Herschel's view of the atomic and molecular content of Herbig Ae/Be discs

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Outline

Herbig Ae stars

★ Correlations with [OI]
★ CO ladders
★ Other detected lines
★ Disc modelling

Herbig Be stars

Conclusions
3.5m mirror! Phot. & spec. 55 to 672 µm.

2 OT Key Projects on protoplanetary discs:

**GASPS** PI: B. Dent


**DIGIT** PI: N. Evans

The longer the wavelength, the further away from the star and the deeper in the disc the emission originates.
Different gas species & transitions trace different regions in disc

Important transitions in far-IR

- Fine structure lines of atoms:
  - [OI] 63.2 and 145.5 µm
  - [CII] 157.7 µm

- Rotational lines of molecules:
  - CO middle to high J-lines
  - OH (OH + H₂ → H₂O + H)
  - H₂O, CH⁺

Far-IR lines trace gas in the OUTER DISC
The Herbig Ae sample at [OI] 63.2 micron: variety in strength

Debris discs
**Trends with [OI] 63 μm line flux**

- **FIR continuum**
  - [OI] versus $L_{\text{UV}}$
  - [OI] versus $L_{\text{PAH}}$

- **$^{12}\text{CO}\ J=3-2\ Cold\ Gas**
  - Continuum flux at 63 μm (Jy) * (d/140)$^2$
  - $^{12}\text{CO}\ J=3-2\ (\text{Jy km/s})\ *\ (d/140)^2$
  - PAH 6.2 μm (W/m$^2$) * (d/140)$^2$
[O\textsc{i}] vs. Accretion indicators

- **Balmer Excess**
- **Bry Luminosity**
- **Acc. contributes little to L\textsubscript{UV} in HAEBEs**

![Graphs showing [O\textsc{i}] vs. Bry Luminosity and Balmer Excess](image-url)

- Group I
- Group II
[O\textsc{i}] 63 µm vs. X-ray Luminosity

[O\textsc{i}] versus $L_X$

Predicted Line flux

*Aresu et al. 2011, 2012*
[OIII] 145 µm: less frequent

- CO J18-17
- HD31648
- HD35187
- HD36112

- CQ Tau
- HD97048
- HD100453
- HD100546

- HD104237
- HD135344B
- HD139614
- HD141569

- HD142527
- HD142666
- HD144668
- HD150193

- KK Oph
- 51 Oph
- HD163296
- HD169142

- 49 Cet
- HD32297
- HR1998
- HR4796A

Debris disc

Gap, hot wall

A lot of gas dissipated

Transitional
Carbonmonoxide: transitions

\( \Delta J = +/- 1 \) (R/P branch)

Cold gas (\( T \sim 30 \text{ K} \)) at far-IR/submm
pure rotational \( \Delta v = 0 \)

Hot gas (\( T \sim 2000 \text{ K} \)) at 4.7 \( \mu \text{m} \):
ro-vibrational fundamental \( \Delta v = 1 \)

Warm gas (\( T \sim 1000 \text{ K} \)) at 2.3 \( \mu \text{m} \):
ro-vibrational overtone \( \Delta v = 2 \)
CO lines: great gas disc diagnostics

CO 1300 µm
Pure rotational
J=2-1

CO 144.78 µm
Pure rotational
J=18-17

CO 4.844 µm
Fundamental
Ro-Vibrational. lines
PACS range spec. observations: 55 to 200 µm; CO detections: J=30-29 down to 14-13

Blue: OH doublet

Flux (Jy)

Wavelength (micron)
Rotational diagrams: single $T_{\text{rot}} \sim 200-300$ K
But HD100546 needs both a warm and hot component
Modelling the CO ladder: PDR (Bruderer et al. 2011)

High and mid J transitions need decoupling $T_{\text{gas}}$ & $T_{\text{dust}}$!
For low J transitions (region > 100 AU) not needed
Modelling the CO ladder: flaring is essential ingredient

Different amount of flaring indicated by $\psi$. The higher the flaring, the larger the mass in warm gas. Disc mass not that critical.
Far-IR CO detections in HAEBEs: 'only' in flaring discs

