A Grid of YSO Models and a Model Fitter

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The Model Grid

The Spitzer Space Telescope is producing a wealth of data on star formation regions. The *GLIMPSE* (Galactic Legacy Infrared Midplane Survey Extraordinare) survey alone combined with 2MASS will provide 1-8 micron data on thousands of star formation regions in the inner Galactic plane. To help interpret these and other datasets, we have calculated a grid of 2000 protostar models using 2-D radiative transfer codes (Whitney et al. 2003a,b,2004b). Our grid and fitter (described at right) are designed to to find all the Young Stellar Objects (YSOs) in a field and determine their evolutionary state, from the earliest embedded protostars surrounded by infalling envelopes, accretion disks and narrow bipolar cavities (Class 0) to the less embedded protostars (Class I), through the envelope dispersal stage leaving a pre- or main sequence star surrounded by a proto-planetary disk (Class II), to the disk dispersal stage (Class III). The models have stellar masses ranging from 0.1 - 40 solar masses and temperatures between 2500 - 42000 K. The stellar ages range between 10^4 - 10^7 years to simulate the time evolution of the YSOs. Also included are ambient models which are stars surrounded by different amounts of constant density dust to simulate stars in molecular clouds.

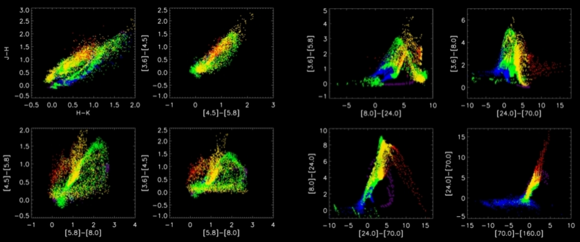


Figure 1 (above): Color-color plots of the entire model grid. The models have been separated into evolutionary state using the following criteria:

Class 0: $\dot{M}_{env}/M_{star} > 10^{-5}\ M_{sun}/yr$

Class I: $10^{-5} > \dot{M}_{env}/M_{star} > 5x10^{-8}\ M_{sun}/yr$

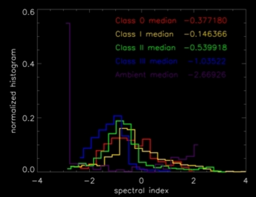
Class II: $\dot{M}_{env}/M_{star} < 5x10^{-8}\ M_{sun}/yr$ and $M_{disk}/M_{star} > 5.x10^{-5}\ M_{sun}$

Class III: $M_{disk}/M_{star} < 5x10^{-5}\ M_{sun}$

Ambient Density: $\rho_{ambient}$=$3.34x10^{-21}$ to $3.34x10^{-20}$ kg/m^3

Notice how blue some of the Class 0 models are. This is due to the dominance of scattered light at these wavelengths in these sources. Furthermore, Figures 1 & 2 do not include foreground extinction which is likely to be higher for Class 0 sources, since these are the most deeply embedded objects. The four color-color plots on the right show how the evolutionary states separate more distinctly when longer wavelength points are included (24μm, 70μm and 160μm)

Figure 2 (right): Spectral Index histograms, (slope of the spectrum at 3.6 -8μm) of the model grid. No foreground reddening has been added. The spectral index is expected to decrease with age. Notice, however, that the Class I median value is larger than the Class 0. The Class 0 models are dominated by scattered light at these wavelengths which has a "blueing" effect on the spectrum.



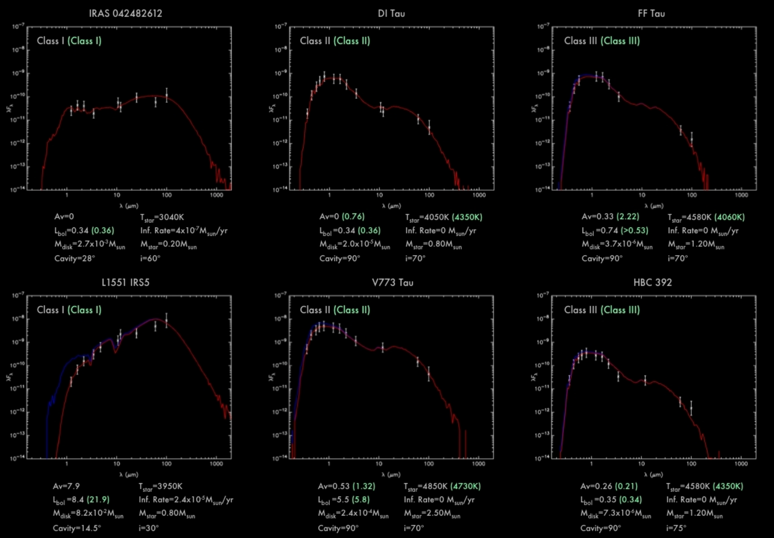
The range of parameters in the Model Grid

Stellar Mass	0.1-40 M_{sun}
Stellar Age	10^4-10^7 yrs
Envelope Infall Rate	10^{-4}-10^{-9} M_{sun}/yr * M_{star}
Disk Mass	10^{-1}-10^{-8} M_{sun} * M_{star}
Disk Radius	10-1000AU
Cavity Size	10-50 degrees
Aperture	1000, 5000, 20000 AU
Viewing Angles	10

