Spiral arms in the disk of HD 142527 with ALMA
(Triptych on HD 142527 - part III)

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Outline

1. Moment maps and detection of spiral arms
2. Description of the spiral arms
3. Geometrical modelling
4. Discussion on their origin
1. Moment maps

- Extended diffuse cloud absorbs signal in the South (Casassus et al. 2013)
- Spiral structures in $I_{\text{int}}$ and $I_{\text{peak}}$ maps; best seen in CO J=2-1 $I_{\text{peak}}$ map
- Keplerian vel. + no significant vel. dispersion under the spirals
- Outer disk too faint to reveal structures in $^{13}\text{CO}$ J=2-1
2. Spiral arms description

★ **S1 in NIR:** diamonds (Fukagawa+ 06) and squares (e.g. Casassus+ 12)
★ **Very large scale:** $R > 300$ au for S1, $R > 500$ au for S2 and $\Delta PA \sim 100^\circ$
★ **S3 signal absorbed by an intervening cloud** (Casassus+ 13)

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<td>$R (au)$</td>
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2. Spiral arms description

- \( T(S2) < 18K \Rightarrow \text{CO should freeze-out} \) (e.g. Leger 83; Qi+ 11)
- \( \Rightarrow \text{dust depleted or settled} \) (e.g. Dubrulle+ 95; Dullemond & Dominik 04)
- and/or \( \text{CO desorbed} \) (e.g. Hersant 09)
- \( T(gap) \approx 42K \) (Fukagawa+ 13; Perez+ 14 submitted) \( \Rightarrow T \propto r^{-q} \) with \( T_b(\text{CO2-1}): q \sim 0.5 \)

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2. Spiral arms description

![CO J=2-1](image)

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<td>38–44</td>
<td>66–76</td>
<td>?</td>
</tr>
<tr>
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★ If $i \sim 28°$ (Perez+ 14, submitted) => H~20au at the wall ($h \sim 0.10–0.15$; Avenhaus+ 14)
3. Spiral arm modelling (points)

★ 20 Points with: 1st derivative null (S2,S3) in radial $I_{\text{peak}}$ profile OR 2nd derivative null (S1)
3. Spiral arm modelling (Muto+ 12)

\[
\theta(r) = \theta_c + \frac{\text{sgn}(r - r_c)}{h_c} \left\{ \left( \frac{r}{r_c} \right)^{1+\beta} \left[ \frac{1}{1+\beta} - \frac{1}{1 - \alpha + \beta} \left( \frac{r}{r_c} \right)^{-\alpha} \right] - \left( \frac{1}{1+\beta} - \frac{1}{1 - \alpha + \beta} \right) \right\}
\]

★ 5 parameters: \(\theta_c, r_c, h_c, \alpha\) and \(\beta\) (with \(\Omega \propto r^{-\alpha}\) and \(c_s \propto r^{-\beta}\))

★ The parameters are degenerate (also noted by Muto+ 12, Grady+ 13, Boccaletti+ 13).

★ \(\alpha := 1.5\) (Keplerian rotation)

\(\beta := 0.25\) \((T \propto r^{-0.5})\)

\(h_c := 0.14\) (best fit value for S1 if set as free parameter)

\[
\begin{array}{|c|c|c|c|}
\hline
\chi^2 & S1 & S2 & S3 \\
\hline
\text{CO 2-1} & 2.38 & 18.0 & 4.67 \\
\hline
\text{CO 3-2} & 2.06 & 36.0 & / \\
\hline
\end{array}
\]

★ \(\sigma\) not independently determined ⇒ S1 is better fit than S2 and S3
3. Spiral arm modelling (Muto+ 12)

★ Inflection point in the curves: best fit location of the planet
★ S1 + S3 ~ Point-symmetric of S2
3. Spiral arm modelling (Kim 11)

\[ r = a\theta + b \]

★ 2 parameters: \( a \) and \( b \) (Archimedean spiral)

\[ \begin{cases} 
    a = r_p/M_p \\
    b = \text{cte} \\
\end{cases} \]

with \( r_p \) = planet's orbital distance; \( M_p \) = planet's Mach number

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<td>0.30</td>
<td>0.40</td>
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<td>CO 3–2</td>
<td>0.18</td>
<td>2.94</td>
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⇒ \text{S1 is also better fit than S2 and S3.}
3. Spiral arm modelling (Kim 11)

