HD 100546: a disk, a gap, and a planet?

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+ a few others
Near IR image of HD100546

Augereau et al. (2001), HST / NICMOS

Discovered by ground based AO, Pantin et al. (2000)
Scattered light (by sub-micron size dust grains)

The star is masked out

The Disk and Environment of HD 100546
C.A. Grady (NOAO, GSFC) and the STIS Investigation Definition Team, NASA

Grady et al. (2001)

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Previous disk models

- Bouwman et al. (2003)
  - Disk geometry
  - Dust Mineralogy

HD 100546 is a Pre- Transitional Disk
In this talk:

- **1- Fit SED -> get overall disk structure**
  - Pre-transition disk (inner disk, gap, outer disk)

- **2- Fit VLTI data -> improve on inner disk**
  - set Rin, surface brightness profile of inner disk
  - Where’s the planet?

- **3- Fit Herschel lines fluxes -> gas content**
  - Discovery of CH+
  - Other lines in GASPS spectra
  - CO rotational diagram

- **4- Future work, concluding remarks**
Our disk model, the SED

Calculations made with MCFOST:
Pinte et al. (2006, 2009)
HD100546: sketch of the disc structure

Not to scale

Outer disk: a = 1 μm – 1 cm

Inner disk: a = 0.1 – 5 μm

Surface layer: a = 0.05 – 1 μm

Gap: ~ 4–13 AU

~ 350 AU

up to 500 AU in CO data (see Panic et al.)

See Poster by Mulders for more on Mineralogy and the surface layer

Benisty et al. 2010; Tatulli et al. 2011
ESO-VLTI data, observing the inner disk

K-band

H-band

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HD100546: a disc with a planet at ~8 AU?

Surface density profile, $\Sigma(r)$

Evolution with time

Effect of Planet mass, @ 1Myr
The gas disc around HD100546: an ALMA test-case

See also Panic et al. 2010
The disc is rich in hot gas (atomic and molecular)

Sturm et al. 2010 A&A 518 L129
Fig. 1. Continuum subtracted Herschel-PACS spectra of HD 100546 around the CH⁺ J=6–5, 4–3, 3–2, 2–1 (DIGIT data), and J=5–4 (GASPS and DIGIT data) lines. The 3σ statistical error levels do not include the 30% calibration uncertainty. A rotational diagram using those transitions is plotted in the lower-right panel. The errors in the diagram is the quadratic sum of all the statistical and calibration errors (err_rad = \( \sqrt{3(\sigma_{stat})^2 + (0.3F_{obs})^2} \)). Blended lines are considered as upper limits (red filled dots).
$CH^+$ is located at the rim

**outer disc rim**

inner disc          outer disc

Calculations made with PRODIMO:
See papers by Woitke et al.; Kamp et al.; Thi et al.

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Dust and gas temperature

\[ T_{\text{gas}} \text{ NOT equal to } T_{\text{dust}} \]
**Table 1. Observed and modelled line fluxes**

<table>
<thead>
<tr>
<th>Transition</th>
<th>$\lambda$ (µm)</th>
<th>obs. $(10^{-17}$ W m$^{-2}$)</th>
<th>model 1</th>
<th>model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>[O I] $^3P_1 - ^3P_2$</td>
<td>63.19</td>
<td>$554.37 \pm 167^a$</td>
<td>785</td>
<td>763</td>
</tr>
<tr>
<td>[O I] $^3P_0 - ^3P_1$</td>
<td>145.54</td>
<td>$35.70 \pm 11.4$</td>
<td>35.7</td>
<td>42.7</td>
</tr>
<tr>
<td>[C II] $^2P_{3/2} - ^2P_{1/2}$</td>
<td>157.75</td>
<td>$31.87 \pm 10.0$</td>
<td>12.7</td>
<td>17.2</td>
</tr>
<tr>
<td>p-H$<em>2$O $3</em>{22} - 2_{11}$</td>
<td>89.90</td>
<td>$\leq 14.32 \pm 1.2^b$</td>
<td>4.6</td>
<td>7.4</td>
</tr>
<tr>
<td>CH$^+$ $J = 4 - 3$</td>
<td>90.02</td>
<td>$\leq 14.32 \pm 1.2^b$</td>
<td>3.7</td>
<td>6.3</td>
</tr>
<tr>
<td>CH$^+$ $J = 6 - 5$</td>
<td>60.25</td>
<td>$10.32 \pm 5.7$</td>
<td>4.2</td>
<td>8.9</td>
</tr>
<tr>
<td>CH$^+$ $J = 5 - 4^c$</td>
<td>72.14</td>
<td>$6.86 \pm 3.4$</td>
<td>3.3</td>
<td>6.7</td>
</tr>
<tr>
<td>CH$^+$ $J = 3 - 2$</td>
<td>119.87</td>
<td>$2.16 \pm 1.1$</td>
<td>1.8</td>
<td>2.9</td>
</tr>
<tr>
<td>CO $J = 3 - 2^d$</td>
<td>866.96</td>
<td>$0.10 \pm 0.03$</td>
<td>0.08</td>
<td>0.24</td>
</tr>
</tbody>
</table>

