

Spectral Energy Distributions of Circumstellar Disks Around Young Stellar Objects

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1 Introduction

Young Stellar Objects (YSOs) are stars in the earliest stages of evolution and are commonly surrounded by gas and dust in circumstellar disks. The central protostar emits approximately as a stellar blackbody, while dust in the surrounding disk absorbs part of this radiation and re-emits it at longer wavelengths. As a result, the spectral energy distribution (SED) of a YSO generally contains an infrared excess beyond what would be expected from the stellar photosphere alone. Because the temperature of dust decreases with increasing distance from the star, the shape of the infrared portion of the SED contains information about the radial structure and thermal profile of the disk.

The goal of this lab was to model the SEDs of circumstellar disks around YSOs and compare idealized models with real observational data. Two disk geometries were considered: a thin flat disk and a flared disk. In both cases, the disk was approximated as a collection of concentric annuli, each with a characteristic area and temperature determined by a radial temperature profile. The total disk flux was then computed by summing the thermal emission from all annuli and adding the contribution from the central protostar. These models were subsequently compared with observational data for the YSO GM Aurigae in order to assess which disk structure provides a better fit and whether additional features, such as an inner cavity, might be required.

2 Model Construction for a Flat Disk

2.1 Disk Structure and Temperature Profile

The first model considered was a flat circumstellar disk. For a flat disk, the temperature profile scales with radius as

$$T(r) \propto r^{-3/4}. \tag{1}$$

A 4000 K protostar was assumed, consistent with a T Tauri star. The inner edge of the disk was set at the dust sublimation radius, $R_{\text{sub}} = 0.07 \text{ AU}$, where the dust temperature was taken to be 1800 K. The outer edge was initially set to 200 AU, and the disk was divided into annuli of width 0.05 AU. A disk scaling parameter $Dscale$ was used to control the strength of the disk emission relative to the star. The initial value used for the flat-disk model was $Dscale = 0.25$.

The area of each annulus was computed from the difference in squared radii, and the temperature of each annulus was assigned using the midpoint radius and the assumed power-law profile. This annulus-based structure allowed the disk flux to be calculated numerically across a wide wavelength range.

2.2 Planck Function and Flux Calculation

For each annulus, the emitted flux at wavelength λ was modeled using the Planck function in wavelength form, $B_{\lambda}(T, \lambda)$. The total disk emission at each wavelength was then obtained by summing the contributions from all annuli after weighting each by annulus area. The flux from the central protostar was also computed using the Planck function for a 4000 K blackbody. After all contributions were computed, the stellar and disk fluxes were normalized and the disk emission was scaled by the factor $Dscale$ before the total model SED was formed.

In the Python implementation, the Planck function was explicitly set to zero when the argument of the exponential became too large. The threshold used in the code was 500. This condition occurs when the ratio $d/(T\lambda)$ is very large, which corresponds to either very low temperature or very short wavelength. In this regime, the exponential term becomes enormous, so the denominator of the Planck function is dominated by the exponential and the function itself becomes negligibly small. For that reason, setting the output to zero under these conditions is both numerically stable and physically reasonable.

The Planck function for each annulus was multiplied by the area of that annulus because the total luminosity contributed by a region depends not only on its surface brightness but also on the emitting surface area. A larger annulus contributes more total radiation than a smaller annulus at the same temperature because it contains more emitting material.

The SEDs were plotted using $\log(\lambda F_{\lambda})$ versus λ rather than simply F_{λ} versus λ . This is the standard SED convention because multiplying by λ gives a more direct representation of how energy is distributed across logarithmic intervals in wavelength. It also makes it easier to compare the relative contributions of different wavelength regimes over a very broad spectral range.

2.3 Flat-Disk SED

The resulting flat-disk SED included three curves on a single plot: the stellar contribution, the disk contribution, and the combined star+disk spectrum. The stellar spectrum dominated at short wavelengths, while the disk produced a clear infrared excess at longer wavelengths. This is expected because the disk consists of cooler material than the star and therefore radiates more strongly at longer wavelengths.

