Radiative Transfer Modeling of Passive Circumstellar Disks: Application to HR 4796A

Thayne Currie
Department of Physics and Astronomy, University of California-Los Angeles, Los Angeles, CA 90095

Dmitry Semenov
Astrophysical Institute and University Observatory, Schillergafchen 2-3, 07745 Jena, Germany

Thomas Henning
Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany

Elise Furlan and Terry Herter
Department of Astronomy, Cornell University, Ithaca, NY 14853

Abstract. We present a radiative transfer model which computes the spectral energy distribution of a passive, irradiated circumstellar disk, assuming the grains are in radiative equilibrium. Dependence on the radial density profile, grain temperature estimation, and optical depth profiles on the output SED are discussed. The best fit model for HR 4796A has a minimum and maximum spherical grain size of 2.2 and 1000 µm respectively, a size distribution slightly steeper than the "classical" -3.5 MRN power law, grains composed of silicates, trolite, ice, and organics and a peak radial density of $1.0 \times 10^{-17}$ g cm$^{-3}$ at 70 AU, yielding a disk mass of roughly $2M_\oplus$.

1. Introduction

Modeling of the spectral energy distribution (SED’s) of circumstellar disks can potentially yield a wealth of information about the system under investigation. Sophisticated disk models have recently been developed by Chiang and Goldreich (1997) and Wolf (1999) for T Tauri disks, and basic modeling of older, optically-thin Vega-like disks was performed by Artymowicz (1989) for β Pictoris and Augereau et al. (1999) (hereafter, AG 99) for HR 4796A.

We present a radiative transfer model of passive, Vega-like dusty disks that more rigorously treats the optical properties of disk grains and emergent intensity from along the observer’s line of sight than AG 99, allowing for better constraints of grain composition, surface density profiles, and disk mass. HR 4796A was chosen as a test system because of the large number of infrared
excess flux measurements in the near infrared to submillimeter regions of the spectrum (summarized in Table 1) and restrictions on disk geometry, providing tighter constraints for disk model input parameters.

Table 1. Infrared and submillimeter flux measurements for HR 4796A used to constrain the model.

| $\lambda$ | Excess Flux (Jy) | Uncertainty (Jy) | Source                  |
|-----------|------------------|------------------|-------------------------|
| 11.6      | 0.086            | 0.070            | Fajardo-A. et al. (1998) |
| 12.5      | 0.101            | 0.018            | Koerner et al. (1998)   |
| 12.5      | 0.133            | 0.027            | Fajardo-A. et al. (1998) |
| 18.2      | 1.100            | 0.150            | Jayawardhana et al. (1998) |
| 20.0      | 1.860            | unknown          | Jura et al. (1993)      |
| 20.8      | 1.813            | 0.170            | Koerner et al. (1998)   |
| 24.5      | 2.237            | 0.700            | Koerner et al. (1998)   |
| 25.0      | 3.250            | 0.130            | IRAS                    |
| 60.0      | 8.630            | 0.430            | IRAS                    |
| 100.0     | 4.300            | 0.340            | IRAS                    |
| 450.0     | 0.180            | 0.150            | Greaves et al. (2000)   |
| 800.0     | < 0.028          |                  | Jura et al. (1995)      |
| 850.0     | 0.0191           | 0.0034           | Greaves et al. (2000)   |

2. Passive Circumstellar Disk Modeling Theory

The emergent flux from a passive, optically thin circumstellar disk at some wavelength equals the wavelength dependent intensity of light emerging from a point in the disk integrated over the solid angle that the disk comprises:

$$F_\nu = D^{-2} \int_0^{2\pi} \int_0^r I_\nu r_m \sin(i) dr_m d\omega$$  \hspace{1cm} (1)

where D is the star’s distance from the Earth, $I_\nu$ is the emergent intensity at a point in the disk with midplane radius $r_m$, and $i$ is the inclination angle where $i = 90$ corresponds to a face-on disk. The intensity emergent from each point in the disk is calculated by solving the radiative transfer equation and integrating the intensity contribution from all grains along the line of sight:

$$I_\nu(r) = \int_0^s B_\nu(T) \kappa(\lambda) \rho(r) ds$$  \hspace{1cm} (2)

where $\kappa$ is opacity, and $\rho$ is mass density of grains. The grains’ effective temperatures, $T_g$, are computed assuming dust grains are in radiative equilibrium:

$$q_{uv}(R_*/r)^2 \sigma T_g^4 = 4 \int_0^\infty q_{ir} B_\nu(T_g) d\nu$$  \hspace{1cm} (3)

