Subaru/COMICS view of star and planet formation

Yoshiko K. Okamot (Ibaraki U)

Collaborators:
H. Kataza (ISAS/JAXA),
M. Honda (Kanagawa Univ.),
H. Fujiwara, I. Sakon, T. Onaka (UT),
T. Yamashita, T. Fujiyoshi (NAOJ),
T. Miyata, S. Sako (IoA, UT)

Joint Subaru/Gemini Science Conference @Kyoto U., May 18-21, 2009
Outline

- Circumstellar disks related to star and planet formation
  - Planet formation in circumstellar disks around low to intermediate mass stars
    - Grain evolution in the disks
    - Structure and dust distribution in the disks
      - Appearance of early planetary systems
  - Disks related to massive star formation
- Summary and Future Prospects
1. Planet formation in circumstellar disks around low to intermediate mass stars
Evolution of circumstellar disks and planet formation

1. Grain growth and sedimentation in a protoplanetary disk (PPD)
   - Gas + dust
   - Protoplanetary disk
   - Star

2. Formation of planetesimals (km size bodies)
   - Planetesimals

3. Formation of protoplanets, accretion onto it, and gas dissipation
   - Protoplanet

4. Planetary system – main sequence star sometimes with a debris disk (DD)
   - Dust cloud or group of small bodies
   - Terrestrial planets
   - Gas giant planets
Dust processes in the disks

Dust in protoplanetary disks – change from the ISM dust

- Inner disk
  - dust formed at high T
  - annealing/crystallization
- Super-Heated layer
- Dust flow from X-wind?
- Material transport by diffusion and turbulent flow
  - inner disk ↔ outer disk
  - surface ↔ midplane
- Disk gap related to (proto)planet formation
- Probing the disk geometry
- PAH emission which can be excited out to >100AU by the direct stellar UV
- Dust dynamics dominated by radiation pressure, Poynting-Robertson drag, and resonance with planets
- Collision of planetesimals
- Group of small bodies and replenished dust cloud
- Comets passing by the star

Dust in debris disks – replenished dust

- Increased speed of grain growth due to ice outside of the snowline
- Grain growth/sedimentation
- Flatening of disk
- Planetesimal formation

Probing the disk geometry with PAH emission which can be excited out to >100AU by the direct stellar UV

Material transport by diffusion and turbulent flow
- inner disk ↔ outer disk
- surface ↔ midplane

Dust flow from X-wind?

Probing the disk geometry with PAH emission which can be excited out to >100AU by the direct stellar UV
Observing disk dust w Subaru/COMICS

- Powerful to study dust processes
  - MIR imaging and spectroscopy w a slit viewer @10/20μm regions
  - Diffraction limited resolution (0.3”@10μm)
    - Observation/Reduction techniques are developed
    - Resolving bright circumstellar disks
  - Probe inner disks corresponding to planet forming region (<~50AU)
  - Many dust features in the MIR
    - Species, composition, temperature, size, crystallinity, and environment of grains
  - High sensitivity

→ Many disk observations
  - Grain evolution, disk structure, dust distribution in the disks
1.1 Grain evolution in the disks

- Silicate features sensitively depend on:
  - Grain size
  - Crystallization ($T > \sim 800 K$)
  - Composition

- Observing the silicate features in the disks is probing the grain evolution in the disks

**Evolution of silicate grains in TTS disks** (Honda+2006)

- R$\sim$250 spectroscopy in the 10$\mu$m region of disks around 30 young low-mass stars
  - Grain growth
  - Crystallization related to high $T$ processes

**Silicate Evolutions**

- Drawn by using data observed with COMICS

- Many peaks due to crystalline silicate
- Mg-rich olivine and enstatite
- 1$\mu$m amorphous silicate
- C/2002V1 (comet)

- Hen 3+6 01A
- LRH10264 (TTS)
Composition analysis by spectral fitting

\[ F_\nu(\lambda) = B_\nu(T, \lambda) \left\{ a_0 + \sum_{i=1}^{5} \sum_{j=0.1, 1.5 \mu m} [a_{i,j} \kappa_{i,j}(\lambda)] \right\} + a_{PAH} F_{\nu,PAH}(\lambda), \]

\[ f_{i,j}[^\circ] = \frac{100a_{i,j}}{\sum_{i=1}^{5} \sum_{j=0.1, 1.5 \mu m} a_{i,j}}. \]

van Boekel et al. 2005. For silicate, 0.1\(\mu\)m radius grains (solid lines) and 1.5\(\mu\)m radius grains (dotted lines).
Correlation

- between the feature strength and the feature shape
- between the feature strength and the fraction of the big grains

→ Suggesting grain growth

2) When large amorphous grains become dominant by grain coagulation, the weak trapezoidal feature develops.