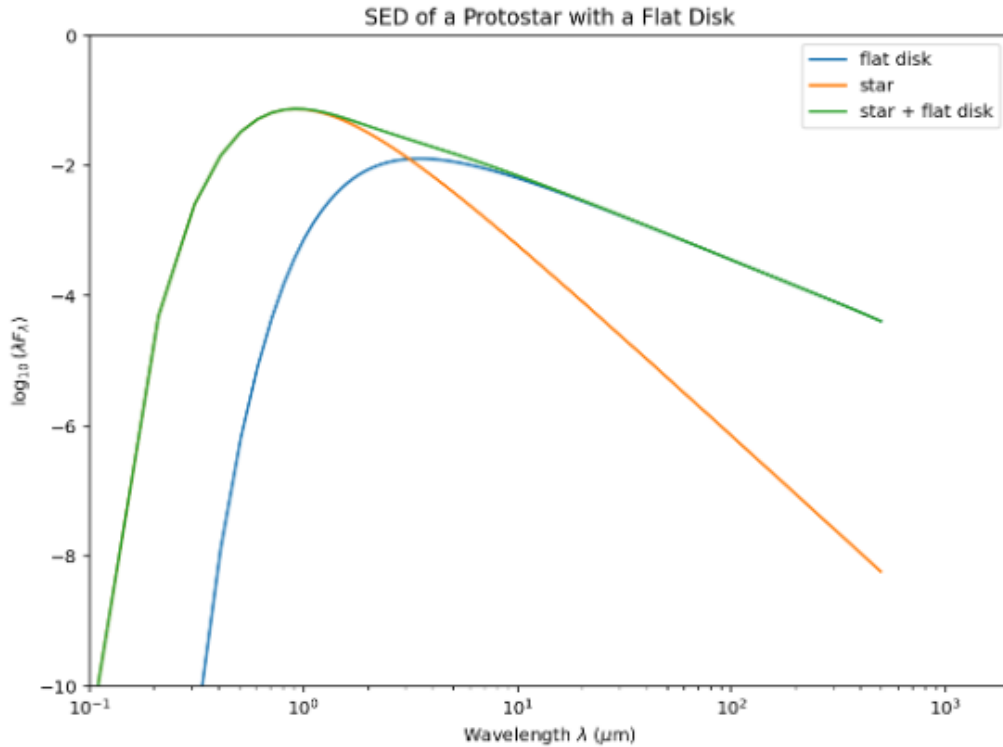


Figure 1: Model SED for a protostar with a flat circumstellar disk. The figure should include the stellar photosphere, the disk contribution, and the total star+disk spectrum.

The disk contribution differs from that of the star mainly in both its peak wavelength and its breadth. The stellar contribution resembles a single hot blackbody and peaks at relatively short wavelengths, whereas the disk contribution is much broader and shifted toward the infrared. This difference occurs because the disk spans a wide range of radii and therefore a wide range of temperatures, so the disk emission is the sum of many cooler blackbody-like components rather than one single-temperature emitter.

2.4 Effect of Changing the Disk Scaling Factor

The value of $Dscale$ controls how strongly the disk contributes relative to the protostar. When $Dscale$ was decreased to 0.1, the infrared excess became weaker and the stellar photosphere dominated more strongly. When $Dscale$ was increased to 0.5, the infrared excess

became more prominent and the disk contribution rose substantially above the stellar spectrum at longer wavelengths. Thus, changing $Dscale$ alters the vertical strength of the disk component while preserving its overall shape.

