Herschel Observations of Protoplanetary Disks

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Herschel2012: “From atoms to pebbles”, Grenoble  3/22/12
All stars form surrounded by disks, and at least some disks truly are protoplanetary!
Disks are not like the ISM!

1. Grains collide, clump and grow.
2. Small grains are swept along by the gas, but those larger than a millimeter experience a drag force and spiral in.
3. At the snow line, local conditions are such that the drag force reverses direction. Grains tend to accumulate and readily coagulate into larger bodies called planetesimals.

Disk of gas and dust

Protosun

2–4 AU

Snow line

Dust spirals inward
How to make giant planets

• Grow dust, $\mu$m $\rightarrow$ km, in presence of gas...
• build $\sim 10M_{\text{Earth}}$ cores for runaway accretion...
• while still having $>1M_{\text{Jup}}$ of gas to make giant planets...
• then disperse gas quickly!
Kepler’s new law

~1000 / 150000 stars have planetary candidates (Borucki+ 2011)

Planets are very common...

... and with a huge diversity

Initial conditions?

Disk evolution?

Stochastics?

kepler.nasa.gov
Micron wavelength observations show the existence of small *micron sized* dust grains on disk surfaces.
Millimeter wavelength observations can measure dust masses of grains up to few mm in size, and show the capacity for planet formation, but are fairly insensitive (for now...)

Andrews & Williams 2005, 2007
Mann & Williams 2009
Lee+ 2011
Mathews+ 2012
How does the gas content evolve?
How does the gas content evolve?

Fedele+ 2010

How does the gas content evolve?

Fedele+ 2010
Dust and Gas Structures

Dullemond+ 2005
Temperature structure

- **Terrestrial planets**: 0.1AU (~1000 K, NIR)
- **Gas and Ice Giants**: 1AU (~300 K, MIR)
- **Icy planetesimals**: 5AU (~100 K, FIR)
- **100AU (~20 K, mm)**

![Temperature structure diagram with wavelength curves and temperature annotations]
Temperature structure

Spectral lines show the gas at the same approximate radius
Icy planetesimals

Gas and Ice Giants

Terrestrial planets

0.1AU

~1000 K

NIR

1AU

~300 K

MIR

5AU

~100 K

FIR

100AU

~20 K

mm

Graph showing the variation of log $L_\nu$ with wavelength $\lambda$.
Icy planetesimals

Gas and Ice Giants

Terrestrial planets

0.1AU  ~1000 K  NIR
1AU    ~300 K    MIR
5AU    ~100 K    FIR
100AU  ~20 K     mm

\[ \log L_\nu \ [L_\odot] \]

\[ \lambda \ [\mu m] \]
Note: these are global measures

Spitzer and singledish millimeter observations only measure the total (spatially unresolved) disk continuum.

Similarly, Herschel does not resolve the disks spatially, or spectrally.

Model fits to the data may not be unique!
Herschel angular resolution
\( \theta_{\text{FWHM}} \approx 5'' \) at 63\( \mu \text{m} \)

\( = 750 \text{AU at 150pc} \)

\( \gg R_{\text{disk}} \approx 100 \text{AU} \)

(and watch out for the outflows)
PACS spectral resolution
\( \lambda/\Delta\lambda \sim 1000-4000 \)
\[ \Rightarrow \Delta v \sim 88 \text{km/s at 63\,\mu m} \gg \Delta v_{\text{disk}} \sim 10 \text{km/s} \ (\text{need HIFI}) \]
PACS line and continuum are unresolved

Detailed modeling is required, and ambiguities remain
(see Peter Woitke talk this afternoon)
The DENT grid of disk models

Woitke+ 2009
\[ r_{\text{cond}} \quad 10 \text{ AU} \quad 100 \text{ AU} \]

- CO ro-vib 2-5 μm
- CO high J
- CO low J sub-mm
- H$_2$O ro-vib
- H$_2$O high $T_{\text{ex}}$
- H$_2$O low $T_{\text{ex}}$
- [OI] 63 μm
- [CII] 157 μm