3) The feature vanishes when grains smaller than a few microns are depleted.

(1) Small subμm amorphous grains dominate in the dust population and result in the strong triangular feature.

![Graph showing correlation between feature strength and feature shape](image)
Relation between the dust and the stellar or disk properties

- Silicate dust properties
  - Feature strength or crystalline fraction

- Stellar or disk parameters
  - \( L(H\alpha) \) as an indicator of accretion activity
  - opacity power-law index \( \beta \) in the radio which probes the grain growth in cold regions
  - stellar age from HR diagram
  - \( M_{\text{disk}} \) from the radio

Only correlation we found is between the feature strength and the \( L(H\alpha) \)
Correlation between the feature strength and $L(\text{H}\alpha)$

- The depletion of small sub-$\mu$m grains occurs as accretion activity ceases
  - Turbulence in the disks stirs the grains up to the surface layer and might make the small grains detectable during the active accretion

No correlation between the feature strength and $\beta$

- The timescale of the dust evolution differs between warm and cold regions
  - Rapid grain growth to mm-sizes
  - Rapid sedimentation of the grown dust grains to the midplane occurs
  - completing $\beta$ evolution at an early TTS phase

No correlation between the crystallinity and the stellar/disk evolution

- 5-20% crystalline grains are regularly present in PPDs from young to old TTSs
  - Crystallization of this level has completed at a very early stage of or before the TTS phase (probably at protostar and/or FU Ori stages)
- Consistent with model calculation including radial material transport, which expects that the crystallinity comes in equilibriuim within $\sim 10^6$ yrs
1.2 Structure and dust distribution of the circumstellar disks

- Size of warm region is closely related to the disk geometry
  - Larger for the disks well irradiated by the stellar radiation to the outer regions
- High resol. imaging survey of disks in the 10 and 20μm-bands for nearby HAEBEs (Okamoto+2005; Honda+2005)
  - Direct test for the thermal structure estimated from SED
  - ~300K~150K region w 0.3~0.6'' PSF
- Group I disks tend to be extended
  - In size or in the fraction of extended samples
  - roughly consistent with the prediction by SEDs but there is variety
COMICS image resolved the cool outer disk of this group I HAE
- Gap between the inner and the outer disks
  - $r \sim 0.85''$ (170AU) for outer component
  - Larger $\tau$ for E (0.057) than W (0.018)
- Color temperature from 18.8/24.5$\mu$m
  - Almost the same (82-85K) for E and W components

Inverse flux distribution for MIR against NIR suggests a disk with a gap inclined
- MIR thermal emission
  - E rim exposed to us, while W rim obscured
- NIR scattered light
  - Forward-scattered light in the western side
**H₂O ice in HD142527 disk**
*(Honda+2009, poster)*

- Ice condensation increases solid mass outside the snowline
  - It helps formation of cores of gas giant planets
  - The radial distribution is important
- Coronagraph multi-band imaging of HD142527 w Subaru/CIAO
  - At H (1.6μm), K (2.2μm), H₂O (3.08μm), L’ (3.8μm)
- The 1st detection of H₂O ice absorption at 3.1μm in the scattered light spectra
  - H₂O ice is ubiquitous at the observed region (R>140AU)

---

![Graph showing HD142527 total and scattered light spectra](image)

- No feature
- Stern spectrum

![Diagram showing snowline and radial distribution](image)

- Increased solid mass
- Grains w/o ice mantle
- Grains w ice mantle
High spatial resolution spectroscopy of the extended debris disk $\beta$ Pic
(Okamoto+2004)

- Study of the silicate dust distribution in planet forming region ($<50$AU)
- Obtained spectra fitted with
  - 0.1$\mu$m amorphous olivine (green)
  - 2$\mu$m amorphous olivine (red)
  - Crystalline forsterite (blue)
  - Power-law continuum (cyan)
  - Total (magenta)

![Graph showing spectra](image)

- Dust disk
- Masked area
- Smith & Terrille 1984
- Okamoto et al. 2004, Nature
Distribution of sub-μm grains shows location of dust replenishment

- Small amorphous silicate grains have distribution peaks at 6, 16, & 30AU
- Grains are replenished there.
  - Since such small grains are blown-out by radiation pressure quickly (∼10yr).
  - Larger grains replenished there infall toward the star due to PR drag.
  - Near the star, grains are crystallized by heating due to stellar radiation.

