# Spiral arms in the disk of HD 142527 from CO emission lines with ALMA

**V. Christiaens[1], S. Casassus[1], S. Perez[1] & G. van der Plas[1]**

[1] University of Chile

valchris@das.uchile.cl

**Abstract**

*With its large gap and previously reported near-IR asymmetries and spiral arms, the transition disk of Herbig Fe star HD 142527 constitutes a remarkable case study in the context of planetary formation. Observations of $^{12}$CO J=2-1, $^{12}$CO J=3-2 and $^{13}$CO J=2-1 emission lines were carried out with ALMA. This paper focuses on the morphology of the outer disk, in which the $^{12}$CO J=2-1 (CO 2-1) peak intensity ($I_{peak}$) map shows three spiral features of different sizes, two of which being only hinted at in the $^{12}$CO J=3-2 (CO 3-2) $I_{peak}$ map. Those three spirals are modelled separately with two different mathematical formalisms assuming they are generated as pressure waves in the gas due to moving embedded planets. While the radially inner spiral could be fit relatively well in the embedded companion picture, this is not so for the two others, which may suggest an alternative scenario such as gravitational instability or a past stellar encounter.*

## 1. Introduction

### 1.1 Context

- Large annular gaps in transition disks are most likely indicators of dynamical clearing by multiple-planets (e.g. Dodson-Robinson et al. 2011, Zhu et al 2012, Zhu et al 2013).
- Previous detections of spiral arms in transition disks were mostly in optical (e.g. Grady et al. 2001, Clampin et al. 2003) and NIR (e.g. Muto et al. 2012, Grady et al. 2013, Boccaletti et al. 2013).
- The only detection of spiral structures in sub-mm/radio wavelength before this work was obtained in AB Aurigae (Corder et al. 2005, Lin et al. 2006, Tang et al. 2012.

### 1.2 HD 142527

- Herbig Fe star of $\sim 2$ M$_{\odot}$ and 2-5 Myr old, at 145±15 pc (Fukagawa et al. 2006, Verhoeff et al. 2011).
- Almost face-on ($i \approx 28°$) transition disk with a large dust depleted gap of $\sim$ 130 AU (Perez et al. 2014 in prep., Verhoeff et al. 2011).
- NIR spirals with their origin at the outer edge of the gap (Fukagawa et al. 2006, Casassus et al. 2012, Rameau et al. 2012).
- Horseshoe dust continuum and gap-crossing filaments (Ohashi et al. 2008, Casassus et al. 2013).

### 1.3 Observations

- $^{12}$CO J=2-1 : ALMA cycle 0, 230.538 GHz (band 6), beam (natural weighting): 0.96"x0.72";
- $^{12}$CO J=3-2 : ALMA cycle 0, 345.796 GHz (band 7), beam (natural weighting): 0.63"x0.40";
- $^{13}$CO J=2-1 : ALMA cycle 0, 220.399 GHz (band 6), beam (natural weighting): 0.97"x0.74".

