Planetary System Formation in Protoplanetary Disk around HL Tauri

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Since the outstanding pictures of HL Tau protoplanetary disk are unveiled, it has been demanded to investigate how much we can constrain the disk structure and physical properties. We re-processed the ALMA long-baseline science verification data taken toward HL Tauri [1] and improved the image quality by modifying data flagging and contriving ways to make deconvolution as shown in Figure 1. Assuming the observed gaps are opened up by currently forming, unseen bodies, we estimate the mass of such hypothetical bodies at the first 4 gaps from the central star based on following two approaches; the Hill radius analysis and a more elaborated approach developed from the angular momentum transfer analysis in gas disks. For the former, the measured gap widths are used for estimating the mass of the bodies, while for the latter, the measured gap depths are utilized [2]. As a result, their masses are comparable to or less than the mass of Jovian planets. By evaluating Toomre's gravitational instability (GI) condition and cooling effect, we find that the GI might be a possible mechanism and can occur in the region beyond $r \sim 52\,\mathrm{AU}$, where both of the conditions are simultaneously met as shown by the shaded area in Figure 2.

Since the disk might be gravitationally unstable only in the outer region of the disk, inward planetary migration would be needed to construct the current architecture of the observed disk. We estimate the gap-opening mass (M_{gap}) to show what type of migration can take place in the HL Tau system, and can be expressed as

$$M_{gap} \simeq 2.7 M_{\oplus} \times \left(\frac{r}{1\ \mathrm{AU}}\right)^{3/2} \left(\frac{M_*}{1 M_{\odot}}\right)^{-1/2} \left(\frac{T}{100\mathrm{K}}\right)^{3/2}. \quad (1)$$

As a result of comparing planet masses with M_{gap}, planets are sufficiently massive to open up a gap in their gas disk via disk-planet interactions, and hence the planets will undergo type II migration. Combining GIs with inward migration, we conjecture that all of the observed gaps may be a consequence of bodies that might have originally formed at the outer part of the disk, and have subsequently migrated to the current locations. While ALMA's unprecedented high spatial resolution observations can revolutionize our picture of planet formation, more dedicated observational and theoretical studies are needed to fully understand the HL Tauri images.

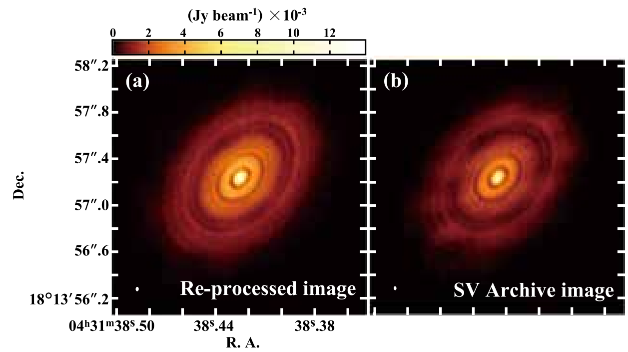

Figure 1: Comparison of the 0.87 mm continuum dust emission of HL Tau between our re-processed image (a) and the archive data (b).

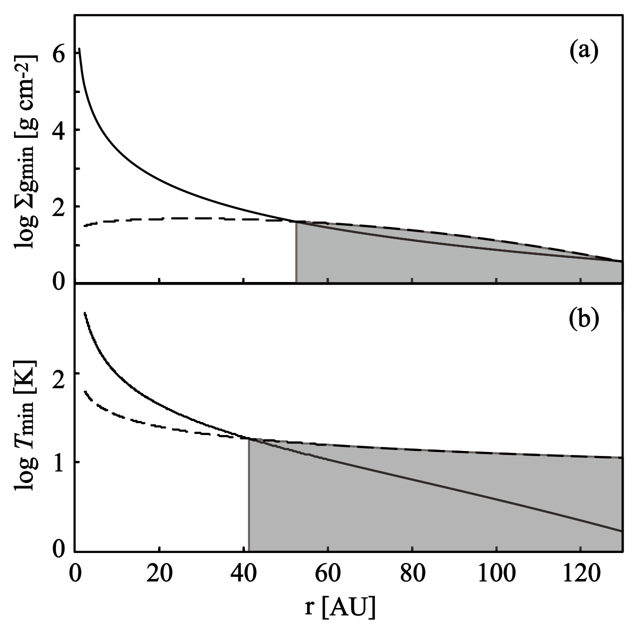

Figure 2: Panel (a) represents the surface density distribution of Kwon et al. (2011) model (solid curve) [3] and the minimum surface density of gas (Σ_{gmin}) that is required to trigger GIs (dashed curve). Panel (b) shows the radial temperature distribution given by power low function (solid curve) and the minimum disk temperature (T_{min}) that satisfies the cooling condition of the GI (dashed curve). The shaded area in both panels represents the region where the GI can be invoked.

References

[1] ALMA Partnership, Brogan, C. L., Perez, L. M., et al.: 2015, *ApJ*, **808**, L3.

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[3] Kwon, W., Looney, L. W., Mundy, L. G.: 2011, *ApJ*, **741**, 3.