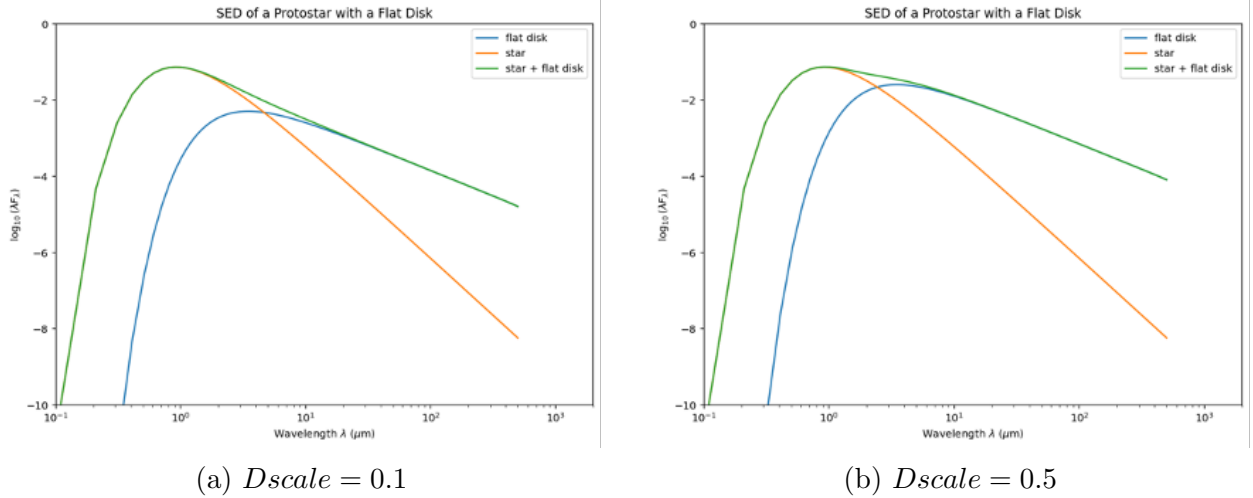


Figure 2: Effect of varying the disk scaling factor on the flat-disk SED.

If the star were hotter, the stellar spectrum would shift to shorter wavelengths and become more luminous. In addition, the sublimation radius would increase because dust could not survive as close to a hotter star. That change would move the inner edge of the disk outward and alter the temperature distribution of the dust, which would in turn modify the infrared portion of the SED.

3 Model Construction for a Flared Disk

3.1 Code Change and Physical Motivation

The flared-disk model was constructed using the same general procedure as the flat-disk model, but with a different radial temperature profile. For a flared disk, the temperature scales as

$$T(r) \propto r^{-1/2}. \quad (2)$$

In practice, this meant that the only essential code change required to generate the flared-disk SED was replacing the temperature power-law exponent from -0.75 to -0.5 .

3.2 Comparison Between Flat and Flared Disk SEDs

The flared disk produced an infrared excess similar in general character to the flat disk, but the shape of the excess differed noticeably. The flat-disk contribution fell off more steeply at

long wavelengths, whereas the flared-disk contribution was broader and remained stronger in the mid- and far-infrared.

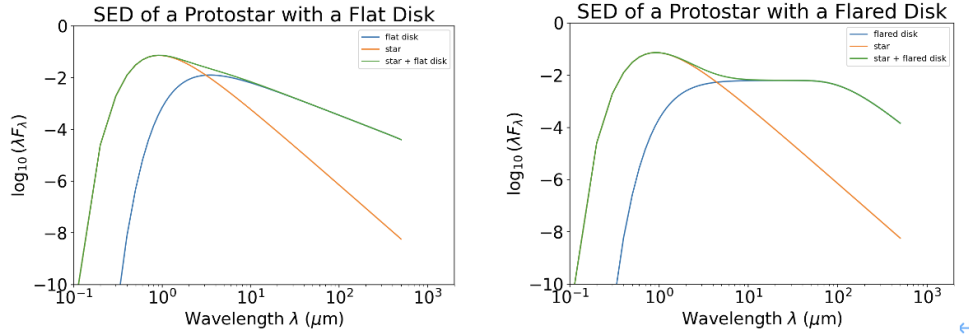


Figure 3: Comparison of the flat-disk and flared-disk models.

This difference makes physical sense. In the flat-disk model, the temperature drops more steeply with radius, while in the flared-disk model the temperature decreases more slowly. As a result, the outer portions of a flared disk remain relatively warmer than in the flat-disk case. Since those outer, cooler regions are the main contributors at long wavelengths, the flared disk naturally produces stronger emission in the infrared and a less steep SED in that regime. The broader infrared output of the flared disk is therefore consistent with the physical meaning of a disk with a shallower radial temperature gradient.

4 Comparison with Observations of GM Aurigae

4.1 Scaling the Observed Data

The model SEDs were next compared with observational data for GM Aurigae, a T Tauri star in the Taurus-Auriga cloud. Since the units of the observational λF_λ data did not directly match the normalized model fluxes, the observational points had to be rescaled before a meaningful comparison could be made. The assumption used was that wavelengths shorter than $1 \mu\text{m}$ are dominated mainly by the stellar photosphere, so the short-wavelength data should align with the stellar part of the model. This is a reasonable first approximation because the infrared excess from the disk is expected to be much less important at optical wavelengths than at longer wavelengths.