Inga Kamp
Herschel protoplanetary disk programmes

- GASPS  (Gas in Protoplanetary Systems)
- DIGIT  (Dust, Ice, and Gas In Time)
- WISH   (Water In Star forming regions with Herschel)
- + several individual programs
Herschel protoplanetary disk programmes

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GASPS

• PACS 70/110/170µm photometry
• [OI]63/145µm, [CII]158µm, CO, H$_2$O, OH
• Class II / III / debris disks
• Nearby (<150pc), range of ages 1-30Myr
  ★ Taurus, Cha II, Upper Sco, ηCha, βPic, TW Hya, TucHor
• T Tauri and Herbig Ae/Be stars
The GASPS Team

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Dieter Poelman  
Suzie Ramsay  
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Veronica Roccatagliata  
Lara Rodrigues  
Goeran Sandell  
Enrique Solano  
Wing-Fai Thi  
Ian Tilling  
Bart Vandenbussche  
Silvia Vicente  
Helen Walker  
Jonathan Williams  
Glenn White  
Peter Woitke
SED evolution

Upper Sco 25th–75th quartiles
Taurus 25th–75th quartiles

Taurus median: Furlan et al. 2006
Taurus median PACS: C. Howard et al., in prep.
UpSco near- mid-IR : 2MASS, WISE,

Geoff Mathews
Detected lines

- $[\text{OI}]$ 63µm, 145µm
- $[\text{CII}]$ 158µm
- $\text{H}_2\text{O}$ 8 lines, $E_{up}=115-1300$ K
- CO 4 lines, $J=18-17$ to $J=36-35$
- OH, CH$^+$

(F$_{63}/F_{145} > 10$) (envelope contamination?) (mainly TTS, not HAeBe) (warm disk atmosphere) (two HAeBes only)
Detection statistics

Fig. 8.— Disk dust mass of the GASPS sample plotted as a function of the stellar effective temperature, for targets where the dust mass is published. [OI] detections are filled circles, and open circles depict upper limits. An additional red circle around the symbol shows the systems which are also detected in [CII].

All the stars of type earlier than K5 ($T_{\text{eff}} = 4500$ K) and with disk masses $M_{\text{dust}} > 10^{-5}$ $M_{\odot}$ were seen in [OI] (top right of plot), but the detection rate for disks of the same mass was smaller for later-type stars.

Detection statistics:

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- All the stars of type earlier than K5 (T$_{\text{eff}}$ = 4500 K) and with disk masses > 10$^{-5}$ M$_{\odot}$ were seen in [OI] (top right of plot), but the detection rate for disks of the same mass was smaller for later-type stars.
Detection limits

[OI] 63 µm correlates with gas mass, but with an order of magnitude dispersion.
Survey mass sensitivity is ~1 M_{Jup}.
[OII]63µm correlates with gas mass, but with an order of magnitude dispersion. Survey mass sensitivity is \( \sim 1 \, M_{\text{Jup}} \).
The combination of [OI]63μm and CO J=2-1 provide a more precise and robust measure of gas mass.
The more lines the better...

1.2mm continuum, CO, $^{13}$CO, C$^{18}$O SMA Reconnaissance of Taurus
Gas lifetimes

*(preliminary!)*
Gas lifetimes
(preliminary!)

- Gas lifetimes graph showing detection fraction vs. Age (Myr)
  - Data points for dust and gas (gasps)
  - TW Hya highlighted on the graph
Gas lifetimes
(preliminary!)

![Graph showing detection fraction vs age (Myr) for dust and gas in the CHa and TW Hya regions.](image)
Gas lifetimes

(preliminary!)

![Graph showing detection fraction vs. age (Myr) for different regions and objects, with markers for dust and gas (gasps) in TW Hya and η Cha regions.](Image)
Gas lifetimes
(preliminary!)

