Observations of debris disks before Herschel

Paul Kalas (Herschel DEBRIS co-I)
UC Berkeley & SETI Institute

"From Atoms to Pebbles: Herschel's view of Star and Planet Formation" Symposium
CNES HERSCHEL 2012
March 22, 2012
Grenoble, France
Observations of debris disks before Herschel
Observations of debris disks before Herschel

- **1700**
- **1984**
- **1998**
- **2004**
- **2005**
- **2008**
- **2012**

Paul Kalas
2012-03-22
1) IRAS 12, 25, 60, 100 $\mu$m (1984 - )
2) Scattered light imaging, ground and space (1984 - )
3) Resolved emission 10 $\mu$m – 850 $\mu$m (1997- )
4) Hipparchos Mission - ages (1997- )
6) Spitzer Space Telescope (2004 - )
"The light at its brightest was considerably fainter than the brighter portions of the milky way... The outline generally appeared of a parabolic or probably elliptical form, and it would seem excentric as regards the sun, and also inclined, though but slightly to the ecliptic."

-- Captain Jacob 1859

Hale-Bopp Dust loss? $10^8$ kg s$^{-1}$
Parent bodies: comets and asteroids

New title for Herschel Symposium:
"From atoms to pebbles to planets, but back to pebbles again.”
Zodiacal Dust also prominent in the infrared due to thermal emission

Leinert & Gruen 1990

~150 K
IRAS Mission
All-sky survey
1983 (Feb. - Nov.)

<table>
<thead>
<tr>
<th>Center Wavelength</th>
<th># working detectors</th>
<th>FOV (arcmin)</th>
<th>Bandpass (µm)</th>
<th>Detector Material</th>
<th>Average 10-sigma Sensitivity (Jy)</th>
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<td>16</td>
<td>.75 x 4.5</td>
<td>8.5 - 15</td>
<td>Si:As</td>
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<td>19 - 30</td>
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<tr>
<td>60</td>
<td>15</td>
<td>1.5 x 4.7</td>
<td>40 - 80</td>
<td>Ge:Ga</td>
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<tr>
<td>100</td>
<td>13</td>
<td>3.0 x 5.0</td>
<td>83 - 120</td>
<td>Ge:Ga</td>
<td>3.0</td>
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</tbody>
</table>

Detectable around other stars?

At 10-20 µm,
F_{dust} = 10^{-7} L_☉
2 x 10^{-4} Jy!
1984: The Vega Phenomenon
The discovery of excess emission from main sequence stars at IRAS wavelengths (Aumann et al. 1984).

Vega
α Lyt BS 7001
A0 V

Fomalhaut
α Ps A BS 1728
A3 V

β Pic
A5 V

Flux Density (Jy)
Microns
12 25 60 100

Log v (Hz)
12.5 25 50
100 µm

Backman & Paresce 1993
"The Big Three"

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1984: The Vega Phenomenon
The discovery of excess emission from main sequence stars at IRAS wavelengths (Aumann et al. 1984).

Grain temperature gives radius from star where most of the dust resides, but distinguishing a shell versus disk architecture requires resolved imaging.

Not a 150K exozody that was discovered, but a cold exo Kuiper Belt/Shell, before the Kuiper Belt was detected in 1992.
Important Parallel Developments

Solar Astronomy: First detection of the solar corona without a lunar eclipse (1932)


Bernard Lyot (1897-1952)  Brad Smith (head of Voyager imaging team)
Direct Image of the β Pic Dust Disk
as early as 1983

Smith & Terrile 1984

Beta Pic was the Rosetta Stone Debris Disk for 15 years
>300 refereed papers
Direct Image of the β Pic Dust Disk
not a shell of dust, but a disk of dust

Smith & Terrile 1984

Beta Pic was the Rosetta Stone Debris Disk for 15 years
>300 refereed papers
What is the origin of dust?

**The Dust Must be Replenished**

Age of system >> lifetime of dust

---

![Graph showing various processes affecting dust lifetime](image)

Artemowicz 1997
From 1984 to 1998:

Debris disk science was mostly concerned with:

(1) The detailed study of Beta Pic

(2) Mining the IRAS catalogs for more debris disk candidate stars
$\beta$ Pic Detailed Studies

$\beta$ Pic

$< 0.4$ AU

1900 - 1999

SpT = A5V

d = 19.3 pc

Beust
Deleuil
Ferlet
Knacke
Lagrange
Lamers
Lecavelier des Etangs
Morbidelli
Vidal Madjar
β Pic Summary

β Pic Detailed Studies

0.5 - 2.2 µm

β Pic

5" = 100 AU
1995 - 1997

Burrows et al. 1995
Beuzit et al. 1996
Mouillet et al. 1997
Heap et al. 2000
β Pic Detailed Studies