10μm brightness of each silicate feature
Planetesimal belts replenishing grains

- Ring-like planetesimal distribution
  - Grain replenishment: $10^{15-16}$ kg/yr
    - $10^{5-6}$ times larger than that of zodiacal dust
  - The belts seem to be in resonance:
    - We predicted that they are in resonance with planets

- Confirming simulations
  (Freistetter+2007)
  - 2-5M$_J$ planet at 12AU, $e<\sim0.1$
    - Warp, 6&16AU belts, FEBs
  - Two more at 25 & 45 AU likely
  - Planet masses are estimated

- Lagrange+2008
  - Direct detection of 8MJ planet at $\sim8$AU?

![Graph showing the number of planets at different semimajor axes (AU)]
2. Formation of Massive Stars
Disks and massive star formation ($\geq 8M_\odot$)

- Massive star formation is much less understood than the formation of lower mass stars
  - For very massive stars (a few tens $M_\odot$), radiation pressure of the forming star may stop the accretion onto the forming star.
  - Rapid evolution and formation in cluster
    - difficult to see the forming massive stars very clearly and separately
  - Accretion through disks or merging of lower-mass stars?
    - There are about a dozen of disk candidates around massive YSOs up to $M_\ast \sim 10\text{-}20M_\odot$ stars
    - Interferometric observations at mm and sub-mm wavelengths
    - Rotating gas fragments with velocity gradient perpendicular to the outflow
    - Little clear disk image in the infrared regions so far
      - In contrast with the situation for the lower-mass stars
Discovery of a disk around HD200775
(Okamoto+ submitted)

HD200775
- d=430 $^{+160}_{-90}$ pc (Hipparcos)
- Herbig B3 (±1) e star
  - Based on optical lines (Hernandez+2004)
  - 5400L$_\odot$ (if Rv=3.0) to 15000L$_\odot$ (if Rv=5.1)
- Exciting star of the reflection nebula NGC7023
  - Located near the center of the E-W extending outflow cavities seen in the CO and FIR
- Closed binary (Pogodin+2004; Monnier+2006)
  - Semi-major axis 15mas=6.5AU@430pc
  - M1+M2=10.4 M$_\odot$, M1/M1+M2=0.825
- Binary of two massive stars? (Alecian+2008)
  - 10.7±2.5 M$_\odot$ + 9.3±2.1 M$_\odot$
N–S extending disk emission

- Unresolved peak emission + diffuse elliptical emission
  - Likely inclined circumbinary disk

- Perpendicular to the outflow cavity

- Parallel to the projected major axis of the closed binary orbit

- 750~1000AU in radius
  - Similar to the radius of disk (candidates) around massive YSOs and lower-mass stars

→ 1\textsuperscript{st} detailed IR disk image around \(\sim 10\text{M}_\odot\) star

**HD200775** seems to have formed through the disk accretion.
Flared disk geometry

- Centers of the elliptical contours of the diffuse disk emission are shifted from the unresolved peak emission source
  - Shift $\Delta$ is larger for the fainter contours
  - Characteristic to a flared disk geometry
  - Similar to the Herbig A0e star HD97048 ($2.5M_\odot$, Lagage+2006)
- Simple model fitting
  - Axisymmetric disk only whose surface emits in the MIR
  - From $r_{in}$ to $r_{out}$
    - $z(r) = z_0 \left(\frac{r}{r_0}\right)^\alpha$
    - Surface brightness $= F_0 \left(\frac{r}{r_0}\right)^\beta$
  - Inclination $i$
  - Convolution of the model disk with the observed PSF

$z(r) = z_0 \left(\frac{r}{r_0}\right)^\alpha$
$F_0 \left(\frac{r}{r_0}\right)^\beta$

Convolution of the model disk with the observed PSF

Similar to the Herbig A0e star HD97048 ($2.5M_\odot$, Lagage+2006)

