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Dust Envelopes around Massive Young Stellar Objects

Kyung-Won Suh
Department of Astronomy and Space Science, Chungbuk National University, Cheongju 361-763, Korea
email: kwsuh@chungbuk.ac.kr

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Abstract

We investigate the spectral energy distributions (SEDs) of Massive Young Stellar Objects (MYSOs) using the various infrared observational data including the Infrared Space Observatory (ISO) data. We model the dust envelopes around the stars using a radiative transfer model for spherically symmetric geometry. Comparing the model results with the observed SEDs of the two MYSOs (AFGL 4176 and AFGL 2591), we derive the relevant dust shell parameters including the dust opacity, the dust density distribution, and dust temperature distribution. We find that the spherical model can produce the SEDs roughly similar to the observations. We expect that the results would be helpful for making more realistic non-spherical dust envelope models for MYSOs.

Keywords: stars: pre-main-sequence,infrared: stars, circumstellar matter, dust, extinction, radiative transfer

1. Introduction

Massive Young Stellar Objects (MYSOs) are generally believed to be the pre-main-sequence (PMS) stars with very large masses ($\geq 10\ M_\odot$). They are surrounded by very thick gas and dust envelopes (e.g., Chan, Henning & Schreyer 1996). The dust grains produced in many type of stellar objects contribute to the interstellar dust in galaxies. In Galactic ecology, Gehrz (1989) pointed out that AGB stars produce overwhelming portion (more than 90 %) of the interstellar dust grains supplied from all stellar objects. When the dust grains formed in AGB stars enter into the interstellar medium, they get mixed up and go through some physical and chemical changes. There are similarities and differences between interstellar dust and dust grains in AGB stars. In the thick dust envelopes around MYSOs, both O-rich and C-rich dust grains can exist together.

There have been a few attempts to fit the observations of MYSOs with theoretical radiative transfer models with various assumptions and approximations, without much success. Due to the non-uniform density distributions and complicated dust opacity functions of the dust envelopes around MYSOs, any theoretical models with limited assumptions can not easily reproduce the observed SEDs in the entire wavelength region. Even the non-spherical models have serious limitations to properly reproduce the complicated nature of the dust envelopes (e.g., Suh 2002, 2006).

In this paper, we perform the radiative transfer calculations for spherical dust distributions with various parameters of the dust envelope. We compare the radiative transfer model results with the observed SEDs of the MYSOs including the $IRAS$ PSC, $IRAS$ LRS, ISO Short Wavelength Spectrometer (SWS), ISO Long Wavelength Spectrometer (LWS), and ground based observations. We derive the relevant dust shell parameters including the dust opacity, the dust density distribution, and dust temperature distribution. These parameters would provide a rough but reasonable estimate to understand the nature of the dust envelopes around MYSOs.

2. Model Calculations

For model SED computations, we use the radiative transfer code DUSTY developed by Ivezić, Nenkova & Elitzur (1999) for a spherically symmetric dust shell. The DUSTY code treats mixtures of different dust grains only as single-type grains whose properties average the actual mix. We have performed the model calculations in the wavelength range 0.01 to 36000 μm. A fixed model parameter for the dust envelope is the wavelength dependence of the dust opacity. The adjustable input parameter is the dust optical depth at 10 μm (τ_{10}).

2.1 Central stars

For the central star, the luminosity is taken to be $1 \times 10^4 L_\odot$. A change in the luminosity does not affect the shape of the output spectra, it only affects the overall energy output. We use a stellar black body temperature of 30,000 K which is typical for MYSOs. A minor change in the blackbody temperature of the central star does not affect the output spectra, especially for the models with optically thick dust shells.

2.2 Dust opacity

Unlike AGB stars, MYSOs have the dust grains that are much more complicated in chemical and physical properties. Silicates (amorphous, crystalline, and hydrous silicates), carbon grains (amorphous grains, smaller graphite grains, and PAH), and water ice grains are believed to be the major components in the envelopes around MYSOs. It is a difficult task to fit the observed SEDs of MYSOs with any mixture of candidate dust grains and various grain size distributions.