where $q_{uv}$ (early A stars like HR 4796A emit mostly UV photons) and $q_{ir}$ are respectively the absorption efficiencies for incident and emitted radiation. Because grain extinction coefficients are wavelength dependent, and, in more rigorous
treatments, cannot be expressed as a simple analytic function, one must numerically solve for the grain temperature. Grain temperatures are calculated over a grid of grain sizes and distances. Resolved images of the HR 4796A disk infer a radial density profile sharply peaked at 70 AU of the form \( \rho(r) = \rho_o(r/rc)^\gamma \) where \( rc = 70\text{AU} \), \( \gamma \) is \( \gamma_{in} \) for \( r \leq rc \) and \( \gamma_{out} \) for \( r > rc \) are the inner and outer radial density power law factors, \( \rho_o \) is the peak radial density, and \( rm \) is the distance at which this occurs. Wavelength-dependent opacities are calculated from the Semenov et al. (2002) compositional model for chemically homogeneous, spherical grains whose primary components are pyroxene, olivine, volatile and refractory organics, water ice, troilite, and iron: similar to the Pollack (1994) compositional model. The optical properties of dust particles are computed via Mie theory. The grain size distribution is initially set to the size distribution for interstellar grains as prescribed by Mathis (1977). Minimum size is set at 5 \( \mu \text{m} \) for HR 4796A: close to the blowout size limit as inferred by AG 99. These two parameters are then adjusted to yield an optimum SED fit.

3. Modeling Results

Results of the disk modeling effort are shown in Figure 1. Optimum fit of the SED was achieved with the following input parameters: \( a_{min} = 2.2 \mu \text{m}, \beta = -3.86, \gamma_{in} = 10, \gamma_{out} = -12, \) and \( \rho_o = 1.0 \times 10^{-17} \text{ g cm}^{-3} \). An additional hot dust component peaked at 9 AU was required to fit the SED. Predicted flux values fall within the margin for error of measured values at nearly all wavelength points. The best fit requires a minimum size smaller than the blowout size limit for the system. Thus, some of the dust grains are not primordial and may be replenished via collisions of larger bodies. This model gives a disk mass of roughly 2.05M\( \oplus \): consistent with dynamical calculations of the disk mass (AG 99) and Greaves (2000) calculation of \( M_{disk} \geq 0.25M_{\oplus} \) and does so without
using scaling factors or 'fitting parameters'. The only true free parameter is the peak radial density. The radial density power laws can be qualitatively inferred from resolved images of the disk. The emergent SED varies so wildly with the grain composition assumptions that only a very small subset of possible compositions (which turn out to be quite similar) will yield empirically accurate model predictions. Finally, the gas/dust ratio, while not known, can be crudely constrained, and from this type of modeling one can produce a grid of models having a range of peak densities and gas/dust ratios. From Greaves (1999), the gas mass must be < 7M⊕ and the age and optical depth of the HR 4796A disk suggest a small gas/dust ratio: this is consistent with our results.

4. Future Tasks

The main remaining task is to make the absorption/extinction coefficient treatment self-consistent. While the grain optical properties of the were treated rigorously in the opacity calculations, grain temperatures themselves were calculated using a crude analytical function characterizing the extinction coefficients for the grains. While the derived grain temperatures concur roughly with previous temperatures derived by AG 99, a self-consistent approach would ensure more accurate grain temperatures. Second, a mechanism for confining HR 4796A's disk material into its narrow, sharply peaked annulus should be sought. Wyatt et al. (1999) suggested that orbital resonances with a jovian mass planet interior to the main disk could be responsible: reminiscent of the Goldreich and Tremaine (1982) discussion of ring confinement by shepherding moons. Finally, similar models could be produced for Vega, a slightly older, early A-type star which seems to be tracking an evolutionary path similar to that of HR 4796A, with results compared to previous modeling attempts for this system.

References

Artymowicz, P., Burrows, C., & Paresce, F. 1989, ApJ, 337, 494
Augereau, J. C., Lagrange, A. M., et al. 1999, A&A, 348, 557
Chiang, E., & Goldreich, P. 1997, ApJ, 490, 368
Fajardo-Acosta, S. B., Telesco, C. M., & Knacke, R. F. 1998, AJ, 115, 2101
Goldreich, P., & Tremaine, S. 1982, ARA&A, 20, 249
Greaves, J. S., Mannings, V., & Holland, W. 2000, Icarus, 143, 147
Jayawardhana, R., Fisher, S., Hartmann, L., et al. 1998, ApJ, 503, L79
Jura, M., Zuckerman, B., et al. 1993, ApJ, 418, L37
Jura, M., Ghez, A. M., et al. 1995, ApJ, 445, 451
Koerner, D. W., Ressler, M. E., et al. 1998, ApJ, 503, L83
Pollack, J. B., Hollenbach, D., et al. 1994, ApJ, 421, 615
Semenov, D., Henning, Th., & Ilgner, M. 2002, A&A, in preparation
Wolf, S., Henning, Th., & Stecklum, B., 1999, A&A, 349, 839
Wyatt, M., & Dermott, S. F. 1999, ApJ, 527, 918