## 2. Results

### 2.1 Moment maps

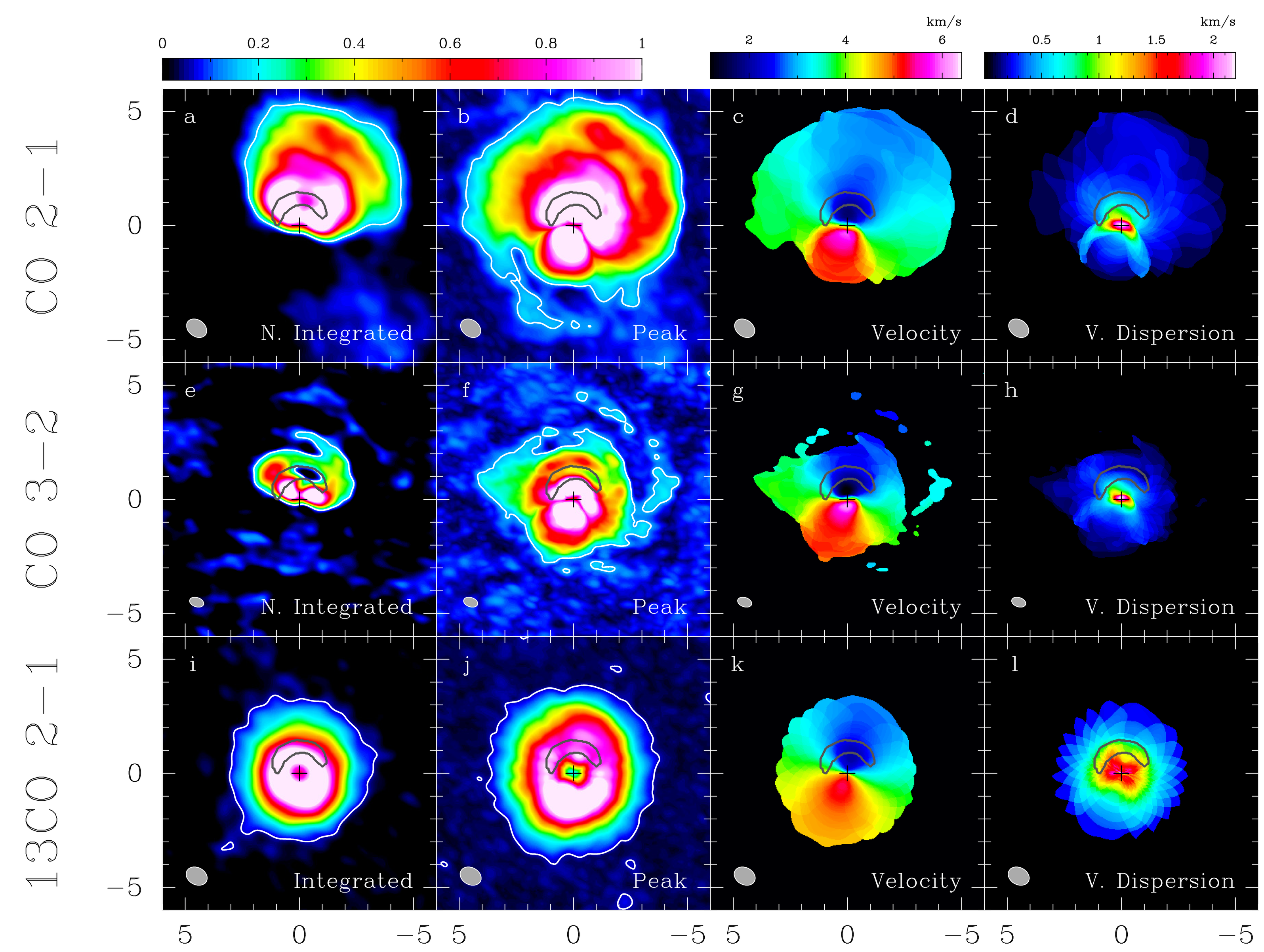


**Figure 1:** *Moment maps computed for CO 2-1, CO 3-2 and $^{13}$CO 2-1 respectively: Integrated specific intensity map in the north (**a** and **e**), and over all channels (**i**); $I_{peak}$ map over all channels (**b**, **f** and **j**); Velocity profile (**c**, **g** and **k**); Velocity dispersion (**d**, **h** and **l**). Intensity signals are circumscribed inside a white mean(noise)+3σ contour. The mean of the noise is ∼0 mJy beam$^{-1}$ for all integrated maps, while it is respectively 27, 42 and 21 mJy beam$^{-1}$ for CO 2-1, CO 3-2 and $^{13}$CO 2-1 $I_{peak}$ maps. The σ for CO 2-1, CO 3-2 and $^{13}$CO 2-1 integrated (resp. $I_{peak}$) maps are respectively 14, 17 and 12 mJy beam$^{-1}$ (resp. 11, 15 and 4 mJy beam$^{-1}$). The color scale for CO 2-1, CO 3-2 and $^{13}$CO 2-1 integrated (resp. $I_{peak}$) maps is normalized respectively to 20, 20 and 50 σ (resp. 40, 40 and 150 σ). For the velocity profile and dispersion, the scales are expressed in km s$^{-1}$. A continuum contour at 180 mJy beam$^{-1}$ from Casassus et al. (2013) is overplotted in dark gray.*