We have tested various opacity functions including the amorphous silicate and amorphous carbon (AMC) grains derived from AGB stars (Suh 1999, 2000) and the silicate and graphite grains derived from interstellar medium (Draine & Lee 1984). We find that a mixture of silicate and AMC grains derived from AGB stars reproduces the SEDs of the two MYSOs (see section 3) much better than that from interstellar medium. The opacity function reproduces the 10 μm and 18 μm absorption features for the MYSOs quite well (see section 3). The dust grain size affects the model SEDs in the wavelength region shorter than 10 μm. We find that spherical grains with a uniform radius of 0.1 μm make the best fitting.

For all the models, we use the mixture of cold silicate (70 % by number) and AMC (30 %) spherical grains derived from AGB stars (Suh 1999, 2000) with a uniform radius of 0.1 μm.

2.3 Dust shell parameters

We use various inner shell dust temperatures (T_c). That determines inner radius of the dust envelope (R_c). The outer radius is always set to be 1000 R_c. The model SED sensitively depends on T_c.

For the dust density distribution, we use a simple power law, $\rho \propto r^{-\beta}$. For AGB stars, we usually assume that the dust envelope density distribution is continuous ($\rho \propto r^{-2}$) in large scale from the inner radius of the dust envelope (R_c) to the outer radius (e.g., Suh 2004). The dynamical structure of young stellar objects requires a very different and complicated density distribution. The

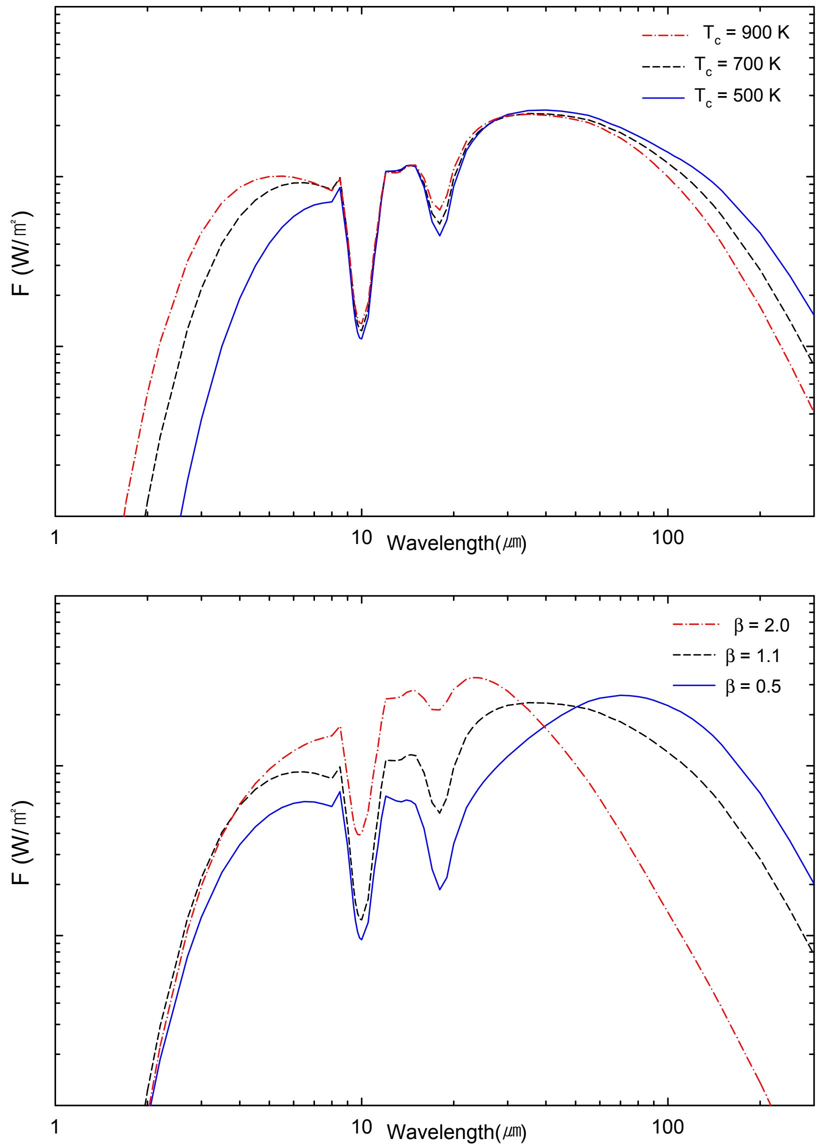

Figure 1. Model SEDs for different dust shell parameters.

overall power index (β) would be smaller than two because of the accretion processes in inner regions (e.g., van der Tak et al. 1999). We may use a different power law index for a different region of the dust shell by using broken power law indexes to represent the density distribution more properly.

