Future Research Proposal

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My research plan for the next few years and for the next decade is to extend my current research to answers the broad questions: (1) How do disks evolve and form planetary systems? (2) What is the origin of life?

We have been taking advantage of the Spitzer Space Telescope to reveal various stages of star formation and evolution of protoplanetary disks. One of our major achievements with *Spitzer* and its Infrared Spectrograph is the identification of a large sample of transitional disks. As suggested by our statistical study on the properties of transitional disks to understand the origin of central hole/gap in the transitional disks (Kim et al. 2009; Kim et al. 2011 in prep) and by some resolved gap/hole images of the transitional disks at the sub-mm or mm interferometer (e.g. Hughes et al. 2009 for GM Aur), giant planet formation seems to be the mechanism responsible for gaps in transitional disks.

Therefore, deeper studies on protoplanetary disks, especially transitional disks, are indispensible to the study of how planetary system form and evolve. With opportunities for significantly improved angular resolution and sensitivity from ALMA, EVAL, SOFIA, JWST, SPICA, and GMT/TMT, as well as *Herschel* operating now (see, Fig 2.), I hereby propose projects which could be carried out in the near future and which would lead us closer to answering to some of the fundamental questions listed above.

1. Mass accretion properties of Class II YSOs in the Orion A star-forming region

The mass accretion rate is a key parameter in young stars and protoplanetary disks. Most of the mass of a new star is accreted in an early phase of development. Most stars younger than 3 Myr have an accretion disk, and the accretion flow in the disk is often important in the disk's thermal state. Protoplanetary disks dissipate by yielding material to their central star, by photoevaporation from starlight, and by planet formation within the disk, and all processes are active 1-10 Myr after star birth. This phase of evolution is represented by the Class II young stellar objects (YSOs), which include classical T Tauri stars (CTTS) with optically thick accretion disks, weak-lined T Tauri stars (WTTS) with optically thin disks and little accretion, and transitional disks (TDs). Details of the relationship between these distinct subclasses raise questions that require better statistics of disk-star accretion rates for their answers. How is the mass accretion rate related to other stellar and disk properties? What is the true range of variation of accretion rate with stellar mass, disk mass, and age, about the trends already observed? Is mass accretion rate related to coronal or chromospheric activity of the central star or nearby object? Do these properties and relations differ with different star-forming environments and initial conditions?

To address these questions, I anticipate using several ground based telescopes (e.g. Keck/Gemini/SMA) and space telescopes (e.g., *Chandra*) in combination with my ongoing program with IRFT-SpeX/SXD to take 0.8 μm - 2.4 μm spectra of Class II YSOs in Orion A to measure their mass accretion rates. The protoplanetary disks in the sample, which had been already characterized from the high quality 5-40 μm spectra of IRS, represent a diverse range of disk evolutionary stages, and exhibit radial and vertical structure which we infer from IRS spectra. With this sample it will be possible to examine the evolution of disk-star accretion in the age range of Orion A Class II (0.7-3 Myr) with high statistical significance and few biases.

2. Gas in the gap/hole of transitional disks

Most of the mass in a protoplanetary disk is of course in the form of gas, but there is not much detailed information on gas in the disk at present: gas lines at millimeter wavelengths probe the outer disk, and gas lines in the mid- and near-IR probe the innermost warm and hot disk regions, but much of the information the lines bear on density, temperature and chemical abundance is beyond our reach at current spatial and spectral resolution.

