“Zody”

Lynne A. Hillenbrand
Caltech

[some slides courtesy John Carpenter]
From Primordial Disks to Debris and Planets

Silhouette disks in ~1-2 Myr old Orion  

Scattered light debris disk AND a candidate planet in ~200 Myr old Fomalhaut

McCaughrean & O’Dell (1996)  
Kalas et al. (2008)
Initial Optically Thick Disk Geometry

- Ultraviolet and blue optical excess from accretion shock and heated photosphere.
- Near- and Mid-infrared excess from hot/warm dust in inner disk. (< 0.1-1 AU)
- Sub- and millimeter emission from cold dust in outer disk. (few to hundreds of AU)

(both continuum and line diagnostics at all wavelengths)
What happens to the gas/dust?

Accretion - also Outflow

Photoevaporation (UV and Xray)

Planetesimals ➔ planets ➔ debris dust
Identifying disks and characterizing timescales for disk dissipation

Stellar Mass Dependence

Stellar Age Dependence

K5 – M stars

Carpenter et al. (2009)

e.g. Hernandez et al. (2008)
Goal to Establish the Frequency Distribution of Disk Lifetimes

$\langle \tau \rangle \sim 3 \text{ Myr}$
with exponential tail to 10 Myr ??

$\langle \tau \rangle \sim 10 \text{ Myr}$
with gaussian width ??

$\Rightarrow$ evolution in $\sigma [\Sigma (r)]$
for comparison to models
Gas and Dust to Planets

- Gas dissipation:
  - viscous accretion on to star
  - outflow in winds/jets
  - photo-evaporation
  - gas giant accretion

- Grain evolution:
  - growth from ISM-sized dust to larger solids:
    $\mu m \rightarrow cm \rightarrow km \rightarrow$ moon/Mars sized “oligarchs” $\rightarrow 1-10 \, M_{\text{Earth}}$ planets

  - rapidly re-generate “debris” dust”
What is the Difference Between “Primordial” and “Debris” Disks?

- **Primordial**
  - \( \tau \geq 1 \)
  - first generation
  - geometry
  - radiative transfer

- **Debris**
  - \( \tau << 1 \)
  - second generation
  - total mass
  - surface area
Debris Disks: HST’s Legacy

(Slide Courtesy of John Mather)

These are mostly young (less than a few hundred million years) and early type (more massive than the Sun) stars!
Evolution of planetesimal belts
Debris luminosity vs. time

Kenyon & Bromley (2004, 2005)
When does debris production start?

5 Myr old Upper Scorpius OB Association

Carpenter et al. 2009
Solar System Minor Planets Provide Ground Truth

• The debris dust that is observed around other stars originates in the collissional cascade of planetesimals that we can not observe.

• Process is induced by giant planets – also mostly as-yet undetected.
Our Debris Disk: Parent Bodies

Primordial Kuiper Disk

Orbits of known Kuiper Belt objects

Stern (1996)

(Jewitt)
Our Debris Disk

Photograph from Mauna Kea showing the zodiacal light and also comet Hale-Bopp

[photo courtesy: Paul Kalas]

Clementine [Hahn et al. 2002]
Our Debris Disk

- Properties of zody dust:
  - silicate and carbonaceous grains 10-100 um in size
  - mass of 1x10 km body ground up = $10^{-7}$ m$^2$/m$^2$ of dust at 1 AU

- Origin of zody dust:
  - Asteroid Belt [collisions and erosion] -- 70%
  - Comets in inner s.s. [sublimation and ejection] -- 20%
  - Jupiter Trojan Asteroids [collisions and erosion] -- few %
  - Kuiper Belt [collisions and erosion] -- <10%
  - ISM grains [passing through] -- 0.1%
Scattered and Thermal Emission

[Zodiacal Dust Cloud]

[Leinert & Gruen 1990]
What is Needed from Measurements

- Sensitivity
- Precision as well as Accuracy
- Contrast (i.e. get rid of the central bright star)
- Attention to Stellar Parameters
  - age (not easy at all)
  - mass, luminosity (relatively straightforward)
  - some dependencies:

\[ T_{\text{dust}} \propto L_*^{1/4} \]

\[ \beta = \frac{F_{\text{rad}}}{F_{\text{grav}}} \propto \frac{L_*(t)}{M_*} \]

grains ejected if \( \beta > 0.5 \)
Sensitivity @ 24μm  (A0 stars)

IRAS: 29 pc
Spitzer: 1100 pc
(log scale)
Sensitivity @ 24μm  (A0 stars)
Sensitivity @ 24μm (G0 stars)
Sensitivity @ 24μm  (M0 stars)
Spitzer Sensitivity to Debris: 24 µm

10% excess @ 24µm

Radius [AU]
Spitzer Sensitivity to Debris: 70 µm
Spitzer Sensitivity to Debris: 8 µm
Dust temperatures inferred with Spitzer

A stars

Su et al. (2006)

G stars

From 24 and 70um photometry only

Carpenter et al. (2008)

Hillenbrand et al. (2008)

From 5-30um spectrophotometry
Warmer debris around solar type stars?

< 3% excess at 8μm

< 15% excess at 16μm

Carpenter et al. (2008)
Yes, indeed a few warm debris disks

- ~ 300 K equiv to ~1 AU
- ~ 2.5% of > 1 Gyr solar type stars have warm dust
- limits: ~ 1400x zodiacal belt

HD 23514

Rhee et al. (2008)

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

1RXS J051111.1+281353

Carpenter et al. (2008)
Photometric Accuracy and Precision

Total Number of targets: 158
Gaussian Distribution: \( \mu = 0.981 \)
\( \sigma = 0.026 \)

3σ excess = 1.059 (55/158)
5σ excess = 1.111 (51/158)

Su et al. (2006)
Fraction of stars with debris disks

- Require > 32% excess
- For ages > 10 Myr disk fraction declines with age
- As for primordial disks, debris decline is mass-dependent

Carpenter et al. (2009)
24μm excess vs. stellar age

- 2.6 sigma “peak” in 24μm excess for F-type stars
- B/A/F/G stars: any trends < 2 sigma for ages < 20 Myr

=> No conclusive evidence for peak in debris production

Carpenter et al. (2009)
Relation of Debris and Planets

Bryden et al. (2006, 2008)
Moro-Martín et al. (2007a,b)

No strong correlation between (known) planets and (known) excess sources
BUT
Incompleteness and bias still dominate.
What can we learn from debris disks?

They are the sign posts of planets
(even if we haven’t found them yet!)
What can we learn from debris disks?

Formation of planetary systems

Kenyon & Bromley (2002)  
Kenyon & Bromley (2005)
What can we learn from debris disks?

Diversity of mature planetary systems
Comparative Sensitivity Limits

- We are approaching KB dust levels.
- We do not yet know how to detect true zody dust!

[figure courtesy Geoff Bryden (2007)]
Goal to Detect Forming/Young Planets

Simulations by Sebastian Wolf (2005)

$L_{IR}/L_* = 10^{-4}$ debris disk with embedded planet at $a = 40$ AU

$S = 82\%$
120nm r.m.s.

$S = 90\%$
90nm r.m.s.

(G2 star in the Pleiades)