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$^a$ The total (3σ statistical + 30% calibration) errors are given for the PACS observations.  
$^b$ The blended H$_2$O+CH$^+$ line is detected.  
$^c$ The PACS values are from the DIGIT programme (Sturm et al. 2010) except for the CH$^+$ $J = 5 - 4$ flux (GASPS programme).  
$^d$ Data from Panić et al. (2010) with 3σ error.
The model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MCFOST(^a)</th>
<th>ProDiMo(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius ( R_{\text{in}} ) (AU)</td>
<td>0.24</td>
<td>1.0</td>
</tr>
<tr>
<td>Outer radius ( R_{\text{out}} ) (AU)</td>
<td>4</td>
<td>UV excess</td>
</tr>
<tr>
<td>Surf. density exponent ( q )</td>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>Scale height ( H_{100 \text{AU}} ) (AU)</td>
<td>6</td>
<td>0.15</td>
</tr>
<tr>
<td>Scale height exponent ( \beta )</td>
<td>1.0</td>
<td>42</td>
</tr>
<tr>
<td>Total dust mass ( M_{\text{dust}} ) ( (M_\odot) )</td>
<td>1.75(−10)(^b)</td>
<td>6.5</td>
</tr>
<tr>
<td>Dust mass ((a \leq 1 \text{ mm}, (M_\odot) )</td>
<td>1.75(−10)</td>
<td>1(−7)</td>
</tr>
<tr>
<td>Min. grain radius ( a_{\text{min}} ) (( \mu \text{m} ))</td>
<td>0.1</td>
<td>0.013</td>
</tr>
<tr>
<td>Max. grain radius ( a_{\text{max}} ) (( \mu \text{m} ))</td>
<td>5</td>
<td>6.5</td>
</tr>
<tr>
<td>Grain power law index ( p )</td>
<td>3.5</td>
<td>1(−17)</td>
</tr>
<tr>
<td>Silicate grain density (g cm(^{-3}))</td>
<td>3.0</td>
<td>1(−3) (model 2)</td>
</tr>
</tbody>
</table>

Notes. \(^a\) Values taken from Benisty et al. (2010) and Tatulli et al. (2011) except for the scale height \( H_{100 \text{AU}} \) at 100 AU. \(^b\) \( \alpha(−\beta) \) means \( \alpha \times 10^{-\beta} \). \(^c\) This work.
2 slides removed
Concluding remarks

DUST:
- Pre-Tansitional disk
- There is a gap between ~4 and ~13 AU
  - may be carved by a 6-8 Jupiter mass planet
  - Difficult to detect directly (disk is bright, gap is narrow)
- We find it necessary to deal with scattering properly in the models
- Inner disk may be variable?

GAS:
- Disk rich in gas, both inner and outer.
- I discussed (and modelled) lines for the outer disk so far.
  - Working on inner disk (CO ro-vib...)
- Modelling of several lines provide first estimates of total gas mass.
- CH⁺ transitions up to J=6-5, first detection in a disk by Herschel
  - probe the upper rim atmosphere of the outer disc

We developed a unique combination of continuum radiative transfer code and a thermo-chemical code to allow extensive modeling.
- Axisymmetric models remain useful (see also remark by David Wilner)
- Don’t explain everything by provide good understanding of disk (structure, temperature, composition...)

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From Atoms to Pebbles: Herschel's view of Star and Planet Formation

A Herschel Meeting on Star and Planet Formation
20-23 March 2012, Grenoble, French Alps

Consult: http://www.herschel2012.com