How does gas affect the planet formation and disk structure? To answer this question, we need to detect gas lines to probe disk structure radially and vertically. If we are able to detect gas in the gaps of transitional disks, we can approach much more closely to the answer because the transitional disks are in the critical stage of gas giant planets formation. We can analyze gas lines of transitional disks along the gap/hole size range in 5-60 AU, the temperature at the inner wall of optically thick outer disks, and gas and dust density in gaps/holes. The comparison between gas line properties of transitional disks and that of radially continuous disks (with same Spectral Type range, similar size of sample) will help us to understand how gas and dust in a disk evolve, setting parameters for disk evolution mechanisms

Therefore, I propose to search for atomic fine structure lines -- [OI] 63 µm and 145 µm, [CII] at 158 µm – of transitional disks in the Orion A region. These lines are quite strong in radially-continuous disks, and furthermore comprise good probes of density and temperature. Currently we can observe these lines with the PACS instrument on *Herschel* (PACS; SPIRE), and future opportunities may be provided by SOFIA (SAFIRE, 2012) and SPICA (SAFARI/BLISS, 2017). The corresponding mid-infrared fine structure emission of our sample of transitional disks was beyond the reach of Spitzer-IRS, but will be within the grasp of the MIRI instrument on JWST (2012).

I will also plan to use a near-IR spectrograph of the Giant Magellan Telescope (GMT) or Thirty Meter Telescope (TMT) to detect atomic lines and molecular gas lines when it available (>2020). In the future, it may be possible to estimate velocity and amount of gas flow from the disk to planets by detecting gas lines with an instrument with high sensitivity and high resolving power, which will be mounted on the GMT or TMT.

3. PAHs in the protoplanetary disks, the origins of organic materials

Polycyclic Aromatic Hydrocarbon (PAH) molecules are generally considered as the carriers of the unidentified infrared emission features (Gillett et al. 1973) at 3.3, 6.2, 7.7, 8.6, and 11.3 µm. Unlike the cases of the environs of high-mass stars, or the disks around HAeBe stars, there are not many PAH detections from disks around T Tauri stars, because stars with spectral type later than G do not radiate enough stellar UV field to excite PAHs efficiently in the disks. Recently, however, I observed strong PAH features in protoplanetary disks around M and K type protostars located near the Trapezium in the Orion Nebular Cluster (ONC) in *Spitzer* mid-IR (5-14 µm) spectra.

There are many reasons why PAHs in protoplanetary disks, especially disks around low mass stars, are important to characterize thoroughly. Some major reasons are the following: (1) The most primitive (carbonaceous chondritic) organic material in our Solar system contains

PAHs in large abundance; thus observations of these features in disks can potentially offer a concordance of organic material in current planet-forming regions with that of our own fossil record. (2) PAHs in protoplanetary disks are in an environment much denser than the ISM. Therefore, PAH species in disks may be different in size, molecular structures, vibrational modes, *etc*. than that in the ISM. We may also expect to detect size variation from the surface layers of disks to the mid-plane, which will help to understand dust evolution through grain growth and dust settling. (3) PAHs provide a probe of how certain environmental parameters -- density, UV strength -- affect the evolution of protoplanetary disks.

There have been difficulties understanding astronomical PAH species in the mid-IR because theoretical and laboratory work focuses mostly on the mid-IR range with compact PAHs; in this range, it is hard to distinguish feature components from different species. Recently, elaborate laboratory and theoretical works have been conducted for various PAH species in the far-IR range (50-1000 μm): Mattioda et al. (2009) for moderate size of neutral PAHs (coronene, ovalene, and dicoronylene); Ricca et al. (2010) for very large neutral PAHs; Ysard & Verstraete (2010) for the long-wavelength emission of interstellar PAHs in their vibrational and rotational transitions; Zhang et al. (2010) for far-IR spectroscopy of cationic PAHs. Based on those models, the wavelength and strength of features in the far-IR/sub-mm range due to lower energy level transitions of different PAH species, sizes, and ionization states are distinguishable, unlike features in the mid-IR range.

Therefore, as the extent of the accepted proposal for *PACS/Herschel* to observe K-M type protostars which show PAH features, the future observation at the far-IR wavelength (200-600 μm) (*SPIRE/Herschel*) and at the sub-mm/mm wavelength (ALMA) will be necessary. I expect that the future observation of PAH features from disks around low mass stars will help us to understand the evolution of organic molecules from the ISM to planets.