2.4 Basic model results and prospect

Figure 1 shows various test model results with the same dust optical depth ($\tau_{10} = 4.5$). The

Table 1. Model parameters.

Object	Model	Dust[1]	T_c(K)	β	τ_{10}
AFGL 4176	Model 1	CS(7)+AMC(3)	700	1.1 (1-1000 R_c)	4.5
	Model 2	CS(7)+AMC(3)	700	1.5 (1-10), 0.7 (10-200), 1.0 (200-1000 R_c)	4
AFGL 2591	Model 1	CS(7)+AMC(3)	600	0.5 (1-20), 2.0 (20-1000 R_c)	4.5
	Model 2	CS(7)+AMC(3)	800	1.5 (1-10), 0.5 (10-500), 1.5 (500-1000 R_c)	4
AGB	T_{star}=2000 K	CS	1000	2 (1-1000 R_c)	14

[1] CS: cold silicate from Suh (1999), AMC: amorphous carbon from Suh (2000)

upper panel of Fig.1 shows the models with the same power law index ($\beta = 1.1$) for the different inner shell dust temperatures (T_c). The model with hotter T_c has more hot material inside so it produces more radiation in shorter wavelength regions. The lower panel of Fig. 1 shows the models with the same inner shell dust temperature (T_c = 700 K) for different power law indexes (β). Smaller β means that hot and cold materials are more evenly distributed so the model produce the radiation more evenly distributed in the entire wavelength range.

3. SED Comparison

We compare the observed SEDs for a selection of MYSOs with model results. We choose two MYSOs, AFGL 4176 and AFGL 2591, which are observed well in a wide wavelength range including ISO SWS ($\lambda = 2.4 - 45.2\mu$m) and LWS ($\lambda = 43 - 197\mu$m). The $IRAS$ 4-color PSC, $IRAS$ LRS, ISO SWS, and ISO LWS data are used for both objects. The ISO scientifically validated and good quality data are taken from the basic science data product archive in online ISO data center without further reduction.

Figure 2 shows the Results of the model calculations superimposed on the observational data for AFGL 4176 and AFGL 2591. Table 1 summarizes the model parameters for the selected stars. The two objects show similar SEDs with conspicuous 10 μm and 18 μm absorption features. Table 1 shows the model parameters. The model SED for a typical high mass-loss rate AGB star is also shown for comparison.

The two MYSOs are very similar in luminosity and overall SEDs. So the model fitting parameters are also similar. For AFGL 4176, the model one with a simple power law index (1.1) reproduce the SEDs fairly well in the near to mid IR and very far IR regions ($\lambda = 2 - 15\mu$m, $\geq 100\mu$m). The model two with the broken power law indexes (1.5, 0.7, 1.0) reproduce the SEDs very well in the near to mid IR region ($\lambda = 2 - 20$). But the deviations in far IR ($\lambda \geq 20\mu$m) could not be avoidable even with other combinations of model parameters.

For AFGL 2591, the model one with simple broken power law indexes (0.5, 2.0) reproduce the SEDs fairly well in the near to mid IR and very far IR regions ($\lambda = 2 - 15\mu$m, $\lambda \geq 100\mu$m). The model two with more complicated broken power law indexes (1.5, 0.5, 1.5) reproduce the SEDs very well in the near to mid IR region ($\lambda = 2 - 20$). Again, the deviations in far IR ($\lambda \geq 20\mu$m) could not be avoidable even with other combinations of model parameters.

