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SCIENCE THEMES

Planet formation and protoplanetary disks
Planet evolution and debris disks
Exoplanet atmospheres and composition
WHAT ARE PP DISK GAS MASSES?

- HD is a million times more emissive than H$_2$ at T ~ 20 K.
- Atomic D/H ratio inside the local bubble is well characterized ($\sim 1.5 \times 10^{-5}$)
- HD will follow H$_2$ in the gas

TW Hya disk mass
$M_{\text{disk}} \sim 0.05 \, M_\odot$

Bergin+ 2013

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Williams and Cieza 2011

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[Histogram showing the number of disks in Taurus with dust masses on a log scale.]
WHAT ARE PP DISK ICE MASSES?

McClure+ 15

Min+ 16
WHAT ARE THE VOLATILE RESERVOIRS OF PP DISKS? WHERE IS THE OXYGEN, CARBON, NITROGEN, FLUORINE, SULFUR, ...?
IS PLANET-FORMING CHEMISTRY INHERITED FROM THE ISM OR CREATED IN THE DISK?

Najita+ 2013

High disk mass

Carbon-rich inner disk

Less ammonia

Pontoppidan+

Tw Hya outer disk (Salinas et al. 2016)
INHERITANCE OR RESET 2: D/H RATIOS IN DISKS

Altewegg+ 2014
OBSERVABILITY OF WATER

Infrared water lines from protoplanetary disks

- High energy lines observable from the ground
- Medium energy lines observable from the stratosphere
- Low energy lines observable from space

Upper level energy [K] vs. Wavelength [μm]
SPECTROSCOPIC EFFECTS OF A SNOW LINE

Model water spectrum

Spitzer (~JWST) range

Herschel-PACS range

Freeze-out

\[ \text{Flux [Jy]} \]

Wavelength [micron]
WHERE IS THE WATER SNOW LINE?

![Graph showing water snow line with wavelength and flux density](image)

Blevins, Pontoppidan+ 2016
Debris Disk Science Theme

• **Planetary Architecture – Is our Solar System an Outlier?**
  o Use debris disk structures to find and characterize the masses and orbits of exoplanets not found by ~2030 with other measurement technique
  o Use debris disk structures to constrain planet formation and migration history
  o Demographic studies of debris disks (disk brightness vs. other parameters: spectral type, metallicity, presence of known planets, stirring mechanisms)

• **Composition in Debris Disks -**
  o Gas in debris disks – where does it come from? Composition?
  o **Dust mineralogy** – silicates, ices, and calcites...etc, hydro-material?
    formation and transportation history, link to protoplanetary disks

• **Planetary Systems beyond Main Sequence**
  o Detecting the reservoir of surviving asteroids and KBOs
Definition of Debris Disks

- dust replenished by collisions or cometary activity
- leftover ∼km-size planetesimals that failed to form planets
- The large surface area of a dusty disk makes it readily observable in Infrared, and optical scattered light in favored conditions.
- The gravity of giant planets determines where leftover planetesimal belts can exist, stirs up collisions in the belts, and sculpts the dust distribution through resonant and secular interactions.
Solar System’s Debris Disk

Two leftover planetesimal (parent-body) belts

**Asteroid Belt** (2-4 AU): km-size bodies
  its structure greatly influenced by Jupiter

**Kuiper Belt** (30-50 AU): large icy bodies
  the inner edge maintained by Neptune
Five Zones of Debris Dust

edge-on view of a planetary system

- **Terrestrial Planets?**
  - ~1500 K
  - ~300-600 K terrestrial zone

- **Giant Planets?**
  - ~150 K asteroidal zone
  - ~50 K Kuiper-belt zone

- **Peak wavelength of emission, \( \lambda(r) \)**
  - ~24 \( \mu m \) warm
  - ~10 \( \mu m \) hot
  - 2 \( \mu m \) very hot
  - ~60-70 \( \mu m \) cold

- **Disk halo**

Distance not to scale
Signpost of Exoplanets

- Current search methods are strongly biased.