10 - 20 μm

β Pic
5" = 100 AU
1994-1997

Lagage & Pantin 1994
Roques et al. 1994
Pantin et al. 1997

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Smith & Terrile 1984

0.5 - 0.8 \(\mu m\)

25" = 500 AU
1984

Smith & Terrile 1984
Kalas & Jewitt 1995, Discovery that Debris Disks can be Asymmetric, Dynamically Complex
Beta Pic's Double Disk
The Latest Optical Image with Hubble (ACS/HRC)
Golimowski et al. 2006

Okamoto et al. 2005

10:00 - 10:20  • Cometary dust in the planetary belts of β Pictoris  
B. De VRIES, Instituut voor Sterrenkunde
Grenoble’s Exoplanet (Beta Pic b)

Dynamics (astrometry) can now be used to estimate exoplanet masses, independently from the luminosity-evolution models (photometry).
Mining the IRAS catalog for new candidate debris disks:

Cross correlate positions of FIR point sources with optical catalogs of stars. Approximately ~15% (±5%) of main-sequence stars have debris disks.

IRAS PSC v.2

IRAS FSC

- Gliese
- Bright Star Catalog
- SAO
- Michigan Spectral

<table>
<thead>
<tr>
<th>Reference</th>
<th>Count</th>
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<tr>
<td>Aumann 85</td>
<td>12</td>
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<tr>
<td>Backman &amp; Gillett 87</td>
<td>25</td>
</tr>
<tr>
<td>Walker &amp; Wolstencroft 88</td>
<td>30</td>
</tr>
<tr>
<td>Backman &amp; Paresce 93</td>
<td>75</td>
</tr>
<tr>
<td>Mannings &amp; Barlow 98</td>
<td>193; 60 new</td>
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</table>

IRAS continues to yield valuable science; e.g. Zuckerman & Song 2004, Moor et al. 2006, Rhee et al. 2007.
From IRAS data can infer the structure of debris disks because temperature gives dust location – all debris disks have central depletions.
IRAS key results (1984 - 2004 – present day):

(1) Frequency of debris disks: ~15% of A – K stars have debris disks
(what about the M stars?)

(2) Temperature -> Location -> Structure of debris disks
(central holes - evidence for planetary systems)
EXPLOITING THE INFRARED: IRAS OBSERVATIONS OF THE MAIN SEQUENCE
D. E. Backman and F. C. Gillett

ABSTRACT. We examined coadded IRAS survey data on samples of nearby main
sequence stars in search of far-IR excesses similar to examples attributed to
clouds of orbiting grains. Of 134 systems, 25 (19\%) show significant
excesses at 25, 60, or 100 \(\mu\text{m}\) with color temperatures greater than 35 K.

Approximately \(15\%\) of the stars have excess more luminous than \(2\times10^{-5}\, L_\odot\),
roughly independent of spectral type. Several stars with excesses appear to
be older than \(2\times10^9\) yrs, indicating that the particle cloud phenomenon is not
solely a feature of young objects.

Models of three prominent clouds that have been spatially resolved (\(\beta\) Pic,
\(\alpha\) PsA, and \(\alpha\) Lyr) imply central depleted regions with radii of order 20 AU.
One possible explanation for maintenance of the depleted regions is that a
planet orbits at and defines each cloud's inner boundary, sweeping up parti-
cles entering that region.

The sun could have a cloud with similar geometry and somewhat smaller optical
depth than these examples which would be difficult to detect from earth
because of bright zodiacal and galactic emission.
After IRAS, we wanted to explore:

Why do some stars have debris disks and others do not?

What is the evolution over time?
Need ages – central importance of the Hipparchos Mission

1. Find moving groups (i.e. derive U,V,W using Hipparcos and RV from ground)
Need ages – central importance of the Hipparcos Mission

1. Find moving groups (i.e. derive U,V,W using Hipparcos and RV from ground)
For example: The Beta Pic Moving Group

Observables: $\alpha$, $\delta$, $\mu_{\alpha}$, $\mu_{\delta}$, $\pi$, $R_v$ ----> $l$, $b$, $U$, $V$, $W$

Hipparcos Catalog: 118,218 stars
Barbier-Brossat & Figon (2000): 36,145 stars
Determine $U$, $V$, $W$ for 21,497 stars

Follow-up with spectroscopy and search for age indicators:
see papers by Zuckerman, Song, Bessel, Webb, Barrado y Navascues, Stauffer, et al.

THE $\beta$ PICTORIS MOVING GROUP
B. Zuckerman and Inseok Song
M. S. Bessell R. A. Webb

Beta Pic moving group
Age ~ 12 Myr, $d < 50$ pc
Sister Disks: The Beta Pic Moving Group (age ~ 12 Myr)

Vexing unanswered question: Stars with a common origin, yet their circumstellar material organized differently?

