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

Observations

Theory
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
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>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>16</td>
<td>.75 x 4.5</td>
<td>8.5 - 15</td>
<td>Si:As</td>
<td>0.7</td>
</tr>
<tr>
<td>25</td>
<td>13</td>
<td>.75 x 4.6</td>
<td>19 - 30</td>
<td>Si:Sb</td>
<td>0.65</td>
</tr>
<tr>
<td>60</td>
<td>15</td>
<td>1.5 x 4.7</td>
<td>40 - 80</td>
<td>Ge:Ga</td>
<td>0.85</td>
</tr>
<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>
</tr>
</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).

Backman & Paresce 1993
"The Big Three"
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.

---

**DISCOVERY OF A SHELL AROUND ALPHA LYRAE**

H. H. Aumann, F. C. Gillett, C. A. Beichman, T. de Jong, J. R. Houck, F. J. Low,
G. Neugebauer, R. G. Walker, and P. R. Wesselius

Received 1983 September 22; accepted 1983 November 18

**ABSTRACT**

IRAS observations of α Lyrae reveal a large infrared excess beyond 12 μm. The excess over an extrapolation of a 10,000 K blackbody is a factor of 1.3 at 25 μm, 7 at 60 μm, and 16 at 100 μm. The source of 60 μm emission has a diameter of about 20″. This is the first detection of a large infrared excess from a main-sequence star without significant mass loss. The most likely origin of the excess is thermal radiation from solid particles more than a millimeter in radius, located approximately 85 AU from α Lyr and heated by the star to an equilibrium temperature of 85 K. These results provide the first direct evidence outside of the solar system for the growth of large particles from the residual of the prenatal cloud of gas and dust.

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)
Introduction: Vega Phenomenon

**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 $\beta$ 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

Artymowicz 1997

Paul Kalas
2012-03-22
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
β 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 Detailed Studies
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

Paul Kalas
2012-03-22
$\beta$ Pic Detailed Studies

$10 - 20 \, \mu m$

$\beta$ Pic

$5'' = 100 \, \text{AU}$

1994-1997

Lagage & Pantin 1994
Roques et al. 1994
Pantin et al. 1997
β Pic Summary

β Pic Detailed Studies

0.5 - 0.8 μm

Smith & Terrile 1984

β Pic

25" = 500 AU
1984

Smith & Terrile 1984

Paul Kalas
2012-03-22
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

Paul Kalas
2012-03-22
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

Aumann 85 12
Backman & Gillett 87 25
Walker & Wolstencroft 88 30
Backman & Paresce 93 75
Mannings & Barlow 98 193; 60 new

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)
This early paper sums up the core findings from IRAS

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 μm with color temperatures greater than 35 K.

Approximately 15% of the stars have excess more luminous than 2x10^{-5} L_\odot, roughly independent of spectral type. Several stars with excesses appear to be older than 2x10^9 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 (β Pic, α PsA, and α 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 particles 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 Hipparchos 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>
</tr>
</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>

Dust depletion

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

Resolved images of dust
structure linked to unseen planets

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
HST Advanced Camera & Spitzer

March, 2002

August, 2003
ACS High Resolution Channel Coronagraph

ζ Lep, V=3.5, SpT=A2V, d = 22 pc, τ_{IR} = 0.1 x β 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

Paul Kalas 2012-03-22
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"
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

> > 800 AU

beta Pic

AU Mic > 200 AU

HD 107146 170 AU

Fomalhaut 140 AU

HR 4796A 70 AU

Sun 50 AU

Paul Kalas
2012-03-22
Spitzer also produced resolved images of debris disks
Fomalhaut at 24 & 70 micron imaging

Spatially resolved at 24, 70 & 160 $\mu$m
Asymmetry could be due to a secular perturbation of a planet at 40 AU.
(see also Marsh et al. 2005, planet at 86 AU)
Spitzer observations of Epsilon Eridani (Backman et al. 2009)

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.
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