic Science and Cycles 1-4. The MIR emission is expected to be a powerful tracer of heated dust in protostellar outflow cavities (De Buizer 2006; Zhang et al. 2013). 15 sources have been observed and 8 more are expected to be completed by the end of Cycle 4.

3. SED Fitting with RT Models

We build spectral energy distributions (SEDs) of the first eight sources in the SOMA survey from 3.6 μm up to 500 μm with photometric data of Spitzer, IRTF, Gemini, SOFIA, and Herschel. We use PHOTUTILS, a PYTHON package to measure the flux photometry. Then we fit the fiducial SEDs (with fixed aperture and without background subtraction) with both ZT (in prep.) RT models (see Figure 1) and Robitaille et al. (2007) RT models. The fitting results are shown in Figure 2. The key parameters of the best fitting models are listed in Table 1. Table 2 shows the best 5 ZT models of G35.20-0.74 as an example to illustrate the fitting preference and the variation in all model parameters.

We also explore the effect of aperture size and background subtraction on SED fitting. We show the fitting results of AFGL4029 with ZT models as an example in Table 3.

4. Conclusions and Future Work

The 8 sources tend to show extended MIR emission that aligns with known outflows, and being brighter on the near-facing, blue-shifted side, which are predictions of Turbulent Core Accretion models.

The fiducial SEDs have been used to constrain theoretical RT models of massive star formation in the Turbulent Core Accretion model. These yield protostellar masses $M_\star \sim 10-30 M_\odot$ accreting at rates of $\dot{M}_{\text{acc}} \sim 10^{-7}-10^{-5} M_\odot/\text{yr}$ inside cores of initial masses $M_\star \sim 30-500 M_\odot$ embedded in clumps with mass surface densities $\Sigma \sim 0.1-3 \text{g/cm}^2$.

Robitaille et al. (2007) model grid trend to give much lower disk accretion rates than ZT models: typically ~100 times smaller. In some cases, the models do not require any disk component.

Future work will present additional sources (see Figure 3). Additional analysis that examines and models flux profiles along outflow cavity axes will be carried out, following methods developed by Zhang et al. (2013b). Ancillary observations that trace the outflowing gas will also be presented.