To determine the multiplicative scale factor, the model flux near $0.35 \mu\text{m}$ was estimated by averaging the two nearest model points at $0.3 \mu\text{m}$ and $0.4 \mu\text{m}$. This approximate model value was then compared to the GM Aurigae data point at $0.3689 \mu\text{m}$. The scale factor was defined by

$$C = \frac{(\lambda F_\lambda)_{\text{model, approx at } 0.35 \mu\text{m}}}{(\lambda F_\lambda)_{\text{GM Aur at } 0.3689 \mu\text{m}}}. \quad (3)$$

Using this procedure, the scale factor obtained was

$$C = 1.0214 \times 10^8. \quad (4)$$

All GM Aurigae flux values were then multiplied by this constant before plotting them against the models.

The choice between a flat or flared disk is effectively irrelevant for determining this scaling factor because the normalization was anchored at a short wavelength where the stellar photosphere dominates the SED. Since both disk models use the same 4000 K stellar component, the short-wavelength part of the SED is nearly the same in both cases, so the same scaling procedure is appropriate regardless of the assumed disk geometry.

4.2 Best-Fit Flat and Flared Disk Models

After scaling the GM Aur data, both the flat-disk and flared-disk models were compared with the observations over an extended wavelength range out to $1000 \mu\text{m}$. The disk scaling factor $Dscale$ was adjusted to improve the agreement between the model and the data.

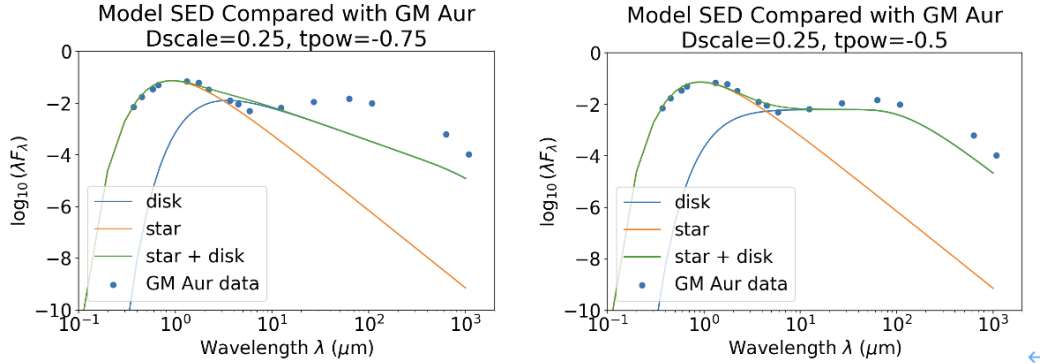


Figure 4: Scaled GM Aurigae observational data compared with the flat-disk and flared-disk models

The flared-disk model provided the better overall match, especially at short and intermediate wavelengths, while the flat-disk model tended to underpredict the infrared emission more strongly. A value of $Dscale = 0.4$ produced the best overall agreement among the models tested.