<table>
<thead>
<tr>
<th>HAEBE</th>
<th>Disc group</th>
<th>$L_{1150-2430,\text{Å}}$</th>
<th>$L_{\text{PAH}}$</th>
<th>CO det.</th>
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<td>*AB Aur</td>
<td>I</td>
<td>4.63</td>
<td>0.203</td>
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<tr>
<td>HD 35187</td>
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<td>HD 50138</td>
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<td>*HD 97048</td>
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<td>-</td>
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<td>HD 135344 B</td>
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<td>0.015</td>
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<td>HD 141569 A</td>
<td>II/TO</td>
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<tr>
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<td>II</td>
<td>0.37–0.68</td>
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<td>HD 179218</td>
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PACS: Meeus et al. 2013; SPIRE: van der Wiel et al., submitted (see talk Ménard)
CO in Herbig Ae/Be discs: summary

★ CO mid to high J detections:
= flared discs: 5/12 sources = flat discs: 0/10 sources
Model shows that flaring is necessary to make line detectable
[a few weak detections are seen in deeper GII line spectra]

★ Highest J_{up} found in HD100546, has hot inner wall

★ Sources with mid-J CO detections have high UV fluxes (= sources with high T_{eff}) and strong PAH bands

★ Pure rot. CO and [OI]63 line fluxes tend to be correlated

★ Rotational diagram gives <T_{rot}> = 271 +/- 39 K, some have (indications of) a hot component
The richest spectra: HD97048 & HD100546

Meeus et al. (2012)
Main CH$^+$ formation reaction: $\text{C}^+ + \text{H}_2 \rightarrow \text{CH}^+ + \text{H}$, efficient at a few 100 K.

*Thi, Ménard, Meeus et al. 2011; DIGIT data from Sturm et al. 2010*
HD100546: modelled with ProDiMo

CH$^+$ is located at the rim

outer disc rim

Thi, Ménard, Meeus et al. 2011
The effect of settling on the observed line flux

The smaller the grain size affected by settling “\(a_{\text{set}}\)”, indicating settling of grains \(a \geq a_{\text{set}}\), the stronger the line flux. When the UV photons penetrate deeper into the disc, higher densities can be reached, causing an increase in line flux.

Tilling, Woitke, Meeus et al. (2011)
HD163296: first H$_2$O detection in a HAEBE

Several high-excitation water lines seen. Nothing known about low-excitation water ($E_{\text{up}} < 100$ K), HIFI observation too shallow.

Test models show that 1) water can form rapidly due to presence of warm gas & UV-pumped H$_2$, 2) only a small mass in water vapour is needed to produce observed line emission, and 3) high-excitation lines formed in inner 10 au.

Meeus et al., in preparation
H$_2$O detections in a HAEBEs: some thoughts

Only (tentative) detections present in flat discs.

Absence of high-excitation water lines in flared discs either due less efficient self-shielding against UV photodissociation or to clearing in inner disc.

Lines also seen through stacking in DIGIT SED range spectra (*Fedele et al. 2012*).

! HD100546 has low-excitation water detected with HIFI, but no high-excitation lines (*Hogerheijde, private communication*).
Summary: gas in Herbig Ae discs

★ [OI]63 is by far the strongest line observed, [OI]145 factor 10-20 weaker

★ [OI]63 correlates with $L_{UV}$, amount of flaring, $L_{PAH}$

★ CO J=18-17 only detected in 8 objects, CO ladder only in flaring discs

★ OH and CH$^+$ detected in 2 HAEBEs

★ High-excitation H$_2$O detected in at least 1 HAEBE, low-excitation in HD100546

★ In HAEBEs, UV is important heating factor, not X-rays

★ Detailed modelling of physics & chemistry crucial to understand disc but difficult to reconcile all available observations
Sample of 29 objects, most observed only in photometric mode with PACS (70, 100 & 160 µm) and SPIRE (250, 350 & 500 µm). A few in spectroscopic mode with both PACS and SPIRE (PDS 27 and R Mon).

Auxiliary data available: SEDs and mid-IR images & spectroscopy (Verhoeff et al. 2012).

Additional optical images (narrow & broadband) with 2.2m/CAFOS on Calar Alto.

Master thesis by MJ Jiménez Donaire (UAM).
Herbig Be discs: SEDs

**PDS 27**  B2?e  $T_{\text{eff}}=22000$ K
Log $L_*=3.8$, $M_*=9.1$, $d=1.25$ kpc

**R Mon**  B8IIIeV  $T_{\text{eff}}=11500$ K
Log $L_*=2.1$, $M_*=3.4$, $d=0.8$ kpc
Beamsize 18"

Beamsize 37"

250 µm
1 pixel
= 6”

500 µm
1 pixel
= 14”

70 µm
1 pixel
= 1”

160 µm
1 pixel
= 2”

350 µm
1 pixel
= 10”
R Mon

70 µm
1 pixel
= 1”

250 µm
1 pixel
= 6”