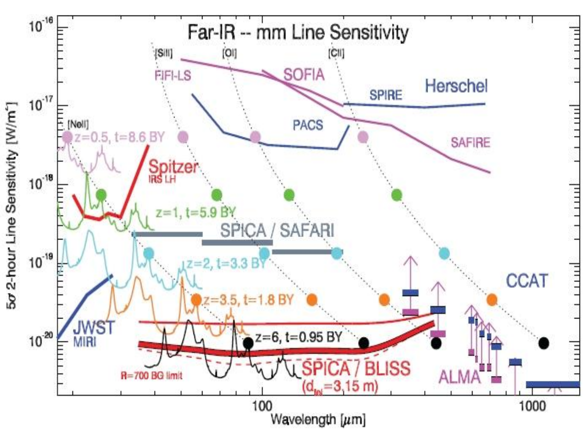

Figure 2. Sensitivities of current and future instruments. (taken from Bradford et al. 2010)

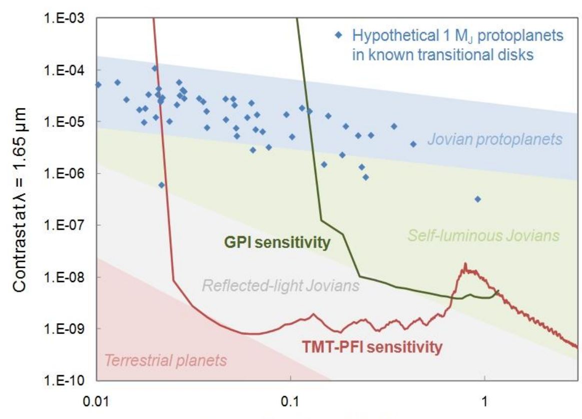

Figure 3. Photometric contrast with respect to parent star required for detection in the astronomical H band of hypothetical, ringless, Jovian-mass protoplanets in the gaps of known transitional disks (blue diamonds; identified and estimated hole sizes of them by Kim. K. H. et al from IRS spectra.). This figure is captured from Figure 4.10 in the Panel Reports—New World, New Horizons in Astronomy and Astrophysics (http://www.nap.edu/catalog/12982.html).

4. High resolution imaging of transitional disks: screen captures of giant planet formation

(1) Resolved images of gap/hole of transitional disks at submm/mm/cm wavelengths:

As well as high-spectral-resolution observation, high resolution (at 10 mas) imaging of protoplanetary disks will be possible at sub-mm/mm (ALMA) and cm/m (EVLA). Exciting outcomes of this future observational advantages is not only to resolve gaps/holes of transitional disks located even far as 400-500 pc in the Orion star-forming region, but also to detect small-scale structures such like spiral waves or clumps that indicate the dynamics of planet formation.

As a beginning step of this project, I plan to propose to observe transitional disks with larger holes (> 20 AU) which may be resolvable with ALMA at early science (2011). Then the survey can be extended to image smaller (< 10AU) gap/holes in transitional disks in long term plan.

(2) Direct imaging survey of giant planets in transitional disks:

Because the mass-luminosity-age relation is very sensitive to the planet formation scenario (Baraffe et al. 2003; Marley et al 2007; Fortney et al 2008), the detections of newborn giant planets (< 5 Myr) can be used to test two most competitive theories of the giant planet formation: whether in a "cold-start" nucleated instability around a rock-ice core (a.k.a "core-accretion" formation), or in a "hot-start', high entropy, gravitationally unstable clump of disk gas.

This is very challengeable project, but there is possible sources which can be detectable with the 5σ contrast sensitivities for the Gemini Planet Imager (GPI, 2012) if we assume that giant planets form in the transitional disks identified from IRS spectra (blue diamonds in the Figure 3) and lie just inside the outer edge of the inferred gaps (Kim et al. 2011 in prep). This project will be fertile when the future near-IR instruments of high resolution with super sensitivity are available at the future facilities like GMT/TMT.

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