Only Taurus and Cha II have $>3$ [OI]63µm detections $\Rightarrow$ median gas mass $< 1M_{\text{Jup}}$ by $\sim 5$ Myr.
Gas lifetimes
(preliminary!)

Only Taurus and Cha II have >3 [OI]63\(\mu\)m detections ⇒ median gas mass < 1M\(_{\text{Jup}}\) by ~5 Myr

BUT there appears to be enough gas to form giant planets up to 3Myr...
Individual regions/sources

- Taurus (see Christian Howard’s talk)
- transitional disks (see Francois Menard’s talk)
- detailed modeling of individual sources
  - dust/gas ratio
  - warm H₂O
  - C⁺, CO, OH, CH⁺
**Thi+ 2010**

- $M_{\text{dust}} = 1.9 \times 10^{-4} \ M_\odot$
- $M_{\text{gas}} = (2-30) \times 10^{-4} \ M_\odot$

**Meeus+ 2010**

- $M_{\text{dust}} = 5 \times 10^{-3} \ M_\odot$
- $M_{\text{gas}} = 1.5 \times 10^{-4} \ M_\odot$

**Tilling+ 2012**

- $M_{\text{dust}} = 7 \times 10^{-4} \ M_\odot$
- $M_{\text{gas}} = 7 \times 10^{-2} \ M_\odot$

**Riviere+ in prep**

- $M_{\text{dust}} = 3 \times 10^{-7} \ M_\odot$
- $M_{\text{gas}} = 3 \times 10^{-9} \ M_\odot$
Warm water in disks

o-H$_2$O $8_{17-707}$  $E_u=1070K$

detected in 8/33 (24%)
of disks with [OI]63

Riviere+ 2012
The 63.32µm water line

The H$_2$O 63.3µm line is seen in 8 TTauri disks but only 1 HAeBe.
The 63.32µm water line

The H$_2$O 63.3µm line is seen in 8 TTauri disks but only 1 HAeBe

Telluric planet formation region
dust grains are covered by ice

Herschel PACS
Herschel- HiFi

snow zone

MMSN disk around a TTauri star

log n$_{H_2O}$ [cm$^{-3}$]

Cont. subtracted Flux (Jy)

Fig. 1. The [O\textsc{i}] 63µm lines for the entire sample. The line is seen in emission in all the HAEBEs, while absent in the more evolved debris disc objects 49 Cet, HD 32297, HR 1998, HR 4796A and HD 158352 (bottom row).

Herbig Ae/Be stars, and absent in the debris discs. For five of our objects, the line flux is larger than 200×10$^{-18}$W/m$^2$, while our faintest detection is 20×10$^{-18}$W/m$^2$. The other fine structure line [O\textsc{i}] 145µm is also one of the strongest lines in our spectra, however it is only detected in five objects (25% of the HAEBEs).

In Figs. 1 and 2, we show the spectra centered on [O\textsc{i}] 63 and [O\textsc{i}] 145µm for the whole sample.

3.2. Carbon fine structure line

When detected, the [C\textsc{ii}] 157.7µm line can be strong - more than 100×10$^{-18}$W/m$^2$. However, it is only seen in six objects (30% of the HAEBEs; see Fig. 3) - these are the same objects for which [O\textsc{i}] 145µm was also detected (see Table 4), apart from HD 36112. The interpretation of the [C\textsc{ii}] emission line is complex. Besides originating in the disc, it could also form in the remaining envelope, or simply in cloud material in the line of sight.

