尋找決定原恆星盤演化過程的物理條件

王嘉瑋、賴詩萍
國立清華大學天文研究所

摘要

瞭解環繞於原恆星四周的原始恆星盤(Primordial disk)的演化機制，包括其中的氣體如何消散、塵埃如何成長以及整體原始恆星盤如何演化成岩屑盤(Debris disk)，可以提供我們對於行星形成環境的重要資訊。近期的觀測的結果推測恆星盤的演化，可能存在至少一種以上的路徑。因此爲了釐清造成不同恆星盤演化路徑的物理條件，我們在此提出一項分析恆星盤演化過程的統計方法。我們定義了兩個用來描述光譜型態的參數，$\lambda_{\mathrm{turnoff}}$和$\alpha_{\mathrm{excess}}$。其中$\lambda_{\mathrm{turnoff}}$定義爲在原恆星光譜中，恆星輻射強度等於恆星盤輻射強度的波長，這個參數可用來描述恆星盤內圈的大小；α_{excess}定義爲波長較$\lambda_{\mathrm{turnoff}}$長的光譜斜率，這個參數主要關係著整個恆星盤的質量。由於目前對恆星盤演化機制的一項主要議題爲「是否恆星盤是由內圈開始消散」，因此我們設定的這兩個參數可以用來檢驗恆星盤的實際演化過程是否如理論預期。我們將用這兩個參數比較Spitzer c2d Legacy Project的觀測結果與 Robitaille et al.(2006)的原恆星模型，並且計算出c2d區域內過渡盤(transition disk)數目的上下限。結果顯示在 Chameleon II, Lupus, Ophiuchus, Perseus, 和 Serpens 區域內，均勻消散盤(homologously depleted disks) 和典型過渡盤(canonical tran- sition disks)都是存在的。而在這五個區域間，均勻消散盤和典型過渡盤的數目比例有著約兩倍的變化，這意味在這些區域中，物理環境或盤面演化階段是不同的。未來針對這些區域間物理條件差異的研究，可以增進我們關於盤面演化的知識。

Searching for the physical conditions that determine the disk evolution

Jia-Wei Wang, Shih-Ping Lai
Institute of Astronomy, National Tsing Hua University

Abstract

Understanding how primordial circumstellar disks of young stellar objects dissipate gas and small dust grains and evolve into debris disks is crucial for advancing our knowledge in planet formation. Recent observations suggest that multiple pathways may exist for the disk evolution. In order to clearly identify the physical conditions influencing the evolutionary paths, here we perform a statistical analysis on two morphological parameters of the spectral energy distributions (SEDs), $\lambda_{\rm turnoff}$ and $\alpha_{\rm excess}$. $\lambda_{\rm turnoff}$ is the wavelength where the disk flux is equal to the stellar flux, which indicates the size of the inner disk, and $\alpha_{\rm excess}$ is the spectral slope at wavelengths longer than $\lambda_{\rm turnoff}$, which traces the total mass of the disk. Since one of the main issues in disk dissipating theories is whether the disks are cleared from the inside out, these two parameters are ideal for examining the theories. We compare $\lambda_{\rm turnoff}$ and $\alpha_{\rm excess}$ of the theoretical SEDs from Robitaille et al. (2006) to those of the observational results from the Spitzer's c2d Legacy project, and derive the upper limit and lower limit of the transition disk population in the c2d regions. The results show that homologously depleted disks and canonical transition disks do exists in Chameleon II, Lupus, Ophiuchus, Perseus, and Serpens clouds. In the five clouds, the population ratios of homologously depleted disks and canonical transition disks are different by a factor of ~2, which suggest that the physical condition or evolutionary stage may be different in these regions. Further work on comparing the physical conditions of these regions could advance our knowledge of disk evolution theory.