- NIR H-band spiral (diamonds, Fukagawa+ 06), Ks-band spiral root (squares, Casassus+ 12), and S1 ⇒ trace the same spiral structure?
- S3 ~ point-symmetric of S2 ⇒ two-armed spiral structure?
4. Discussion: Origin of the spirals

1/ Late envelope infall? (Tang+ 12)

- AB Aur: Herbig star, large gap, only TD with known sub-mm spirals

- AB Aur spiral arms have a larger pitch angle.
- AB Aur spiral arms seem to counter-rotate with the disk (vel. disp.).
  \[ \Rightarrow \text{Late envelope infall above or below the mid-plane of the disk.} \]

For HD 142527? NO
2/ Planetary companion?

- S1 is better fit with Muto and Kim equations than S2 and S3.
- The very large scale of S2 and S3 argue against a planetary origin.
- Object (stellar companion?) detected at \( \sim 12 \text{ au} \) (Biller+ 12, Close+ 14)

Companion origin? Maybe for S1, less likely for S2 and S3
4. Discussion: Origin of the spirals

3/ Tidal interaction? (e.g. Larwood & Kalas 01, Quillen+ 05)

a) Past stellar encounter

★ Galaxy encounters are able to create $m=2$ spiral structures (Toomre 1972)

★ Stellar encounters with pp. disks too (Larwood & Kalas 01, Quillen+ 05)

★ Transient ($\sim 10^3$ yrs) => very recent encounter
=> culprit still in the neighbourhood.
No such object in a FOV of 20” (Fukagawa+ 06).

Past stellar encounter?
Requires larger FOV; cannot be ruled out.
4. Discussion: Origin of the spirals

3/ Tidal interaction? (e.g. Augereau & Papaloizou 04, Quillen+ 05)

b) Bound external companion

- Large scale (~325 au) tightly wound spiral in the disk of HD 141569A due to one of its M-dwarf companions (Augereau & Papaloizou 04, Quillen+ 05)

- For HD 142527, no external companion of $M > 4M_J$ (Casassus+ 13)

Bound external companion? Not likely
4. Discussion: Origin of the spirals

4/ Gravitational instability (GI)? (e.g. Boss 1998, talk by G. Lodato)

★ Disk self-gravity can lead to multi-arm spiral pattern (with perhaps some unresolved modes here)

★ The stability of a disk against self-gravity is characterized by:

\[ Q = \frac{c_s \Omega}{\pi G \Sigma} \]  

(Toomre 1964)

\[ \approx \frac{M_*}{M_d} h \]  

(Gammie 2001)

★ If \( Q \lesssim 1 \): disk instability

★ \[ \begin{aligned} M_* & \sim 2^{+0.2}_{-0.1} M_\odot \\
M_d & \sim 0.1 M_\odot \\
h = h_s & \sim 0.1 
\end{aligned} \]  

(Fukagawa+ 06, Verhoeff+ 2011)

⇒ \( Q \sim 2 \) (similar to Fukagawa+ 13)

GI? Marginal stability, but very rough estimated
Summary

★ Three CO spiral arms in the disk of HD 142527:
  - S1 is radially shifted outward w.r.t. NIR spirals
  - S2 and S3 are new and at larger scale (> 500au)
★ S2 has T ≲ 18K: dust is depleted or settled or CO is desorbed.
★ h ≈ 0.11-0.13 in the outer disk
★ S1 better fit than S2 and S3 to eqs. assuming embedded companion.
★ Other possible origins: past stellar encounter
  gravitational instability
Thank you for your attention!
Appendix

S1 in NIR: diamonds (Fukagawa+ 06) and squares (e.g. Casassus+ 12)

Very large scale: $R > 300$ au for S1, $R > 500$ au for S2 and $\Delta PA \sim 100^\circ$

S3 signal absorbed by an intervening cloud (Casassus+ 13)