The Statement of Research

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1. Introduction

How are stars and planets formed? This is a question fundamental to our understanding of the origin of solar system and the origin of life. A widely accepted, well established scenario is the following: gravitational collapse of a clump of molecular cloud forms a disk around a growing protostar, and bipolar outflows enable growth by discarding the disk's angular momentum. After all the envelope material has been accreted on to the disk and the material ejection from the outflows ceased, what remains is the central star surrounded by a circumstellar accretion disk (a.k.a. protoplanetary disk) which planets form.

Even though the scenario paints the big picture of star and planetary system formation, there are still many details unseen and puzzles to solve. When and how are planets formed? How is a star-forming system affected by the surrounding environment? How do gas and dust evolve from ISM to planetary-system ingredients?

My research has been focused on trying to understand how protoplanetary disks evolve from Class II sources to Class III sources, i.e., from protoplanetary disk to planetary systems by using mid-IR spectra of young stellar objects (YSOs), observed with Infrared Spectrograph (*IRS*; Houck et al. (2004)) on board the Spitzer Space Telescope (Werner et al. 2004).

I'll describe some highlights of my current research and achievements.

2. Current Research Achievements

I have been deeply involved in the reduction and analysis of the IRS spectra of over 600 Class II YSOs from a large survey in five nearby star-forming regions - Taurus-Auriga (henceforth Tau-Aur), Chamaeleon I (henceforth Cha I), Ophiuchus (henceforth Oph), L1641, and the Orion Nebular Cluster (henceforth ONC) - conducted by the IRS instrument team and its IRS Disks guaranteed-time and general observing team. My focus has been on the analysis of transitional disks: disks which have a gap or central hole. I have carried out a statistical study in search of trends among disk properties and stellar properties. I have been in charge of reducing and analyzing IRS data of protoplanetary disks (~ 300 Class II YSOs) in the Orion A star-forming region (including ONC and L1641), which offers star-forming environments radically different from those of Tau-Aur, Cha I, and Oph regions, as well as some that approach conditions in these clouds.

In addition to the analysis of mid-IR spectra from *Spitzer*-IRS and protoplanetary-disk properties, I also analyze near-IR spectra, far-IR spectra, and sub-mm spectra: (1) near-IR spectra of IRTF-SpeX to understand mass accretion behavior from disk to the host star; (2) accepted proposal to acquire FIR spectra with *Herschel*-PACS to analyze Polycyclic Aromatic Hydrocarbon (PAH) molecules in disks around low-mass T Tauri stars, which will illuminate the origin of organic molecules in the solar system; (3) broadband sub-mm single-dish observations proposed to measure masses of transitional disk to help understanding of planet formation process. Below, I describe the highlights of my current research work.

2-1. Observational constraints on mechanisms of Transitional disks

Transitional disks are protoplanetary disks around young stars that have inner holes or gaps on AU scales. The characteristics of the SEDs of these object are a significant deficit of flux in the near-infrared (at <10 μm) wavelengths relative to those of the optically thick disks of Class II objects and a steeply rising continuum beyond 13 μm indicating substantial excess at mid- and far-infrared wavelengths. Self-consistent models of transitional disks in Tau-Aur have shown that the deficits correspond to gaps or central holes in the transitional disks. Several different inner disk structures of transitional disks have been also discovered with the detailed models (D'Alessio et al. 2005; Calvet et al. 2005; Espaillat et al. 2007a,b, 2008): transitional disks with central clearing (TD), e.g., DM Tau; optically thin inner disk separated from optically thick outer disk by a gap (WTD), e.g., GM Aur; optically thick inner disk and optically thick outer disk separated by a gap, pre-transitional disk (PTD), e.g., LkCa 15.

While modelers elaborately tune disk models to suggest disk structure and properties of each transitional disk, and theorists work on mechanisms to explain the existence of a gap/hole and time scales of transitional disks, I conduct statistical studies of large samples of transitional disks. I collected over 60 transitional disks in the five star forming regions and applied a simple radiative transfer model to estimate the hole size of each (see, Kim et al. (2009) for detail), and seek trends between a disk property (the location of inner edge of an optically thick outer disk, R_{wall}) and other stellar properties such as T_{eff}, M_{star}, dM/dt , and L_X. I found a significant correlation between R_{wall} and T_{eff}, and R_{wall} and M_{star}.

dM/dt is a key parameter to examine different mechanisms because each of them predicts distinctive trends between dM/dt and disk properties (R_{wall} and M_{disk}). However, dM/dt was not available from preceding work for most of our transitional disks. To get dM/dt of transitional disks in ONC and L1641, I have so far observed some 30 transitional disks in the Orion A star-forming region with SpeX mounted on the 3-m telescope at the NASA Infrared Telescope Facility (IRTF). From these spectra I measured mass accretion rates from hydrogen recombination lines (Pa β, and Br γ). From the results emerges a relation between dM/dt and R_{wall}, and I found that dM/dt of transitional disks are generally factor of 10 lower than that of general Class II objects with optically thick full disk, as expected by Najita et al. (2007), but we didn't find any significant correlation between dM/dt and R_{wall} after normalizing those two parameters to M_{star} (Fig 1.; Kim et al. 2011 in preparation).