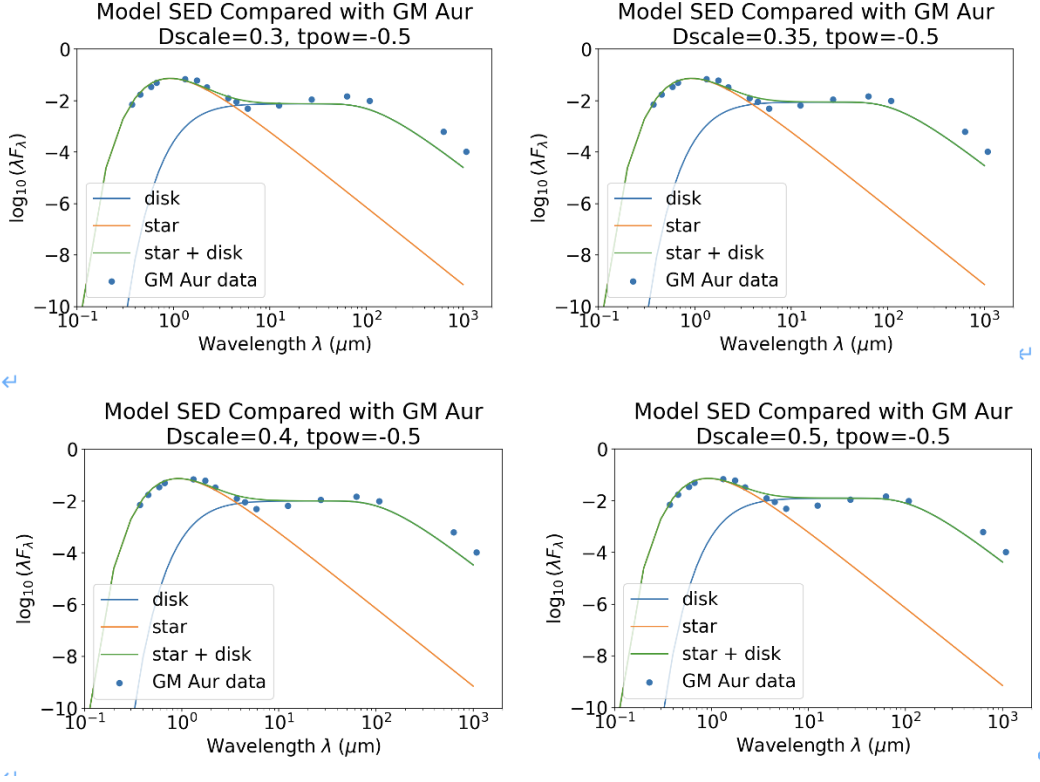


Figure 5: Scaled GM Aurigae observational data compared with the flat-disk and flared-disk models

Even with the best-fitting flared model, however, there remained a wavelength region—particularly around 20 to 100 μm —where neither model reproduced the observational data well. In this region, the GM Aur data lie above the model curves, indicating that the real disk structure is likely more complicated than either idealized model. The longest-wavelength points also remained imperfectly fit. Thus, the flared disk appears to capture the overall trend of the SED better than the flat disk, but neither model is fully adequate.

5 Testing an Inner-Cavity Model

5.1 Modification of the Model

To investigate whether the mismatch could be explained by a large inner cavity, the best-fitting disk model was modified so that the inner disk began at 4 AU instead of the sublimation radius. The outer radius was also extended from 200 AU to 300 AU. These changes required recomputing the number of annuli, the radii of the annuli, their areas, and their temperatures before constructing a new SED.

Physically, moving the inner edge outward removes the hottest dust from the model, while extending the outer radius preserves the contribution from cooler dust at large distances.

The purpose of this modification was therefore to test whether a disk with a large central cavity could better reproduce the GM Aurigae observations.

5.2 Effect of the Inner Cavity on the SED

Introducing the cavity reduced the near- and mid-infrared emission because the warmest inner dust was no longer present. This change is physically sensible: if no dust exists within the inner few AU of the disk, then the disk cannot produce as much emission at shorter infrared wavelengths. The outer disk still contributes at longer wavelengths, so the far-infrared portion of the spectrum remains present.