### 2.2 Spiral arms

The spiral arms extend, in projected angular separations but deprojected physical distances:

- from ∼1.9" (∼330 AU) at a PA of ∼-110° to ∼2.8" (∼430 AU) at a PA of ∼0° for S1;
- from ∼3.0" (∼520 AU) at a PA of ∼-100° to ∼4.2" (∼640 AU) at a PA of ∼0° for S2;
- from ∼3.2" (∼520 AU) at a PA of ∼100° to ∼4.4" (∼650 AU) at a PA of ∼190° for S3.

#### 2.2.1 Physics in the spirals

- Assuming optical thickness of CO 2-1, the Rayleigh-Jeans formula yields brightness temperatures of T$_b \sim$ 13-15 K (S1) and T$_b \sim$ 5-10 K (S2).
- However, assuming LTE, the ratio of CO 2-1 and CO 3-2 intensities in the spirals provides T$_{ex} \sim$ 22-25 K (S1) and T$_{ex} \sim$ 13-15 K (S2).
- Under 20K, CO gas is expected to condensate on grains. The fact that we still see CO gas is probably evidence for dust settling in the mid-plane as suggested by Dullemond & Dominik (2004).
- Combining equations of sound speed and scaleheight for a protoplanetary disk (see e.g. Armitage 2010) and inserting the values of T$_b$, we obtain $H_{S1} \sim 11$ AU and $H_{S2} \sim 17$ AU.