關鍵字(Key words)：主序前星(stars: pre--main-sequence)、行星系統的形成(stars: planetary systems: formation)、前行星盤(stars: planetary systems: protoplanetary disks)

Received : 2010.10.29; Accepted: 2010.12.28

1. Introduction

Most young (~1 Myr), solar-type pre-main-sequence stars are surrounded with circumstellar disks (Strom et al. 1989). These disks are expected to be the sites of the formation of planets because the disks have masses (Beckwith et al. 1990), sizes (McCaughrean & O'Dell 1996; Dutrey et al. 1996) and compositions (Hillenbrand 2002) consistent with those of the assumed primitive solar nebula. As the disks evolves, both gas and dust in the primordial disks will dissipate on timescales between 1-10 Myr, and the gas-to-dust ratio will reduce from ~100 in the primordial disk stage to << 1 at the debris disk stage (Currie et al. 2007; Hern´andez et al. 2007). The debris disks surrounding > 10 Myr old stars are typically optically thin and show little evidence for substantial reservoirs of circumstellar gas (e.g. Dahm 2005a; Currie et al. 2007c). Debris disks have very low masses of residual gas, << 1 Mass of earth (Roberge and Weinberger 2008; France et al. 2007). This mass is too small to construct a gaseous envelope with a mass comparable to those found in Jupiter and Saturn, thus the time when most primordial disks evolve into debris disks sets an empirical time constraint for the formation timescale of gas giant planets.

The disks in the transition stage from the gas and dust rich, optically thick primordial disks to nearly gas-free, optically thin debris disk are defined as transition disks. Since how the transition disk evolves determines the environment of planet formation, both observational and theoretical research of those objects are a focus of interest (e.g. Eisner et al. 2006; Cieza 2007). The key issue in such studies is the characterization of the transition disks. The transition disks were first identified by analysis of their SEDs, which suggested the presence of an inner opacity hole surrounded by an optically thick outer disk, but recent Spitzer Space Telescope observational results reveal the diversity of the morphologies of transition disks. Currie et al. (2009) observed YSOs in NGC 2362 and studied their disk morphology based on the interpretation of their SEDs. Their result suggests that at least two evolutionary paths exist for transition disks, canonical transition disks and homologously depleted disks (Fig. 1). The canonical transition disks are predicted by current disk evolution models, which suggest that the disks are cleared from the inside out. The homologously depleted disks can be explained by a homologous depletion process, which suggests that the dominating dissipation mechanism is likely grain growth over the whole disk.

In order to understand the dominant dissipation mechanism for transition disks, we perform a statistical analysis on SED features of transition disks in five molecular clouds, Chameleon II, Lupus, Ophiuchus, Perseus and Serpens. We drew our samples from the young stellar object (YSO) candidates in the catalog of “Cores to Disk” (c2d) Spitzer Legacy Project, and select the YSO candidates with the object type “YSOc_star+dust”. The object type “YSOc_star+dust” is defined if the SED of one object can be fit well with a reddened stellar SED in JHK band but has identified excess at longer wavelengths, which is expected for YSOs with transition disks or with low-mass primordial disks. For a detail description of c2d data products, see Evan et al. (2007). Cieza et al (2005) have shown that some classical T Tauri stars with primordial disks have excesses in J, H or K bands. As a result, our samples will lack those objects and thus underestimate the number of those young primordial disks. Nevertheless, the large size of the sample (757 sources) allows us to reveal the tendency of disk evolution, which can be used to examine disk evolution theory for transition disks.

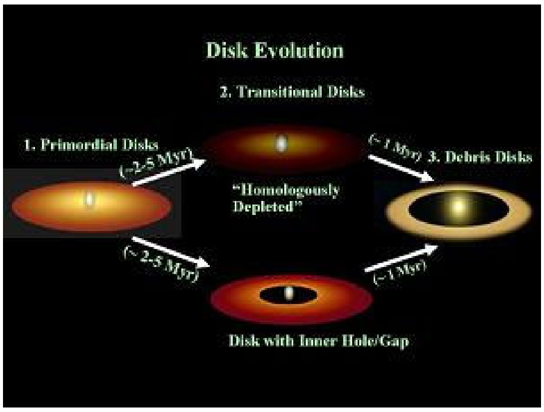

Fig. 1: A schematic illustration of disk evolution from the primordial disk phase to the debris disk phase (Currie et. al 2010).

2. Determine the $\lambda_{\rm turnoff}$ and $\alpha_{\rm excess}$

To describe the morphology of the SED, we introduce two parameters $\lambda_{\rm turnoff}$ and $\alpha_{\rm excess}$. $\lambda_{\rm turnoff}$ is the wavelength where the disk flux is equal to the stellar flux, which traces the position of the gap in SED, and α_{excess} is the spectral slope at wavelengths longer than $\lambda_{turnoff}$, which indicates the flux strength from disk.

