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MODEL INFRARED SPECTRA FOR PROTO STARS [1]

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ABSTRACT

We have modeled the infrared spectral energy distributions of proto stars with close attention to the dust envelopes around the stars. The observed spectral energy distributions are closely compared with our models. The model results and observations are compared on *IRAS* color-color diagrams. Typical model results can explain the observations fairly well.

1. INTRODUCTION

Proto stars are generally considered to have thick dust envelopes around them. Depending on the evolutionary stage of the star, the physical structure of the dust envelope should be very different. As the stars evolve into main sequence, the structure of dust envelope changes. The dust envelopes become thinner, and the accretion disks become more prominent.

The main sources of interstellar dust grains are believed to be AGB stars. Oxygen rich silicate dust grains or carbon-rich dust grains form in the envelopes around AGB stars according to the chemical composition of the material. The dust grains expelled from AGB stars get mixed up and go through some amount of change in interstellar medium. Therefore, the chemical composition and the solid structure of the dust grains in the envelopes around proto stars are believed to be different from those in AGB stars.

The infrared spectral energy distributions (SEDs) of proto stars are modeled by a number authors with various methods and degrees of sophistication. Adams *et al.* (1987) made approximate analytic calculations to simulate the SEDs of proto stars. Recently, Miroshnichenko *et al.* (1997) made more exact numerical calculations for 6 Herbig Ae/Be stars.

In this paper, we have made model SEDs for proto stars. The model results are compared with observed infrared SEDs including *IRAS* data for 251 proto stars. Depending on the dust envelope and central star parameters, the results are very different.

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2. MODEL CALCULATIONS

For this paper, we have used the radiative transfer code developed by Ivezic & Elitzur (1997) for spherically symmetric dust shells. A fixed model parameter for the dust envelope is the wavelength dependence of the dust opacity. The inner boundary of the dust shell is determined from the dust temperature of 1500 K. The outer radius of the dust shell is always taken to be 10000 times the inner boundary. The radii of spherical dust grains have been assumed to be 0.1 μm uniformly. The adjustable input parameters are the dust optical depth at 0.55 μm ($\tau_{0.55}$) and the radial dust density distribution.

For the central star, a stellar black body temperature of 5000 - 10000 K is used for low temperature stars. And SEDs of the model atmospheres by Kurucz (1979) are used for high temperature stars. A change in the luminosity does not affect the shape of the output spectra, it only affects the overall energy output. A significant change in the blackbody temperature of the central star does affect the output spectra, especially for the models with optically thin dust shells. This is due to the fact that in optically thin dust shells the underlying energy distribution of the star strongly influences the emergent near infrared continuum.

Most of the radiative transfer models for AGB stars assumed a smoothly distributed spherically symmetric dust shell with a power law description of the radial density distribution. The dust density distribution have been most often taken to be inversely proportional to the square of the distance, as would be expected for the constant velocity winds found in AGB stars. But for proto stars, the density distribution is believed to be less steep. We assume a continuous $r^{-1.3}$ density distribution for our model calculations.

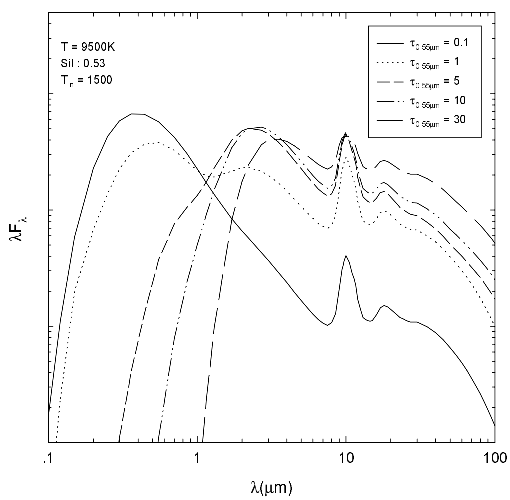

Figure 1. Typical model results with different optical depths.

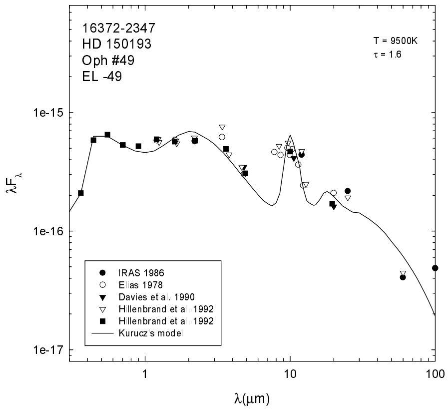

Figure 2. Model results compared with observations of HD 150193.

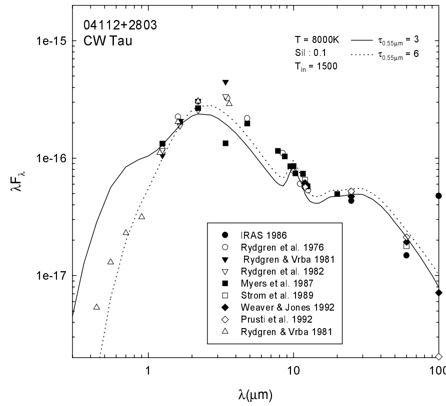

Figure 3. Model results compared with observations of CW Tau.

