Planets, planetesimals and dust
Lessons from Spitzer

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These dust disks (a.k.a debris disks) host planetary systems

Dust is not primordial but is replenished by planetesimals (like asteroids, comets and KBOs).

Dust Removal Time Scales $< 10^4$-$10^6$ yr

Poynting-Robertson: $t_{PR} = 7.10 \times 10^{-4} \left( \frac{b}{\mu m} \right) \left( \frac{\rho}{g/cm^3} \right) \left( \frac{R}{AU} \right) \left( \frac{L_\odot}{L_*} \right) \frac{1}{1 + \text{albedo}} \text{ yr}$,

Grain-grain collisions: $t_{col} = 1.26 \times 10^4 \left( \frac{R}{AU} \right)^{3/2} \left( \frac{M_\odot}{M_*} \right)^{1/2} \left( \frac{10^{-5}}{L_{dust}/L_*} \right) \text{ yr}$

Radiation Pressure: $\frac{\tau_{blowout}}{\text{yr}} = 0.5 \sqrt{ \left( \frac{R/\text{AU}}{M_\odot/M_\odot} \right)^3 }$

Debris disks are indirect evidence that the first steps of planet formation have taken place

Stellar age $> 10^7$ yrs
dust particle
Alligators are cold-blooded. They cannot generate their own heat. Instead, they take on the temperature of their environment. Notice in the infrared images, how the alligator is cool compared to the warm-blooded human holding it. The alligator's temperature is close to room temperature. Notice also how cold the alligator's eyes are. In the wild, alligators will adjust their body temperature by entering water to cool off, or by basking in sunlight to warm up.
β-Pictoris
Pre-Herschel...

(1) Most disks have high dust content
(2) Most disks are spatially unresolved
(1) Pre-Herschel: most disks have high dust content

**Solar System debris disk:**
Kuiper Belt dust: \( \frac{L_{\text{dust}}}{L^*} \sim 10^{-7}-10^{-6} \)
Asteroid Belt dust: \( \frac{L_{\text{dust}}}{L^*} \sim 10^{-8}-10^{-7} \)
(1) Pre-Herschel: most disks have high dust content

Solar System debris disks:
Kuiper Belt dust: $L_{\text{dust}}/L^* \sim 10^{-7}-10^{-6}$
Asteroid Belt dust: $L_{\text{dust}}/L^* \sim 10^{-8}-10^{-7}$

Herschel faintest disk:
$L_{\text{dust}}/L^* = \text{few } 10^{-7}$

(Herschel)

(2) Pre-Herschel: most disks have high dust content
(1) Pre-Herschel: most disks have high dust content
Herschel: Is the dust content of the Solar System average? Are planetesimal-clearing events common?

Bryden et al. (2006)
(2) Pre-Herschel: most disks are spatially unresolved

Solar System debris disk:
Classical Kuiper Belt $\sim 50$ AU
Scattered Kuiper Belt $> 1000$ AU
Spectral Energy Distributions

Star

Star + disk

Star + disk with inner cavity
Fomalhaut debris disk

24 μm

70 μm

450 μm

Spitzer/MIPS Stapelfeldt et al. (2004)
Frequency and timing of planetesimal formation in the terrestrial planet region.

Maximum dust production rate when the largest planetesimals reach 1000 km and excite the orbits of the smaller bodies increasing their collision rate.
Percentage of stars with warm dust emitting at 24 μm

Observations limited to 100-1000 x zodis

Interpretation depends on duration of dust production epoch, $\tau_{dpr}$:

- $\sim 32\%$: if $\tau_{dpr} < 10 \times$ age bin
- $> 60\%$: if $\tau_{dpr} <$ age bins

18% 3-30 Myr
12% 30-300 Myr
2% 300-3000 Myr

(Meyer et al. 2008)
Is the history of the Solar System common in other planetary systems?
Evolution of dust in the Solar System

- Very high in the past; evidence of massive young planetesimals belts.

- Steady $1/t$ decrease due to planetesimal erosion.

- Peak due to Late Heavy Bombardment; triggered by orbital migration of giant planets; sweeping of secular resonances through AB; ejection of asteroids into planet-crossing orbits.

- Peaks due to the individual collisions of large bodies.
  (E.g. the formation of the Veritas family 8.3 Myr ago; responsible for 25% of the zodi)

\[ \log \left( \frac{F_{\text{dust}}}{F_*} \right) \text{ (at 24 \( \mu \text{m} \))} \]

\[ \log \text{ Time (yr)} \]

(Kenyon & Bromley 2005)
Are processes like the LHB common in other planetary systems?

Main feature: sharp decrease of the frequency of debris disks after the clearing of planetesimals.

The study of the dust excess emission as a function of stellar age does not show a sharp decline.

LHB-type of events don't seem to be common.