- Look for solar analogs that have giant planet at large radial distance. The existence of habitable terrestrial planets relies on gas giants remaining at large orbital radii.

- Planets inferred by debris disk structures are good analogs.
Planet-Disk Interaction - structures created by planet(s)

- Particle Distribution for Solar System
  - Warp Disk – β Pictoris
    - HST/WFPC2
    - HST/STIS
    - VLT/NaCo
    - Liou & Zook 1999
    - Heap et al. 2000
    - Lagrange et al. 2009, 2010

- Offset Narrow Ring – Fomalhaut
  - HST/ACS Scattered light
  - Kalas et al. 2005
  - Herschel 70 µm
  - Acke et al. 2012
  - also see Boley et al. 2012

- Particle Distribution for Solar System with planets without planets
  - Heap et al. 2000
  - Liou & Zook 1999
  - Acke et al. 2012
  - also see Chiang et al. 2009

- Lagrange et al. 2009, 2010
HR 8799 Debris Disk and Four Giant Planets

Spitzer 24 µm
Su+ 2009

Herschel 70 µm
Matthews+ 2013

unresolved

PA \sim 60^\circ, \ i \sim 25^\circ

Su et al. 2009

Matthews+ 2013

Star

Asteroid belt

KBO zone

Disk halo

Marios+2008, 2010

6-8 AU

100-250 AU

up to \sim 1000AU
The β Pic Disk – clump

dust clump at 52 AU with $T_d \sim 190$ K, $M_d \sim 4 \times 10^{20}$ g
The β Pic Disk – clump

A: Resonance due to unseen planet

>10 $M_\oplus$ planet at 54 AU

B: Giant impact

A planet with a few Mars mass

ALMA CO velocity information puts the clump at 85 AU

Dent et al. 2014
Debris Evolution due to Giant Impact

Jackson et al. 2014
Far-Infrared Spectroscopy – Trace Material in the cold Zone

**ISO – Long Wavelength Spectrometer (LWS)**

Herbig Ae/Be Stars: *crystalline silicates, crystalline water ice, phyllosilicates*

No debris disks (~ 2 orders of mag. fainter)

Malfait et al. 1998, 1999
Far-Infrared Spectroscopy – Trace Material in the cold Zone

**Herschel – PACS spectroscopic mode**

- 69 µm low-iron Olivine feature (one debris disk: β Pic)

- ~20-30% Iron asteroidal, warm, equilibrated

- ~1% Iron cometary, cold, un-equilibrated

Other solid-state features:
- Olivine, Pyroxene: high temperature formation/alteration
- Calcite, Dolomite: low temperature, link to water (life)

De Vries et al. 2012
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IS THERE WEATHER AND CLIMATE ON EXOPLANETS?

Spitzer 24 micron phase curve of HD 189733b

POTENTIAL FOR TRANSITING HABITABLE PLANETS AROUND M DWARFS?

Fig. 9 Earth’s mid-infrared spectrum as observed by Mars Global Surveyor enroute to Mars [59]. Major molecular absorption features are noted.
WHAT IS THE ATMOSPHERIC COMPOSITION OF COOL PLANETS?

Boccaletti+ 2014

Simulated MIRI coronagraphy of HR 8799
WHAT IS THE ABUNDANCE OF NH₃/PH₃ IN EXOPLANETS?
COMMONALITY WITH SOLAR SYSTEM JOVIANS?

Burgdorf+ 2002
EXTRAS/TECHNICAL
Debris/Fragments Evolution

Jackson et al. (2014)
- 1st orbit – clump
- ~2-10 orbits – spiral
- After ~10 orbits – smooth asymmetric disk lasting for ~1000 orbits

• Two special locations that all fragments must go through.
SPATIAL REGIONS TRACED