These findings strongly support the explanation that a radial gap is opened and the inner disk is cleared by the dynamical effects of stellar or planetary companions (Forrest et al. 2004; Quillen et al. 2004; Ireland & Kraus 2008; Artymowicz & Lubow 1994).

One of most important properties to understand in the origin of transitional disks and planet formation is the mass of disks (M_{disk}), because planets form in circumstellar disks. The mass of disks can be measured form the continuum flux density at sub-millimeter/millimeter. Therefore, I have proposed to observe our sample of transitional disks in the Orion A region with SHARC-II bolometer camera at Caltech Submillimeter Observatory (CSO). From the accepted proposal, we will be able to see not only the distribution of disk mass along the diverse transitional disks, but also the degree of grain growth in the transitional disks. I expect that this study will help to enhance our understanding on planet formation.

2-2. Environmental effects on the evolution of protoplanetary disks

Do planets form in every T Tauri star – accretion disk system? If not, what would control the efficiency of planet formation and location of planet formation in a disk? How do host stellar properties affect its circumstellar disk and materials (gas and dust) of the disk? How do different density and radiation environments affect disk evolution, and how does this proceed with increasing age? Furlan et al. (2009) compared the median mid-infrared spectra of objects in Tau-Aur, Cha I, and Oph regions and found that they are similar in shape, suggesting, on average similar disk structures. My preliminary analysis with about 240 Class II YSOs observed with the Short-Low (SL; 5-14 μm) and Long-Low (LL; 14-35 μm) modules of IRS, however, tells that the median spectra of Class II objects in L1641 and ONC are rather different than that in Tau-Aur. Some disk parameters deduced from the IRS spectra are (1) the equivalent width of 10 μm silicate feature (EW_{10}), (2) the flux ratio of $F_{11.3}/F_{9.8}$, and (3) the spectral index between 13 μm and 31 μm ($n_{13\text{-}31}$). EW_{10} is a good indicator of the degree of dust processing: objects with low EW_{10} values show evidence for highly processed dust grains (crystallinity, grain growth, or both) and objects with high EW_{10} values show relatively unprocessed grains. The flux ratio of $F_{11.3}/F_{9.8}$ also has been considered as a measure of dust processing, in the inner 1-2 AU of the disk (e.g. McClure et al. 2010). The higher the value of the ratio $F_{11.3}/F_{9.8}$, more processed are the dust grains emitting it. The spectral index, $n_{13\text{-}31}$, tells us how the outer disk is flared. From the comparisons of median IRS spectra of L1641, ONC, and Tau-Aur, we find the following: (1) EW_{10}: ONC ~ L1641 > Tau-Aur; (2) $F_{11.3}/F_{9.8}$: Tau-Aur ≥ L1641 > ONC; (3) $n_{13\text{-}31}$: ONC ~ L1641 ~ Tau-Aur. Thus disk structures in these various regions may be similar (similar $n_{13\text{-}31}$), but the degree of dust processing may be weaker in protoplanetary disks in ONC than L1641 and Tau-Aur. If I consider the median ages of ONC (< 0.8-1 Myr), L1641 (~1 Myr), and Tau-Aur (~2 Myr), there may be an age dependence on dust processing (Kim et al. 2011b, in preparation).

I found that the frequency of transitional disks in ONC and L1641 is higher than that in Tau, Cha I and Oph. An interesting result is that the frequency of PTD is higher than that of TD for ONC, which has the youngest median age among the five star-forming regions. Similar results are obtained for the NGC 1333 star-forming region (Arnold et al. 2011 in preparation), which is younger than the median age of ONC. This may be because there are gap openings in young protoplanetary disks (< 1 Myr), but a planet which opens a gap may not yet grow or have completed enough orbits to clear out their inner disks.