The Model Fitter

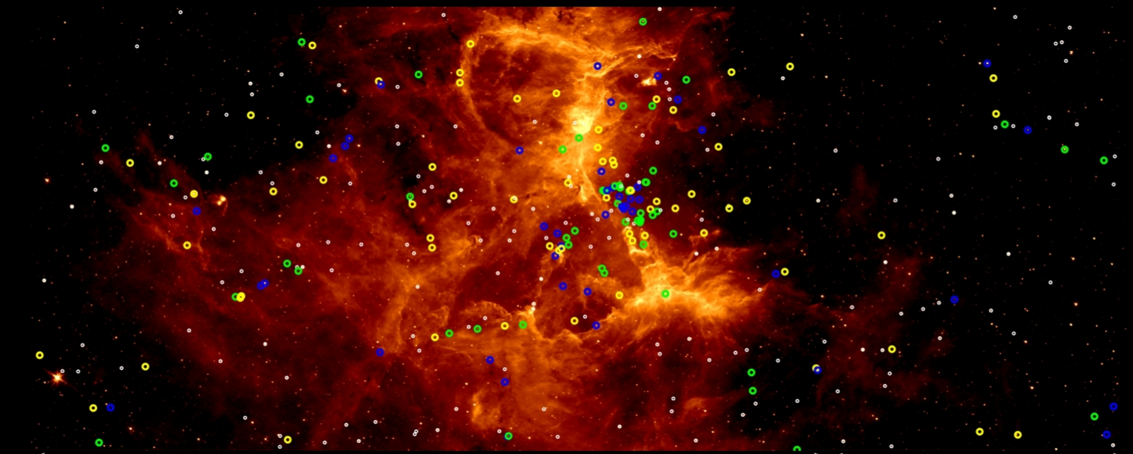
The model fitter uses linear regression to determine which models from the YSO grid best fit a source. Both a scaling factor (based on luminosity and distance) and an extinction value providing an optimal fit are determined for all the models in the grid. Stellar atmospheres have been added to the YSO grid to fit the large proportion of objects in a field of view that are likely to be foreground or background stars. The models are ordered according to the quality of the fit to the source. A range of acceptable scaling factors (e.g., a distance range for a cluster, if known) and extinction values can be specified as input parameters, and a tolerance level for the quality of the fits can also be specified. Statistics of the models that are within the tolerance level are then produced. The model fitter is designed to work with large numbers of sources (10^4-10^7) and has been tested with source catalogs from the *GLIMPSE* survey. We plan to expand the grid and make the model fitter web accessible.

The model fitter was tested on sources in the Taurus star forming region using data from Kenyon & Hartmann (1995) (KH95). In the following plots we present model fits to six selected sources. On all plots, the red line indicates the best fit, and the blue line indicates the same model without extinction. The values given are the parameters for the best fit, and the values in green are from KH95.



The model fits are in good agreement with the results from KH95. In their case the stellar parameters (T_{star}) and Av are better determined since they are based on optical spectra, information that was not included in the grid/fitter results. The major uncertainty in the grid/fitter luminosities are in the determination of the inclination, since the integrated flux varies by a factor of 4 depending on inclination (Whitney et al. 2003a). The L_{bol} results in KH95 suffer from the same uncertainty.

Large-scale model fitting - M16



"Star-Forming" Region

"Field" Region

The mosaic on the left shows the star forming region M16 at 7.8μm from the *GLIMPSE* survey, and covers a field of 1.33°x0.55°. The model fitter was used on this region, using 2MASS data (J, H and K bands), and *GLIMPSE* data from the four *IRAC* bands at 3.6μm, 4.5μm, 5.8μm and 7.8μm for 61078 sources.

In the whole field, 60746 sources were fit by stellar atmosphere models (fitting for luminosity/distance scale factor and extinction), representing 99.45% of all sources. 166 sources (0.27% of all sources) were very well fit by our YSO models. The class of the best fit for these sources is indicated on the mosaic as colored circles using the color convention defined in Figure 1. A further 63 sources were moderately well fit, and 109 were not well fit at all by any of our models. These two type of sources (0.28% of all sources) are shown by white circles on the mosaic.

We can look at the difference in statistics between the main "Star-Forming" and "Field" regions indicated below the mosaic. We find that in the star-forming region, 99.35% of sources are well fit by stellar atmospheres, whereas this number increases to 99.69% in the field region. The proportion of well fit YSOs in the star forming region is 0.34%, and this drops to 0.10% in the field region. The same decrease is observed for the moderately well fit YSO, with a drop from 0.13% to 0.04%, suggesting that these are in fact YSOs, but that we do not have the correct models to fit them. Finally, the proportion of remaining sources which are not well fit by any models is similar in both regions, with 0.18% in the star-forming region and 0.16% in the field region, indicating that these sources are probably not simply YSOs for which the models are missing, and are unrelated to star-formation.