To determine the stellar contribution in the SED, we assume the J, H and K band flux is totally from the stellar component, thus we can use the J and H band flux to deredden the spectrum. We then estimate the approximate contribution of the stellar component with a stellar spectral slope of -2.8.

The $\lambda_{turnoff}$ is the wavelength where the disk flux is equal to the stellar flux. To determine the contribution of stellar and disk component (Fig. 2). In a typical SED composed of disk and stellar components, the spectral slope of the disk component increases as wavelength decreases, but start to decreases only when the wavelength decrease to the value where the stellar flux is comparable to the disk flux. Once we find the wavelength where the spectral slope turn off, the approximate contribution of the disk component can be derived from bands after the turnoff wavelength.

The assumption that the J, H and K band flux is entirely from the stellar component may lead to an overestimation in $\lambda_{turnoff}$, if there is a significant amount of disk flux in these bands. We estimate this bias using the JHK color-color diagram. Fig. 3 shows that most of our sample is distributed

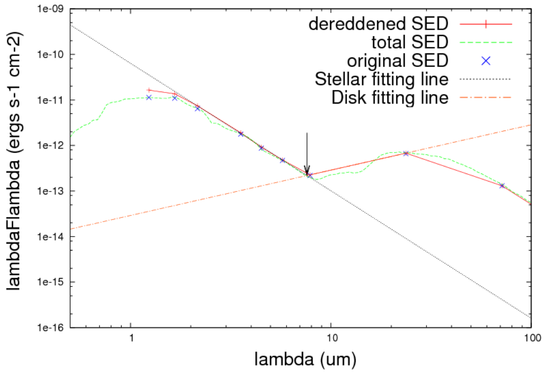

Fig. 2: Example of the determination the $\lambda_{turnoff}$ and α_{excess} in an SED. The black and orange lines are the estimated disk and stellar contribution. The arrow shows $\lambda_{turnoff}$.

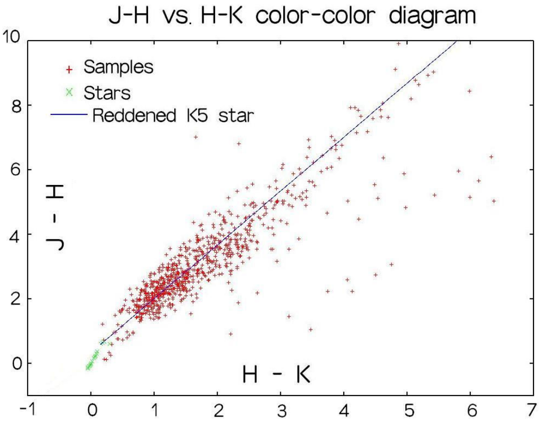

Fig. 3: J-H vs. H-K color-color diagram for all the samples. The red points are our sample, green points are the main sequence stars and the blue line shows a K5 type star with extinction. Some points have high extinction value due to the high uncertainty of J, H or K flux in observation.

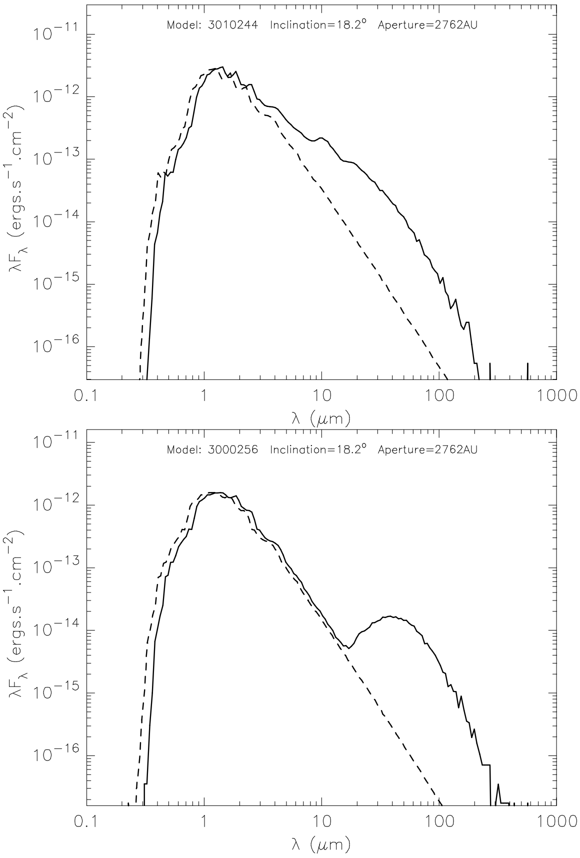

Fig. 4: Example of two types of transition disk. (Top panel) Without inner hole, the SED is relative smooth.. (Bottom panel) The inner holes in transitional disks result in a gap in SED.