Spitzer observations of extra-solar debris disks

Evolution of dust in the Solar System (model)

Peak due to LHB

Age (Myr) (Booth et al. 2009)
Evolution of dust in extra-solar debris disks (Spitzer)

- A-type stars

1/t decay
- planetesimal clearing
- Large variability at a given age
- stochastic collisions

(Su et al. 2006)
Evolution of dust in extra-solar debris disks (Spitzer)

Solar type stars

1/t decay
- planetesimal clearing
Large variability at a given age
- stochastic collisions

(Siegler et al. 2006)
Hints on parent planetesimal composition
Hints on parent planetesimal composition

Comet Hale Bopp

Flux Density (Jy) vs. Wavelength (μm)

HD 69830

K0V, 0.8M_\text{sun}, 0.45L_\text{sun}
age: 3000-10000 Myr

Three planets:
≥ 10.2 M_⊕, 0.0785 AU
≥ 11.8 M_⊕, 0.186 AU
≥ 18.1 M_⊕, 0.63 AU.

Spitzer IR excess:
Strong excess at 24 μm
No excess at 70 μm

Transient event:
dpr is too high to be sustained (Wyatt et al. 2006)

(Beichman et al. 2005)
(Lisse et al. 2007)

Best fit: highly processed low carbon P- or D-type asteroid (like Veritas)

Comet Hale Bopp

Flux Density (Jy) vs. Wavelength (μm)
Characterization of the population of small bodies in extra-solar planetary systems
Kuiper Belt-like belts are the most common

Best fit parameters

with 70 μm excess

without 70 μm excess

From fits to spectra (12–35 μm)

N = 44 (FGK)

(Carpenter et al. 2009)
Kuiper Belt-like belts are the most common

Frequency of disks is different in old A stars and M stars than in FGK stars.

(Trilling et al. 2008 and Gautier et al. 2007)

Sensitivity:
70 μm: ~100xKB
24 μm: ~1000xAB
Kuiper Belt-like belts are the most common

- 1-σ error

- Sensitivity:
  - 70 μm: ~100xKB
  - 24 μm: ~1000xAB

- Improve sensitivity

- Herschel data
Kuiper Belt-like belts are the most common

no correlation observed

Frequency of cold disks around solar-type stars: ~6-16%
(Sensitivity: 100 x KB).

Frequency of giant planets (<20 AU): ~17-19%
(Sensitivity: Jupiter and Saturn-like planets)

KB-like disks could be very common around solar-type stars

Planetesimal formation...
- is a robust process (debris disks are found around stars with a stellar luminosities spanning more than 2 orders of mag).
- is more common than giant planet formation (unlike planets, debris disks are not correlated with high stellar metallicities)
Location of planets at large semi-major axes
ε-Eri 850 µm

Irregular rings
Off-centered disks

Greaves et al., JCMT
size of the solar system

Kalas et al., HST

Off-centered disks

Fomalhaut

50 AU

Fomalhaut b Planet

2006

2004
Fomalhaut
- 24 µm
- 70 µm
- 450 µm

AU Mic
- 1.63 µm

20 AU

β-Pic 0.2-1 µm

40 AU

HD 32297 1.1 µm

70 AU

Heap et al.
(Liu 2004)

size of the solar system KB

Warped disks

100 AU
Spiral structure
Brightness asymmetries

Schneider et al. 2005 (HST)
Model of Kuiper Belt Dust

Irregular rings
Brightness asymmetries

Moro-Martín and Malhotra (2002)
Planets can affect the debris disk structure

- Gravitational ejection
- Resonant perturbations
- Secular perturbations

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(Log(N) vs. a(AU))

(\(\beta=0.00156\))

(\(\beta=0.00625\))

(\(\beta=0.025\))

(\(\beta=0.1\))

(\(\beta=0.4\))

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(Moro-Martin et al. 2007)
Sensitive to a wide range of planet masses and semi-major axes.

Complementary to radial velocity and transit methods (sensitive to planets closer to the star) and to direct imaging (sensitive to young planets).
Planets can affect the debris disk structure

Off-centered disks
Sharp inner edge

But most disks are unresolved

Need spatially resolved observations

(Kalas et al. 2008)
(Chiang et al. 2009)
Need spatially resolved observations

**HD 82943**

G0 V

age ~ 5 Gyr

Multiple-planet system:

- **b:** $M = 1.46 \, M_{\text{Jup}}$
  - $a = 0.75 \, \text{AU}$
  - $e = 0.45$

- **c:** $M = 1.73 \, M_{\text{Jup}}$
  - $a = 1.19 \, \text{AU}$
  - $e = 0.27$

(Moro-Martín et al. 2010)
Need spatially resolved observations

HD 82943

(Moro-Martín et al. 2010)
Need spatially resolved observations

Need to know $R_{\text{out}}$

(Moro-Martín et al. 2010)
Need spatially resolved observations

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(Moro-Martín et al. 2010)
We need spatially resolved observations with Herschel!