160 µm
1 pixel
= 2”

500 µm
1 pixel
= 14”
PACS and SPIRE spectra

- **PDS 27 PACS**
  - No lines detected

- **R Mon PACS**
  - [OI], OH, [CII]
  - CO up to 30-29
  - No forsterite

- **PDS 27 SPIRE 200 to 700 μm**
  - CO up to 10-9
  - [CI] 610.9 μm

- **R Mon SPIRE 200 to 700 μm**
  - CO up to 13-12
  - [CI] 610.9 μm
Herbig Be discs: rotational diagrams

Rotational diagram for PDS27

Rotational diagram for RMon

$\ln \frac{N_u}{g_u} \text{ m}^2$ vs $E_{up} \text{ (K)}$

$T_{rot} = 37 \text{ K}$

$T_{rot} = 100 \text{ K}$

$T_{rot} = 308 \text{ K}$
Herbig Be discs

*Detections of CO, OH, [OI], [CII], no forsterite*

*Gas lines observed similarly to those found in Herbig Ae discs. The earliest spectral type has less lines*

*Emission in extended regions needs to be analysed & disc parameters derived*

*TBC...*
Ro-vibrational emission at 4.7 µm: HAEBEs

★ Excitation mechanism both collisional + UV fluorescence
★ Correlation found between CO line flux and PAH strength
★ Self-shadowed discs: \( R_{\text{in}} \sim 0.5-5 \) AU, \( T_{\text{rot}} \sim 1600 - 2500 \) K
  Dominant excitation mechanism is \textit{thermal}, \( T_{\text{rot}} \geq T_{\text{vib}} \)
★ Flared discs: \( R_{\text{in}} \sim 10-50 \) AU, \( T_{\text{rot}} \sim 900 - 1400 \) K, \( T_{\text{rot}} < T_{\text{vib}} \)
  Dominant excitation mechanism \textit{fluorescence}: \( L_{\text{UV}} \) important!

Modelling the CO ladder: a small grid

Different amount of flaring indicated by $\psi$
H₂ 1-0 S(1) transition at 2.12 µm: only detected in HD97048 & HD100546

+ H₂ 0-0 S(1) at 17.035 µm detected in HD97048 & AB Aur

Carmona et al. 2011, Martin-Zaïdi et al. 2007 & Bitner et al. 2007
Line (non-)detections give clues about gas in surface layers disc

When \( T_{\text{gas}} \sim T_{\text{dust}} \), weak lines produced by thermal excitation

\[ L_{\text{PAH}} \text{ important for thermal budget: highest AB Aur, HD97048 & HD100546} \]

\[ \Rightarrow \text{more direct heating of upper layer (more flaring)} \]

If non-LTE, UV Fluorescence (\( T_{\text{vib}} > 5000 \text{ K} \)) \( \Rightarrow T_{\text{gas}} >> T_{\text{dust}} \)

\[ \text{CO } T_{\text{vib}} >> T_{\text{rot}} \text{ in flaring discs} - \text{ CO } T_{\text{vib}} \approx T_{\text{rot}} \text{ in flat discs } (\text{van der Plas}) \]

CO rot.-vib. at 4.7 \( \mu \text{m} \):
- AB Aur, HD97048 & HD100546: \( T_{\text{Rot}} \sim 1000 \text{ K} \)
- HD141569: \( T_{\text{Rot}} \sim 200 \text{ K} \) (kinetic T of gas) & \( \text{H}_2 \) absent


\( \text{H}_2 \) detected only in UV-strong objects: AB Aur, HD97048 and HD100546
Location of $\text{H}_2\text{O}$ and CO ice in HD163296's disc

The 'snowline'

$\text{H}_2\text{O}$ ice: from 3 AU

CO ice: from 50 AU
Origin of $\text{H}_2\text{O}$ emission lines in HD163296

- 29.85 $\mu$m, $E_{\text{up}} \sim 1100$ K
- 63.323 $\mu$m, $E_{\text{up}} \sim 1070$ K
- 179.525 $\mu$m, $E_{\text{up}} \sim 114$ K

Is there cold water vapour in HAEBEs?
Efficient formation of water and OH due to the presence of warm UV pumped H₂ in the disc atmosphere. OH is located higher up than water, due to the rapid photodissociation of water.

Model only needs a small amount of mass in warm water (260 K, ~ 1 M⊕) to match the observed line fluxes.

Nothing known about low excitation water (HIFI observation too shallow)

Most of the water mass is in the form of ice (2.3 $10^{-4}$ M⊕), located > 3 AU.