around a line for a reddened K5 star with a dispersion of ~0.3 magnitude which results from the uncertainty of the measurements. Those samples with large color excess indeed have much larger measurement errors compared to samples with small color excess. For a source with color excess of ~0.3 magnitude (distance to the reddened K5 star line), we calculate that $\lambda_{\rm turnoff}$ will be overestimated 40%~16% for $\alpha_{\rm excess}$ of -1 to 1.

3. Model SED for transition disks

In order to calculate the expected $\lambda_{\rm turnoff}$ and $\alpha_{\rm excess}$ of YSOs with transition disks, we adopt the theoretical SED models of YSOs in Robitaille et al. (2006) and select the low mass models without envelopes (stellar mass $<1.4M_\odot$ and envelope mass $< 10^{-6}$ $M_\odot$). Currie et al. (2009) observed different types of disks in NGC2362, and estimated the range of disk mass and inner hole radius for different types of disks, which we took as the criteria to select YSO models from Robitaille et al. (2006). We select the models for primordial disks, transition disks, and debris disks with disk masses of 10^{-1}-$10^{-2.5}$ $M_\odot$, 10^{-5}-10^{-7} $M_\odot$, and $< 10^{-9}$ $M_\odot$, respectively. In addition, we separated transition disks into those with or without inner holes if the inner hole radius is larger or less than 1AU.

4. Results and Conclusion

4.1 $\alpha_{\rm excess}$ and $\lambda_{\rm turnoff}$ from theoretical model

Fig. 5 shows the face-on and edge-on model SEDs on the $\lambda_{\rm turnoff}$–$\alpha_{\rm excess}$ diagram. In the edge-on diagram, the $\lambda_{\rm turnoff}$ and $\alpha_{\rm excess}$ of primordial disks are larger than those on the face-on diagram, but the distributions of homologously depleted disks and canonical transition disks are similar in the two diagrams. The different distributions can be explained by the fact that the high disk mass in primordial disks will absorb more light from stellar radiation in edge-on systems and thus have a larger influence on SEDs, but the low disk mass in transition disks will not change the SEDs significantly. The results suggest that the face-on models are enough to predict the distribution of the transition disks on the diagram.

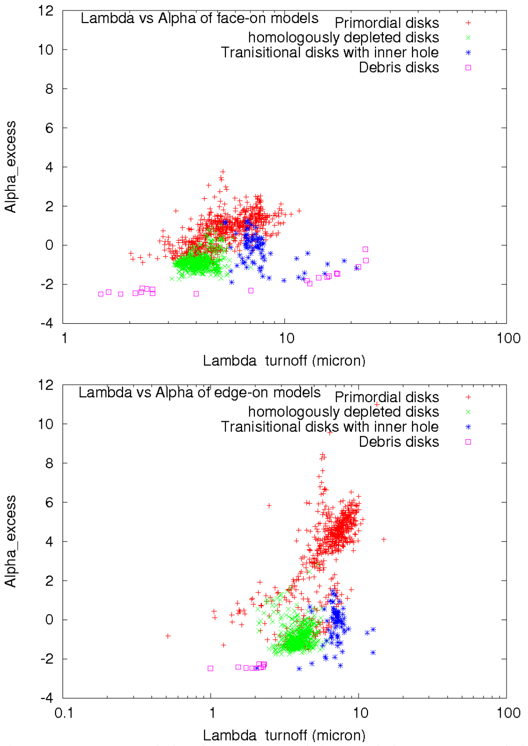

Fig. 5: Top panel is face-on models, and bottom panel is edge-on models. The diagram shows that the four types of disks are in different region. Inclination angle only has a large influence on primordial disks.