2.1. Dust Opacity Functions

For given characteristics of the dust material (the optical constants, the size, and the shape) the absorption and scattering efficiency factors can be calculated at any given wavelength (*e.g.*, Bohren & Huffman 1983). The optical constants of the dust grains in AGB stars are probably different from that obtained from laboratory measurements of terrestrial or meteoritic material. It is also clear that interstellar grains might be strongly modified by chemical and physical processing after their expulsion from AGB stars. For silicate dust grains, we have used the optical constants from Ossenkopf *et al.* (1992). For carbon-rich dust grains, we find that graphite is more appropriate for proto stars than amorphous carbon which is widely used for AGB stars. We have used the optical constants from Draine & Lee (1984) for graphite dust grains.

2.2. General Model Characteristics

Figure 1 shows the results for a series of models the same dust opacity (silicate 53% and graphite 47%) and central stellar blackbody temperature (9500K) with various optical depth ($\tau_{0.55}$ = 0.1 - 30). All models show the prominent 10 μm silicate emission feature which is often shown for many proto stars. As the optical depth gets lower, the shape of model SED becomes closer to main sequence stars.

3. SPECTRAL ENERGY DISTRIBUTION COMPARISON

For modeling, we have selected 2 proto stars. Results of the model calculations (lines) superimposed on observational data (symbols) for HD 150193 and CW Tau are shown in Figures 2 and 3 respectively. Both are well fit by basic models with two dust grains (silicate and graphite). For HD 150193 the optical depth ($\tau_{0.55} = 1.6$) with dust opacity having more silicate (silicate 53% and

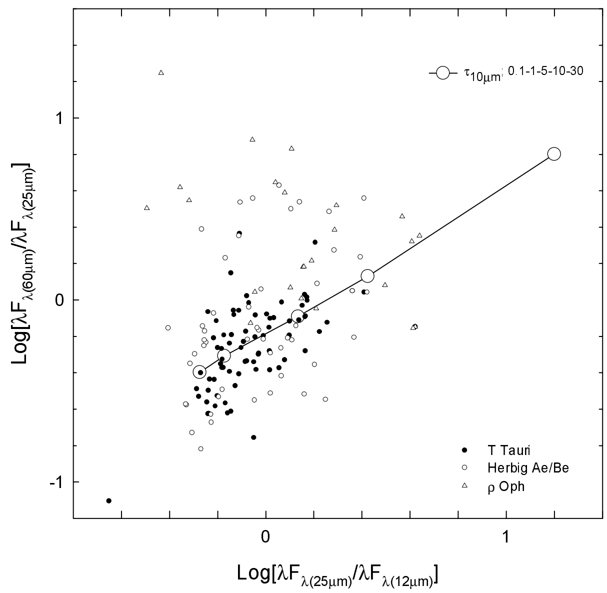

Figure 4. Loci of models in the IRAS 2-color Diagram.

graphite 47%) fit observed SED fairly well. The central black body temperature is assumed to be 9500 K. But for CW Tau, overall fitting is worse than HD 150193. For this star, a thicker dust shell ($\tau_{0.55} = 3 - 6$) with the dust opacity having more graphite (silicate 10% and graphite 90%) fit better. The central black body temperature is assumed to be 8000 K which is lower.

4. COLOR-COLOR DIAGRAMS

Only a relatively small number of proto stars have complete or nearly complete SEDs. $IRAS$ 4-color photometric data ($IRAS$ 1986) are available for 251 proto stars (Strom $et\ al.$ 1989, Bouvier 1990, Weintraub 1990, Hillenbrand $et\ al.$ 1992, Andre & Montmerle 1994, The $et\ al.$ 1994). Figure 4 plots 161 proto stars in an $IRAS\ \lambda F_\lambda$ 2-color diagram using [60]–[25] versus [25]–[12]. Stars with only upper limits at any wavelength were not used. The small symbols (open circles: Herbig Ae/Be stars; closed circles: T Tauri stars; open triangles: ρ Ophiuchi infrared cluster stars) are the observational data and large symbols with the line are the model calculations for a range in dust shell optical depth of $\tau_{0.55} = 0.1 - 30$. All models assume that the same central black body temperature (9500 K) and the opacity (silicate 53% and graphite 47%). In this diagram the differences among the different classes of proto stars are pronounced. The models can not extend much beyond the central portions of the diagram, even with very high optical depths ($\tau_{9.7} = 40$). Other models with different chemical composition and central star parameter may explain other regions in the diagram.

5. CONCLUSIONS

In this paper, we have made model infrared spectral energy distributions (SEDs) for proto stars. The model results are compared with observed infrared SEDs. Depending on the dust envelope and central star parameters, the results are very different. The models with silicate and graphite dust grains and a central blackbody source can explain some observations of proto stars.

We need to make more comprehensive model results with various input parameters to be able to compare with more observations in detail.

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