#### 2.2.2 Modelling of the spirals

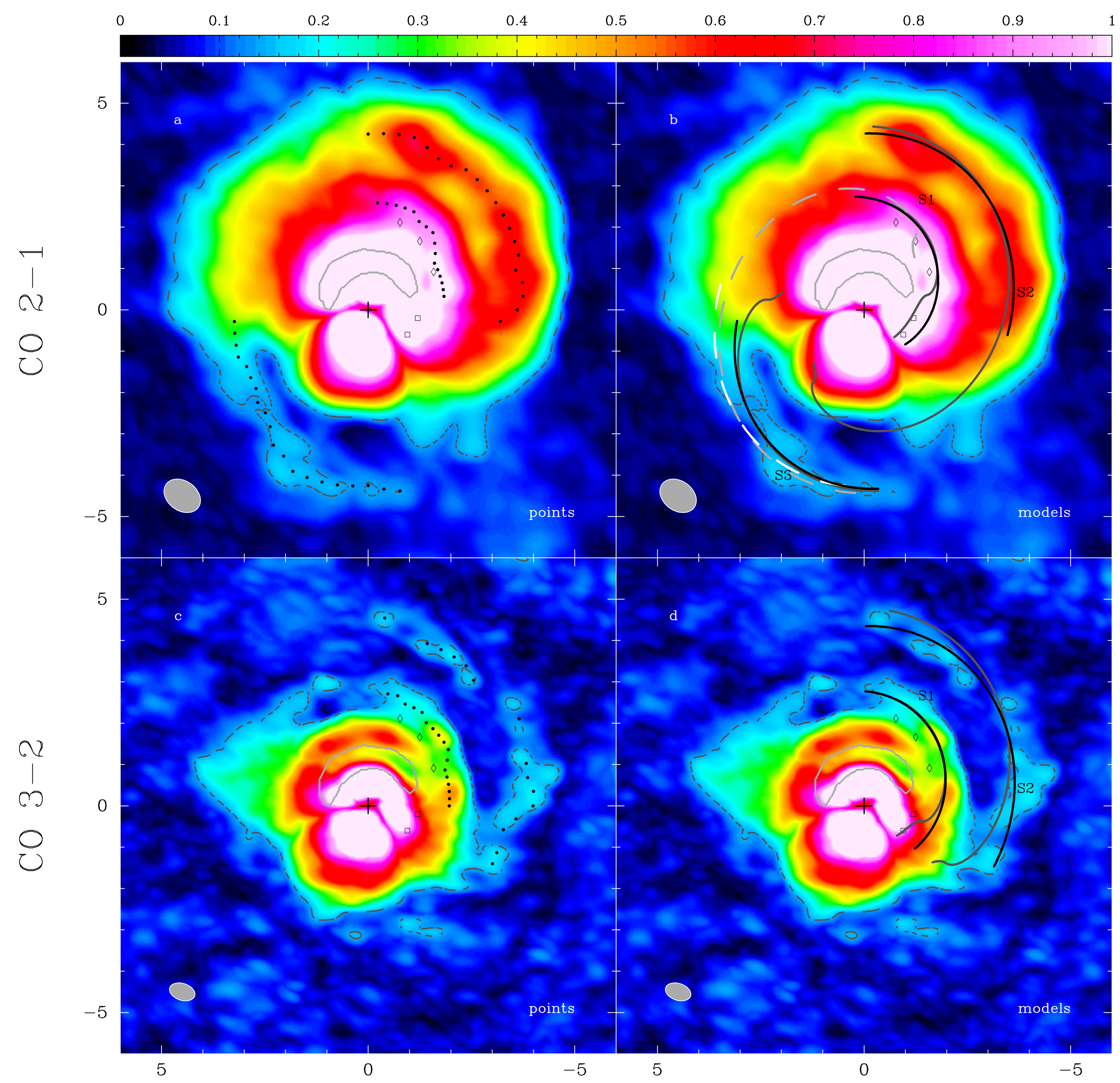


**Figure 2:** *CO 2-1 and CO 3-2 $I_{peak}$ maps with overlaid spiral models. (**a**): Points tracing the spirals used for the modelling, obtained as local maxima in the radial profile in the CO 2-1 $I_{peak}$ map. (**b**): Modelling of the three spiral arms based on the spiral density wave theory following Kim et al. 2011 (solid black lines), and Muto et al. 2012 (solid dark gray lines). The dashed white (resp. dashed light gray) spiral arm represents the axisymmetric of model S2 in black (resp. in dark gray) with respect to the star; both match S3 relatively well. (**c**) and (**d**): Identical to (a) and (b) but with the CO 3-2 $I_{peak}$ map. The H-band spiral arm of Fukagawa et al. 2006 (diamonds) and Ks-band most prominent spiral's outer end of Casassus et al. 2012 (squares) are given for comparison.*

- Points tracing the sample were obtained as local maxima in the radial profile of intensity for 1° azimutal slices, in both CO 2-1 and CO 3-2 $I_{peak}$ maps.
- Spirals were modelled independently through a least-square fit between the coordinates of the points and two different approximations of the spiral density wave theory, following:
  1) Muto et al. 2012, characterized by spirals with inflection point at location of the planet:

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

  2) Kim et al. 2012, characterized by Archimedes spirals:

$$r(\theta) = a\theta + b \quad (2)$$

- Values of $\chi^2$ for the best fit parameters to Eq. (1) and (2) are higher for S2 and S3 than S1:

| | CO 2-1 | | | CO 3-2 | | |
|---|---|---|---|---|---|---|
| | S1 | S2 | S3 | S1 | S2 | S3 |
| Eq. (1) | 2.38 | 18.1 | 4.66 | 2.04 | 36.0 | / |
| Eq. (2) | 0.16 | 0.30 | 0.40 | 0.18 | 2.94 | / |

## 3. Discussion: origin of the spiral arms

- Late envelope infall above or below the main disk plane (Tang et al. 2012)? NO, because of the Keplerian velocity profile.
- Past stellar encounter (e.g. Quillen et al. 2005)? Probably no, because it requires to have happened within a few thousand years ago, and no reliable candidate has been found in the vicinity (so far).
- Planet(s)? Possible for S1 (see location of the inflection point). Less probable for S2 and S3 because of the poor quality of the fit between points and models.
- Gravitational instability (e.g. Boss et al. 2005)? Interesting possibility, in particular for S2 and S3, but difficult estimate of the Toomre parameter yet.

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