The diagram shows that the primordial disks, homologously depleted disks and canonical transition disks can be separated in most regions. It is possible to classify the disks by the position on the $\lambda_{\rm turnoff}$–$\alpha_{\rm excess}$ diagram. In order to compare the distribution of theoretical $\lambda_{\rm turnoff}$ and $\alpha_{\rm excess}$ to those from observational results, we derive the

$\lambda_{turnoff}$ and α_{excess} from the Hartmann et al. (2005) Taurus class II YSO data, whose median SED is often taken as a standard primordial disk SED, and plot them on $\lambda_{turnoff}-\alpha_{excess}$ diagram to examine the theoretical results (Fig.6). The diagram shows no Taurus class II YSO located in the $\alpha_{excess} > 1$ and $\lambda_{turnoff} > 5.5$ region where part of the theoretical primordial disks are located. The reason for the inconsistency may be that the YSO models have unrealistically large parameter ranges and not all of the models exist in real life. If we assume the class II Taurus YSO samples can represent the complete set of primordial disks, the samples in the $\alpha_{excess} > 1$ and $\lambda_{turnoff} > 5.5$ region are more likely canonical transition disks.

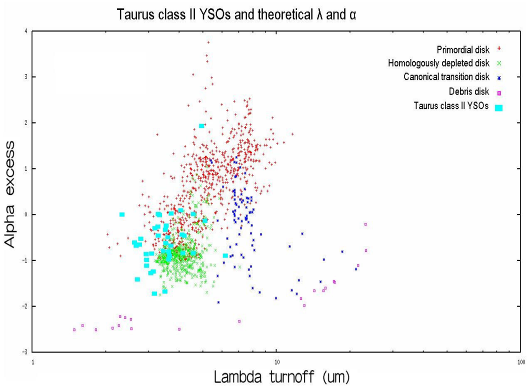

Fig. 6: Comparing the SED models to the Taurus class II YSO data in Hartmann et al. (2005). The median SEDs of Taurus class II sources often are taken as the standard SED of primordial disks.

Except for the $0.5 > \alpha_{excess} > -0.5$ and $\lambda_{turnoff} < 5.5$ region where the primordial disks and homologously depleted disks are mixed, the primordial disks, homologously depleted disks and canonical transition disks can be separated on the $\alpha_{excess}-\lambda_{turnoff}$ diagram. Here we suggest that we can classify the disk by the position of the disk in α_{excess} and $\lambda_{turnoff}$ space by the following criteria: the disks within $\lambda_{turnoff} < 5.5$ and $\alpha_{excess} > 0.5$ are primordial disks, the disks within $\lambda_{turnoff} < 5.5$ and

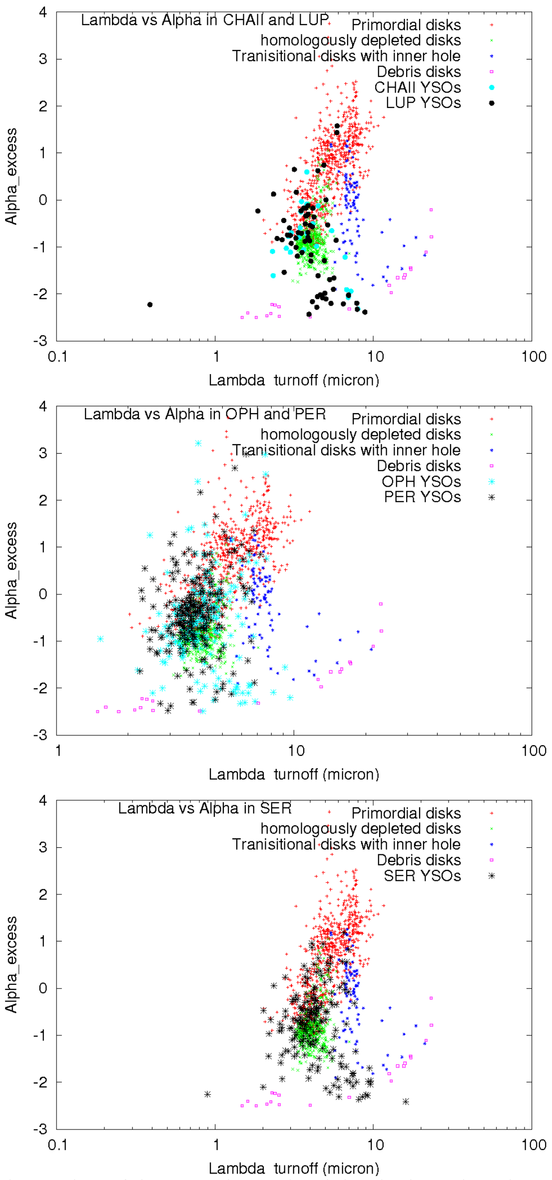

Fig. 7: Plots of the YSO observational data in the c2d catalog from CHA-II and LUP (top panel), PER and OPH (middle panel), SER (bottom panel) regions for the face-on models (Fig. 5). Most objects are in the homologously depleted region.