We expect that the model two would be more appropriate for both objects. The model two reproduces the SEDs quite well in a wavelength range ($\lambda = 2 - 20$) but produces too much radiation in the longer wavelength region. If relatively cold materials are placed in non-spherical shape, they will produce less radiation in the far IR region than those in spherical shape do. Hutawarakorn & Cohen (2005) reported that a huge OH maser ring surrounds AFGL 2591. The cold material in the

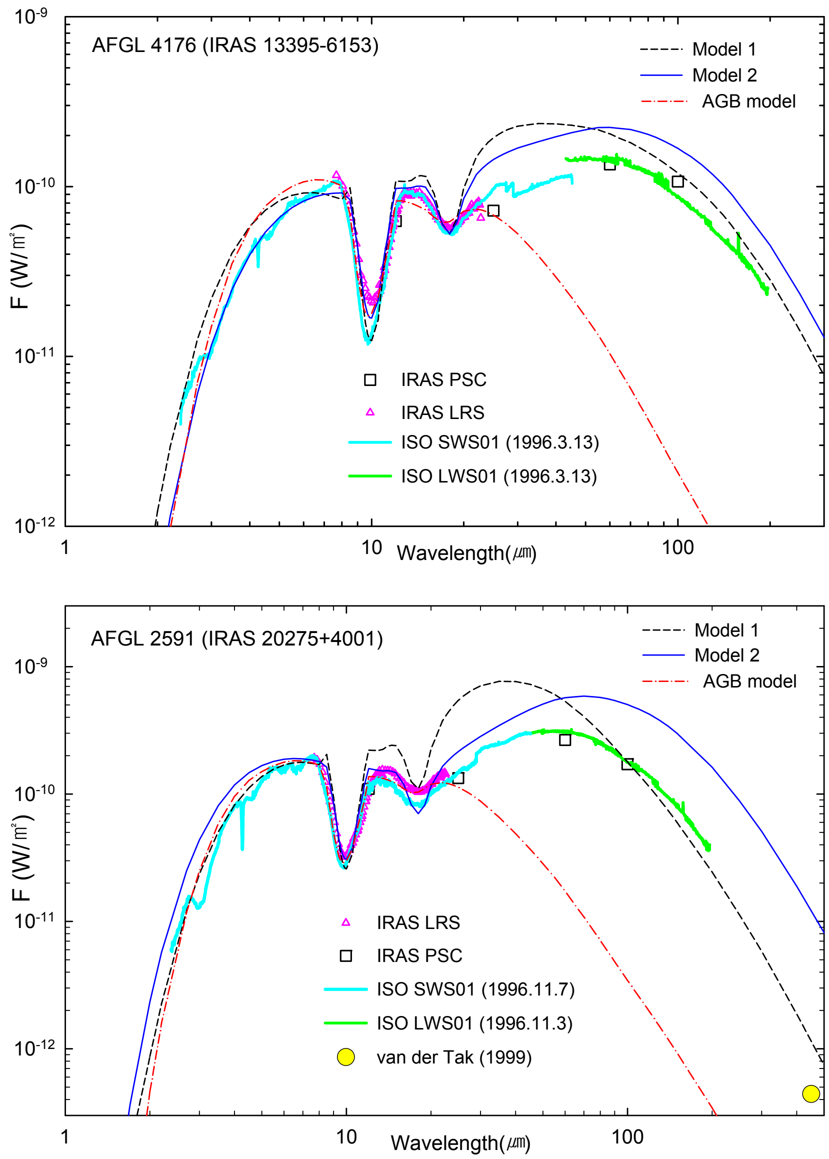

Figure 2. The SEDs for selected MYSOs.

ring may produce such deviations in the far IR ($\lambda \geq 20\mu$m).

By comparing dust shell models with the observed SEDs, we find that the inner shell dust temperatures for MYSOs (600-800 K) are lower than 1000 K which is typical for high mass-loss rate AGB stars (Suh 2004). The best fitting power law index (β) for a MYSO is usually much smaller than two. Therefore, the SEDs of MYSOs show that the radiation is more evenly distributed in wider wavelength range than those for AGB stars. Though the broken power law indexes could improve the fitting, the dust density distribution may require an even more complicated form. We hope that more realistic non-spherical models will be able to produce better results.

4. Conclusions

We find that the spherical models can produce the SEDs roughly similar to the observations. A mixture of silicate and AMC grains derived from AGB stars reproduces the SEDs of the two MYSOs (AFGL 4176 and AFGL 2591) by producing the similar 10 μm and 18 μm absorption features. The models cannot reproduce the observed SEDs in entire wavelength region probably due to the non-spherical nature of the dust envelope.

We have derived the relevant dust shell parameters including the dust opacity, the dust density distribution, and dust temperature distribution. These parameters would provide a rough but reasonable estimate to understand the nature of the dust envelopes around MYSOs. We expect that the results would be helpful for making more realistic non-spherical dust envelope models for MYSOs.

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