Radiative transfer models of protoplanetary disks: Theory vs. observations

Mulders, G.D.

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Appendices
4.A Taurus median

As mentioned in section 4.3.1, we have added the 850 micron flux point to the existing Taurus median from Furlan et al. (2006). Although the original Taurus median from D'Alessio et al. (1999) is based on the same sources and includes millimeter photometry, its coverage is incomplete. It is strongly biased toward brighter - and thus heavier - disks and was ’meant to be indicative rather than definitive’. Andrews & Williams (2005) have created a nearly complete census of the Taurus star-forming region at millimeter wavelengths, allowing us to complete the median fluxes at 850 micron. The median flux we derive is \( \log(\nu F_\nu [\text{erg} / \text{s} / \text{cm}^2]) = -12.70 \), with the upper and lower quartiles at \(-13.05\) and \(-12.13\), respectively. These fluxes are roughly an order of magnitude lower than those included in the original median, but are consistent with the average disk mass in Taurus found by Andrews & Williams (2005).

4.B Herbig median

The Herbig median SED is based on the samples of Acke et al. (2009) and Juhász et al. (2010). Because knowing the dust mass is crucial in measuring the degree of settling in the outer disk, we selected only those sources with a millimeter detection. Following Acke et al. (2009), we also excluded transitional disks, since their mid-infrared SEDs should be explained in the context of gaps and inner holes, rather than dust settling.

The sample consists of 32 sources, and has a complete wavelength coverage in bands, B, V, J, H, K, L, Spitzer IRS longward of 10 micron, IRAS 12, 25 and 60 and millimeter wavelengths. U- and M-band photometry were also included because they lacked only one and two measurements, respectively. The Spitzer spectra were reduced to narrow-band photometry following the same method as in Furlan et al. (2006). At the shortest wavelengths (5.7, 7.1, 8.0, 9.2 \( \mu \text{m} \)) the coverage is sometimes incomplete (lacking 5, 5, 3 and 3 measurements respectively), and was supplemented with ISO data where available. We only included the IRAS 60 micron fluxes, because the 12 and 25 micron regions is covered by Spitzer, and results in the same median fluxes. Although all sources have millimeter detections, not all are measured at the same wavelength. We therefore constructed one photometric point at 850 \( \mu \text{m} \), and interpolated fluxes according to \( \nu F_\nu(\text{mm}) = \nu F_\nu(\text{obs}) \cdot (\lambda_{\text{obs}} / 850 \mu \text{m})^{-4} \), averaging if more than one measurement was available.

The median star in our sample is a Herbig A6 star, with a median effective temperature of 8500 K, luminosity of 21 \( L_\odot \) and mass of 2 \( M_\odot \). Because these stars are not in a single star-forming region, we scaled their SEDs to a distance of 140 parsec and their luminosity to the median luminosity before constructing the median. The
median including quartiles are given in table 4.4, and are displayed in Figs 4.6 and 4.16. This approach results in an SED that has a small spread in photometry at stellar wavelengths, and a similar spread as the Taurus median SED at disk wavelengths. Typical features like the 2 micron bump and silicate features are clearly visible.

### 4.4 The inner regions of Herbig stars

As mentioned in section 4.3.2, the inner regions of Herbig stars deserve special attention in disk modeling. The strong 2 micron bump is a prominent feature in most
4.C The inner regions of Herbig stars

Figure 4.16: Observed median SED of Herbig stars (diamonds) with quartiles (gray area). Overplotted is a disk model with a puffed-up inner rim with a scale height 2.5 times the pressure scale height and turbulent mixing strength of $\alpha = 10^{-2}$ (solid line). Also plotted are a model with the same inner rim and a modified grain size distribution with a power-law index of 4.0 (dotted line) and a model without a puffed up inner rim, but with millimeter sized grains within the dust evaporation radius (dashed line). The gray line denotes the stellar photosphere. The inset shows the millimeter regime.

Herbig Ae and Be stars (Meeus et al. 2001), and has been explained as the fully illuminated surface of a disk truncated at the dust evaporation radius by Dullemmond et al. (2001). Because of the large fraction of reprocessed light in the near-infrared, this would require the rim to be ‘puffed up’, a natural cause of its high temperature down to the midplane (Natta et al. 2001).

However, Vinković et al. (2006) showed that a rim in hydrostatic equilibrium does not puff up far enough to explain the near-infrared fluxes. To fit the SED, the inner rim has to be puffed up beyond hydrostatic equilibrium by a factor 2-3 (Verhoeff et al. 2010; Acke et al. 2009). Other explanations have also been proposed, ranging from dust halos (Vinković et al. 2006; Verhoeff et al. 2011) to optically thin gas or dust within the inner rim (Kraus et al. 2008; Tannirkulam et al. 2008a), as well as theoretical motivations for an increased scale height in the inner rim (Thi et al. 2011b) or the presence of such a halo (Krijt & Dominik 2011). For the context of this paper, it is important whether or not the added emission in the inner disk influences the geometry and emission of the outer disk, and could affect our estimate of the turbulent mixing strength. A puffed-up inner rim casts a shadow on the outer disk, decreasing the flux at longer wavelengths (Acke et al. 2009), whereas material within
the inner rim or a halo does not cast a shadow (Mulders et al. 2010).

Figure 4.16 shows the SEDs of these alternative inner disk geometries. When we increased the scale height in the inner rim by a factor 2.5 to fit the near infrared part of the SED (Fig 4.16, solid line), it cast a shadow over almost the entire outer disk, and we were unable to fit the far-infrared flux even with a turbulent mixing strength of $\alpha = 10^{-2}$ or higher. We were able fit the far infrared flux by increasing the amount of small grains, which we did by increasing the slope of the grain size distribution to $q = 4.0$ (dotted line). However, the strong effect of the inner rim shadow remains, suppressing the mid-infrared flux. We tried several prescriptions to modify the inner rim structure, such as rounding it off, but they did not provide enough mid infrared flux. The reason why the puffing up the inner rim does not work well in our model - in contrast to e.g. Acke et al. (2009) and Thi et al. (2011b) - is that the median SED requires additional flux at 2 micron - whereas previous work focused mainly on the 8 micron region. This requires a hot inner rim, 1500-1700 K, which is consistent with observations and dust evaporation, but which does not produce enough MIR emission.

Alternatively, dust or gas within the inner rim can also contribute to the near-infrared flux. Additional components originating in that region have been observed for a number of Herbig stars, such as MWC 147 (Kraus et al. 2008; Bagnoli et al. 2010), HD 163296 and AB Aurigae (Tannirkulam et al. 2008a,b; Benisty et al. 2010a) and HR599 (Benisty et al. 2011). Material within the inner rim can increase the near-infrared flux if it generates extra luminosity from accretion (Kraus et al. 2008) or if it captures additional radiation that would otherwise not reach the disk.

For the second option, the material needs to extend sufficiently close to the star, such that starlight is captured that crosses the midplane and would normally not be reprocessed by the disk. We modeled this by extending the largest grain component in our model down to two stellar radii, or 0.02 AU (Fig 4.16, dashed line). Because even the largest grains in our model at this location become extremely hot, we were unable to fit the shape of the near-infrared SED this way, but it does capture roughly sufficient energy at shorter wavelengths. Because this solution to the near-infrared flux problem is similar to a halo in the sense that it captures additional energy, we did not explore it in more detail. We limited ourselves to modeling a halo, where we note that this could also represent a solution with material within the inner disk.