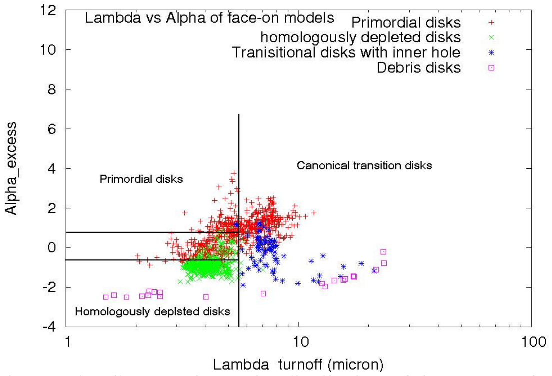

Fig. 8: The diagram shows the distribution of four types of disks, and the lines present the criteria we suggested to classify disks. The region between primordial disks and homologously depleted disks is difficult to separate.

$0.5 > \alpha_{excess} > -0.5$ are possible homologously depleted disk or primordial disks, the disks within $\lambda_{turnoff} < 5.5$ and $\alpha_{excess} < -0.5$ are homologously depleted disks and the disks within $\lambda_{turnoff} > 5.5$ are canonical transition disks (Fig. 8).

4.2 Implications for disk evolution

In Fig. 7 we plot the c2d YSO candidates on the $\lambda_{turnoff}$-α_{excess} diagram and compare them to theoretical predictions. The diagrams show that the distribution of most of the sample is locate in the primordial disk and homologously depleted disk region, which strongly favors the homologusly depleted disk as one evolutionary path. In addition to the homologously depleted disks, we also find a few of the sample located in the canonical transition disk region. The results are consistent with Currie et al. (2009) who suggest that at least two evolutionary path exist in transition disks. The diagrams also show variations in the distribution of the samples from different clouds. We will examine the difference by comparing the population ratio between disk types in the five regions.

Since we can classify the disks by the position in α_{excess} and $\lambda_{turnoff}$ space, it is therefore possible for us to estimate the population for different types of disks. Because there is no clear boundary between primordial disks and homologously depleted disks, if we take $\alpha_{excess} < -0.5$ to separate the homologouly depleted disks and primordial disks, the result will underestimate the number of homologously depleted disks, and the population of homoglously depleted disks will be the lower limit. On the other hand, if we take $\alpha_{excess} < 0.5$ to separate the homologouly depleted disks and primordial disks, the population of homologously depleted disks will be the upper limit. Therefore, we will derive both upper and lower limit for the population of the disks.

The ratios of primordial disks to both types of transition disks in Chameleon II, Lupus, Ophiuchus, Perseus, and Serpens clouds are 0.052-0.26, 0.044-0.29, 0.053-0.52, 0.091-0.90, and 0.045-0.45, which is much lower than previous results (Wolk & Walter 1996; Skrutskie et al. 1990). However, the ratio is underestimated since our samples may lack the primordial disks with excess in J, H or K bands and is highly uncertain because of the uncertainty in separating primordial disks and homologously depleted disks.

The ratios of canonical transition disks to homologously depleted disks are 0.21-0.375, 0.20-0.26, 0.20-0.29, 0.11-0.19 and 0.32-0.48 in the Chameleon II, Lupus, Ophiuchus, Perseus, and Serpens clouds. These ratios are roughly ~0.2, and are all lower than 1, which suggests that the most common disk dissipation mechanism is the homologous depletion process in these clouds. The ratio in Serpens is higher than other regions by a factor ~2 and the ratio in Peruses is slightly lower than other regions. The different ratios suggest that the physical conditions or the evolutionary stage may be different in these regions. Further work on comparing of the physical conditions of these regions could advance our knowledge on the disk evolution theory.

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