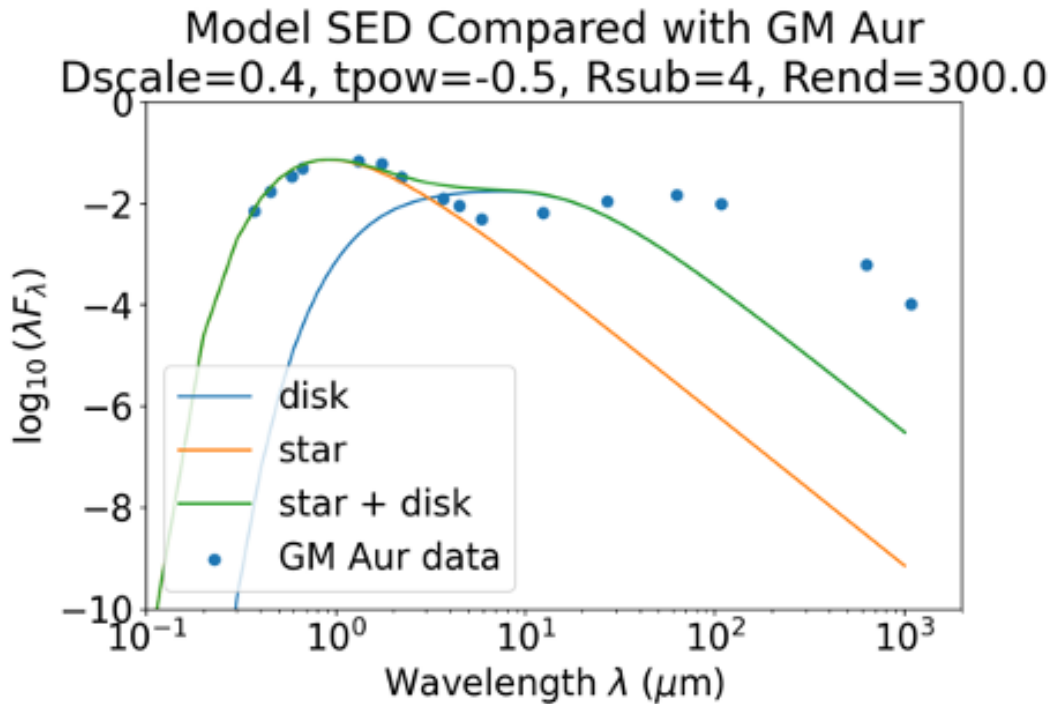


Figure 6: Comparison of the GM Aurigae data with the best-fitting model including an inner cavity from 0.07 AU to 4 AU.

Although the cavity changed the SED in the expected physical direction, it did not improve the fit to the GM Aurigae data in this particular analysis. This suggests that the discrepancy between the simple models and the observations cannot be explained solely by inserting a large inner cavity.

5.3 Possible Physical Interpretation

A cavity extending to 4 AU is much larger than the dust sublimation radius, so it cannot be explained simply by dust being heated and evaporated by the star. A more plausible

explanation would be clearing by disk evolution or by one or more forming planets. A planet embedded in the disk could gravitationally open a gap or cavity, while accretion and other disk-clearing processes could also remove material from the inner region. If such a cavity were truly present, GM Aur might be classified as a transition-disk system. However, because the cavity model did not improve the fit in this analysis, the observational evidence from this simple fitting exercise alone is not sufficient to conclude that such a cavity is required.

6 Conclusion

In this project, model spectral energy distributions were constructed for a 4000 K protostar surrounded by either a flat disk or a flared disk. The SEDs were generated by dividing the disk into concentric annuli, assigning a temperature to each annulus according to a radial power-law profile, and summing the thermal emission of all annuli together with the stellar blackbody contribution. This process showed how the shape of an SED is linked to disk geometry and temperature structure.

The flat- and flared-disk models both produced infrared excesses beyond the stellar photosphere, but the flared disk generated a broader and less steep infrared contribution because its temperature decreases more slowly with radius. When the models were compared to the GM Aurigae data, the flared disk provided the better overall fit, with $D_{scale} = 0.4$ giving the best agreement among the models tested. Even so, neither simple model reproduced the observations particularly well in the 20–100 μm region, indicating that the real circumstellar environment is more complex than these idealized cases.

A cavity model was then tested by moving the inner edge of the disk outward to 4 AU and extending the outer radius to 300 AU. This modification reduced the near- and mid-infrared emission in a physically sensible way, but in this case it did not produce a better fit to the GM Aurigae data. This result suggests that while inner cavities can strongly influence the shape of an SED, the observed structure of GM Aur likely depends on additional physical effects not included in the simplified models used here.

Overall, this lab showed that SED fitting is a powerful tool for inferring the structure around YSOs, but it also highlighted the limitations of simple disk models. A broad match to the data can suggest the general disk geometry, yet the confidence in a unique physical interpretation remains limited when the models are idealized. To reduce the uncertainty, more realistic models could include additional structural features such as variable dust composition, different grain sizes, vertical disk structure, nonuniform surface density, or partial gaps rather than a single clean cavity. Additional observations, especially more densely sampled mid- and far-infrared data, would also help constrain the disk structure more reliably.