2-3. Contribution to Spitzer data reduction

It is very important to minimize artifacts of the instrument and the natural backgrounds when one reduces data. My major contribution to the Spitzer data reduction is not only testing several versions of source extraction methods but also identifying transiently-bad ("rogue") pixels and eliminating them when necessary. Mask files of rogue pixels, pixel fixing (replacement) software, and calibration with relative spectral response functions improve spectra dramatically over "untreated" spectra. Using the data-cleaning method developed by me and colleagues in the IRS Disks team is particularly important for spectra which contain many emission lines (e.g. NGC 1333-IRAS 4B, Watson et al. (2007)). Most rogue pixels and bad pixels in IRS data taken by our team were weeded using my library of Grand Rogue Pixel Masks and then were interpolated out of the data.

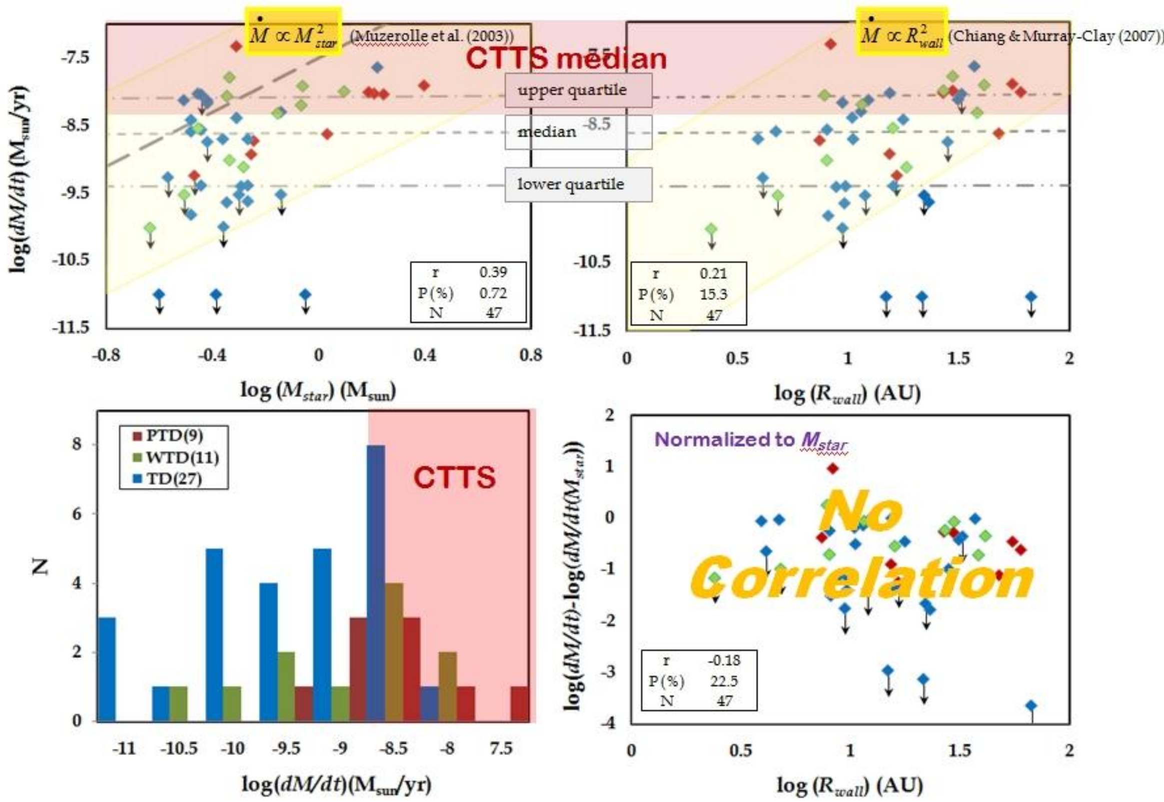

Figure 1. The properties of mass accretion rate of transitional disks. The different color codes (red, green, and blue) indicate various types of transitional disks (pre-transitional disks like LkCa 15 (PTD), transitional disks having a gap separated between optically thin inner disk and optically thick inner disk like GM Aur, weak-transitional disks (WTD), and transitional disks with a hole like DM Tau (TD)). In the figures the yellow shadow and the gray long dashed line are to guide the relation of *dM/dt* and M_{star} from radially full disks in Taurus star-forming region. The pink shadows indicate the range of median mass accretion rate of ordinary CTTS. Upper left panel: a correlation between *dM/dt* and M_{star}.. Lower left panel: Mass accretion rates distribution of transitional disks.. This histogram indicate the mass accretion rates of transitional disks are lower than that of CTTS . Upper right panel: a transitional disks distribution in *dM/dt* and R_{wall}. Lower right panel: No correlation found between *dM/dt* and R_{wall} after decoupling M_{star} correlated to *dM/dt*.

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