<table>
<thead>
<tr>
<th>Star</th>
<th>SpT</th>
<th>Optical depth</th>
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</thead>
<tbody>
<tr>
<td>Beta Pic</td>
<td>A5V</td>
<td>24.3 +/- 1.1</td>
</tr>
<tr>
<td>HD 15115</td>
<td>F2V</td>
<td>4.9 +/- 0.4</td>
</tr>
<tr>
<td>HD 181327</td>
<td>F5.5V</td>
<td>29.3 +/- 1.6</td>
</tr>
<tr>
<td>AU Mic</td>
<td>M2V</td>
<td>4.0 +/- 0.3</td>
</tr>
</tbody>
</table>

Paul Kalas
2012-03-22
After IRAS, we wanted to explore:

Why do some stars have debris disks and others do not?

Some nearby stars were discovered to be young, and debris disks are detectable at early ages.

Nevertheless, there is significant diversity – not all 10 Myr old stars have debris disks, and there is diversity in the debris disks that are detected.

What is the evolution over time?
ISO (1999 –)

“Disappearance of stellar debris disks around main-sequence stars after 400 million years” Habing et al., 1999
“The Vega Phenomenon around G dwarfs” Decin et al. 2000
“Dusty debris around solar-type stars: Temporal disk evolution” Spangler et al., 2001
“Incidence and survival of remnant disks around main-sequence stars” Habing et al. 2001
“The age dependence of the Vega Phenomenon: Observations” Decin et al. 2003

Spangler et al. 2001, solid line fit shows $\text{age}^{-1.76}$ dependence
Out of the 15 stars younger than 380 Myr, 60% have a disk. Only 9% older than 380 Myr have a disk.

Habing et al. 1999 (see also Habing et al. 2001)
After IRAS, we wanted to explore:

Why do some stars have debris disks and others do not?

Some nearby stars were discovered to be young, and debris disks are detectable at early ages.

Nevertheless, there is significant diversity – not all 10 Myr old stars have debris disks, and there is diversity in the debris disks that are detected.

What is the evolution over time?

ISO results suggest $t^2$, but with significant differences at any given age.

Delayed stirring (late planet formation far from star) could cause rapid evolution overall, and older stars could have prominent debris disks (Dominik & Decin 2003, Kenyon & Bromley models).

In general, the frequency of debris disks drops significantly to $<10\%$ at around 400 Myr. Need a larger sample.
Resolved images of dust structure linked to unseen planets

1998-1999 HST/NICMOS & JCMT SCUBA2
New resolved Images & connection to planetary dynamics

See the Image Gallery in the Circumstellar Disk Learning Site for citation information on each image shown above:
http://www.disksite.com

Paul Kalas
2012-03-22
ACS High Resolution Channel Coronagraph

ζ Lep, V=3.5, SpT=A2V, d = 22 pc, $\tau_{IR} = 0.1 \times \beta$ Pic
Telescope Roll with PSF Self Subtraction

ζ Lep, V=3.5, SpT=A2V, d = 22 pc, $\tau_{IR} = 0.1 \times \beta$ Pic
Finally have sensitivity to image debris disks around solar type stars

HD 139664  
SpT=F5V  
d=17.5 pc  
age = 300 Myr  
60 - 109 AU  
Kalas et al. 2006

HD 107146  
SpT=G2V  
d=28.5 pc  
age = 100 Myr  
60 - 185 AU  
Ardila et al. 2004

HD 53143  
SpT=K1V  
d=18.4 pc  
age = 1.0 Gyr  
>110 AU  
Kalas et al. 2006

HD 92945  
SpT=K1V  
d = 22 pc  
age = 100 Myr  
>146 AU  
Clampin et al. 2006
M star at 10 pc
1 arcsec = 10 AU

One of the closest flare stars:
Distance = 9.9 pc
SpT = M1Ve
Mass = 0.5 $M_{\text{Sun}}$
Radius = 0.56 $R_{\text{Sun}}$
$T_{\text{eff}}$ = 3500 K
Luminosity = 0.1 $L_{\text{Sun}}$
$M_v$ = 8.8 mag
Period = 4.865 d
Avg. Mag. Field: B = 4000 G
H$\alpha$ Equivalent Width = 8.70
Quiescent X-ray flux:
$log_{10} (L_x) = 29.8$ erg/s
Age: Young

R-band, UH 2.2 m telescope, 0.4"/pix, 900 s, seeing FWHM = 1.1"
### Debris Disk Snapshot: 2008


<table>
<thead>
<tr>
<th>λ (µm)</th>
<th>0.6</th>
<th>1.6</th>
<th>2.2</th>
<th>450</th>
<th>850</th>
<th>1.1</th>
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<td>AU Mic</td>
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<td>Beta Pictoris</td>
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</table>
Possible disk “types”:

1. Do these trace fundamentally different distributions of underlying planetesimal population?
2. Are these different stages of debris disk evolution, or fundamentally different, long lived architectures?
3. Where does the solar system fit in?
Architectures: Physical extent

beta Pic

AU Mic

HD 107146

Fomalhaut

HR 4796A

Sun

>>800 AU

>200 AU

170 AU

140 AU

70 AU

50 AU
Spitzer also produced resolved images of debris disks
Fomalhaut at 24 & 70 micron imaging

Spatially resolved at 24, 70 & 160 µm
Asymmetry could be due to a secular perturbation of a planet at 40 AU.
(see also Marsh et al. 2005, planet at 86 AU)
Eps Eri SED after subtracting the stellar photosphere

Planet between the warm & cold dust belts? Planets produce both the ring edges and the clumpy azimuthal features seen in sub-mm maps?
Multiple planet systems that also have debris disks (Moro-Martin et al. 2010)

Gray lines are the locations of planetesimal belts that could be inferred from Spitzer data, but need spatially resolved images to pin down the correct inner and outer belt boundaries.

Greaves 2004, Beichman et al. 2005, Bryden et al. 2009 also explore whether or not the frequency of debris disks differs between samples of stars that have detected planets, or do not have detected planets.
Spitzer: Evolution over time

Plots show 24 $\mu$m dust emission divided by stellar emission for A stars (Su et al. 2006) and FGK stars (Siegler et al. 2007)

Significant diversity at any given age, but evolution as $t^{-1}$ seems to describe the 24 $\mu$m (warm dust) data instead of $t^{-2}$.
Spitzer: Frequency of Debris Disks

Carpenter et al. 2009

Trilling et al. 2008: For ages >0.6 Gyr

Herschel, please provide:

- Resolved images of debris disks
- Frequency of debris disks around lower mass stars & older main sequence stars
- Relationship between debris disk properties and stars with known exoplanets (& their properties).

See talks/posters today & tomorrow

Kalas et al. 2012
Why is Fomalhaut b optically bright?

Protogalilean, circumplanetary disk

Kalas et al. 2008
Planet + 16 - 35 $R_p$ rings
For comparison, Callisto at ~27 Jupiter radii

or

Irregular Satellite Cloud

“The observations of the planet Fomalhaut b can be explained as scattered light from dust produced by the collisional decay of an irregular satellite swarm around a $\sim 10 M_\oplus$ planet. Such a swarm comprises about 5 Lunar masses worth of irregular satellites.”

see also

A Ringed Earthlike Planet
Direct detection planet candidates

<table>
<thead>
<tr>
<th>Host</th>
<th>SpT</th>
<th>Distance (pc)</th>
<th>Separation (AU)</th>
<th>Mass (M_J)</th>
<th>Age (Myr)</th>
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<tbody>
<tr>
<td>Fomalhaut</td>
<td>A3V</td>
<td>7.69</td>
<td>119</td>
<td>&lt;1.0</td>
<td>400-500</td>
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<tr>
<td>Beta Pic</td>
<td>A5V</td>
<td>19.3</td>
<td>8</td>
<td>7 - 12</td>
<td>8 - 20</td>
<td>Lagrange et al. ‘08</td>
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<tr>
<td>HR 8799</td>
<td>A5V</td>
<td>39.4±1.0</td>
<td>68,38,24,15</td>
<td>5-13</td>
<td>30 - 160</td>
<td>Marois et al. ‘08,’10</td>
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<tr>
<td>AB Pic</td>
<td>K2</td>
<td>47.3±1.8</td>
<td>258</td>
<td>11 - 16</td>
<td>30 – 40</td>
<td>Chauvin et al. ‘05</td>
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<tr>
<td>2M1207</td>
<td>M8</td>
<td>52.4±1.1</td>
<td>54</td>
<td>2 – 7</td>
<td>5 – 12</td>
<td>Chauvin et al. ‘04</td>
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<tr>
<td>GQ Lup</td>
<td>K7</td>
<td>140 ± 50</td>
<td>100</td>
<td>4 – 39</td>
<td>&lt;2</td>
<td>Neuhauser et al. ‘05</td>
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<tr>
<td>CT Cha</td>
<td>K7</td>
<td>160±30</td>
<td>440</td>
<td>11 - 37</td>
<td>&lt;2</td>
<td>Schmidt et al. ‘08</td>
</tr>
</tbody>
</table>

Visible light: Fomalhaut
Orbital motion: Fomalhaut, HR 8799, β Pic and GQ Lup

What is a planet? Formation matters?

Starting in 2012/2013: Gemini Planet Imager, SPHERE, 1640, Subaru
Direct imaging: progress in recent years.

GQ Lup

2M1207

AB Pic

Fomalhaut
Kalas et al. 2008

HR 8799
Marois et al. '08,'10

Beta Pic
Lagrange et al. 2009

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2012-03-22