The low detection rate for [C\textsc{ii}] is surprising, given the high detection rate (83%) in ISO/LWS spectra reported by Lorenzetti et al.
DIGIT

- PACS and some SPIRE photometry
- Full PACS spectroscopy 52-210μm
- Embedded protostars and protoplanetary disks
- Close (<350pc), young (~1 Myr) regions
  - Taurus, Ophiuchus, Cha, Perseus, Serpens, Lupus
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Jo-hsin Chen
Mike Dunham
Hyo-Jeong Kim
Johan Olofsson
Bernhard Sturm
Ke Zhang
Gijs Mulders
Some DIGIT disk highlights
(reviewed yesterday by Bouwman)

• Forsterite 69µm feature (Mulders)
• Warm disk atmospheres (Bruderer)
• WTTS structure
The transition from protoplanetary to planetary debris

(a) Early in its evolution, the disk loses mass through accretion onto the star and far-UV (FUV) photoevaporation of the outer disk.
(b) At the same time, grains grow into larger bodies that settle onto the mid-plane of the disk, where they can grow into rocks, planetesimals, and beyond. Accordingly, the scale height of the dust decreases and the initially flared dusty disk becomes flatter (Figure 6b). This steepens the slope of the mid- and far-IR SED as a smaller fraction of the stellar radiation is intercepted by circumstellar dust (Dullemond & Dominik 2005). The near-IR fluxes remain mostly unchanged because the inner disk stays optically thick and extends inward to the dust sublimation temperature.
(c) As disk mass and accretion rate decrease, energetic photons from the stellar chromosphere are able to penetrate the inner disk and photoevaporation becomes important. When the accretion stops, extreme-UV (EUV)-induced photoevaporation becomes important; the outer disk is no longer able to resupply the inner disk with material, and the inner disk drains on a viscous timescale (∼10^5 years). An inner hole is formed, accretion onto the star ceases, and the disk quickly dissipates from the inside out.
(d) Once the remaining gas photoevaporates, the small grains are removed by radiation pressure and Poynting-Robertson drag. Only large grains, planetesimals, and/or planets are left. This debris disk is very low mass and is not always detectable.

Figure 6: The evolution of a typical disk. The gas distribution is shown in blue and the dust in red.
The transition from protoplanetary to planetary debris

Figure 6
The evolution of a typical disk. The gas distribution is shown in blue and the dust in red. (a) Early in its evolution, the disk loses mass through accretion onto the star and far-UV (FUV) photoevaporation of the outer disk. (b) At the same time, grains grow into larger bodies that settle to the mid-plane of the disk. (c) As the disk mass and accretion rate decrease, extreme-UV (EUV)-induced photoevaporation becomes important; the outer disk is no longer able to resupply the inner disk with material, and the inner disk drains on a viscous timescale ($\sim 10^5$ years). An inner hole is formed, accretion onto the star ceases, and the disk quickly dissipates from the inside out. (d) Once the remaining gas photoevaporates, the small grains are removed by radiation pressure and Poynting-Robertson drag. Only large grains, planetesimals, and/or planets are left. This debris disk is very low mass and is not always detectable.

As disk mass and accretion rate decrease, energetic photons from the stellar chromosphere are able to penetrate the inner disk and photoevaporation becomes important. When the accretion...
PACS/ SPIRE photometry of WTTS
new constraints on outer disk structure

Lucas Cieza
T Cha: a planet forming disk?

Sharp rim dynamically carved?

Cieza+ 2012
Transition disks caused by planets are great candidates for direct imaging
Disks → Planets

LkCa 15 disk

50 AU

LkCa 15

11 AU

(76 mas)

Kraus & Ireland 2012
Merci ESA!
Herschel Observations of Protoplanetary Disks

• Herschel spectra reveals the gas in the gas giant planet forming zone of disks!
• Herschel photometry constrains dust properties and disk structure in the outer parts of protoplanetary disks
• \( M_{\text{gas}} > 1M_{\text{Jup}} \) for >40% of Class II disks in Taurus and Cha II (~1-3 Myr)
• dust/gas ratio varies by (at least) an order of magnitude
• warm \( \text{H}_2\text{O} \) from disk surface at \( R \approx \) few AU is found in many T Tauri disks

→ disks are diverse...
  ...how does this relate to the diversity of exoplanets?