Shift $\Delta$ is larger for the fainter contours

Inclination $i$
Disk geometry derived by the fitting

- Model images reproduce the observed images very well
- Parameters of the disk
  - $r_{out} = 665 \pm 8\text{AU}$
    - radius where the observed brightness profile becomes much steeper in the north
  - $r_{out} = 665 \pm 8\text{AU}$
  - $F \propto r^{1.5 \pm 0.2}$
    - brightness profile inside $r_{out}$
  - $i = 55.5\text{deg}$
    - inclinations of the binary orbit and of the stellar rotation (Alecian+2008)
  - $r_{in} = 140 \pm 14\text{AU}$
    - Might be larger than the real inner radius due to the fitting procedure.
  - $z(r)_{\text{AU}} = (16.8 \pm 2.8) \times (r_{\text{AU}}/280\text{AU})^{2.1 \pm 0.9}$
    - Not a hydrostatic disk ($\alpha < 1.5$)?
Properties of the disk

- Color temperature from $I_{11.7\mu m}/I_{18.8\mu m}$
  - 180-330K
  - $>> T_{\text{dust}}$ of black grains
    - 149K@430AU, 97K@1000AU
- Effectively heated small grains ($\sim0.1\mu m$ radius) in the disk atmosphere
- Vertical thermal structure similar to that modeled for passive disks around lower-mass stars

- $\tau_v$ of $10^{-3} - 10^{-5}$ for the diffuse emission
  - << the value expected by usual disk models ($\sim z(r)/r \sim 0.1$)
  - Surface ripples due to thermal waves? (Watanabe & Lin 2008)
Properties of the disk

- Photoevaporation from the disk surface
  - 3.4mm free-free emission by Fuente+2001 is very similar in size and shape to the MIR disk and tail emission
  - Photoevaporation radius
    - Inner radius where the sound speed of ionized gas exceeds the escape speed against stellar gravity
    - $r_g \sim 70\text{AU}$ for a 10$M_\odot$ star
    - Possible ionized gas flow from the disk surface at $r > r_g$

Hollenbach+1994
Inner disk and dust in the diffuse disk

- The unresolved peak emission
  - Featureless, ~1600K (>1000K w 1σ error) blackbody
  - Circumprimary (or circumsecondary) disk

- Diffuse disk emission
  - Amorphous silicate feature with a peak ~9.2μm
    - Shorter than the peaks of silicate features of circumstellar disks around young lower-mass stars, ISM extinction, and envelopes around massive YSOs
  - Likely from pyroxene (MgSiO₃) or amorphous silicate with more SiO₂ fraction

- Grain properties characteristic to massive stars may be revealed by separating the disk emission with high spatial resolution.

Amorphous pyroxene (MgSiO₃): 0.1μm radius (dotted) 1μm radius (solid)
Amorphous Mg₀.₇SiO₂₇: 0.1μm radius (blue) 1μm radius (green)
More results by COMICS/MIR

- Takahashi+ poster
  - Dust emission toward M17 shows characteristic 9μm feature
    - Relation to those observed toward HD200775?

- de Wit+ 2009 (also poster)
  - 24.5μm images of massive YSOs
  - ~1000AU scale density structure revealed by model fitting to the image and SEDs
  - Density profile shallower than larger scale observed by the radio
  - Some sources cannot be explained with spherical density distribution
More results by COMICS/MIR

- Okamoto+ 2003
  - Diagnostics of the embedded massive YSOs from emissions of their surrounding ionized regions
  - See also Crowther+ poster (Development w Gemini)

- Fujiwara+ 2009 (also poster)
  - Follow-up observations of debris disks with COMICS and Gemini/T-ReCS by AKARI, the Japanese IR satellite
  - For HD106797, 10-13μm excess is detected
  - Td~190K, dust ring of r~14AU

Fujiwara+2009
Summary and future prospects

Many results from Subaru/COMICS MIR observations to understand the star and planet formation

- Grain evolution in the PPDs
- Thermal structure of the disks
- Grain distribution in the PPDs and DDs
- Early planetary systems
- Disks, dust, and density distribution of massive YSOs, etc...

Future prospects

- Further study w Subaru/COMICS
  - Detailed dust distribution of resolved disks
  - Search for the embedded massive YSOs and their properties
- Realizing MIR observations w TMT
  - Improved spatial resolution (0.08") is very powerful to resolve the planet forming regions with 1 to 10AU scale