CO spiral arms in the outer disk of HD 142527 with ALMA

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1. Introduction

1.1 Context

- Large annular gaps in transition disks => probable 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: mostly in optical and NIR (e.g. Grady et al. 2001, Clampin et al. 2003, Muto et al. 2012, Grady et al. 2013, Boccaletti et al. 2013).
- Spiral arms detection in sub-mm/radio wavelength before this work: only 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 ($i \approx 28^\circ$) 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".

2. Results

2.1 Moment maps

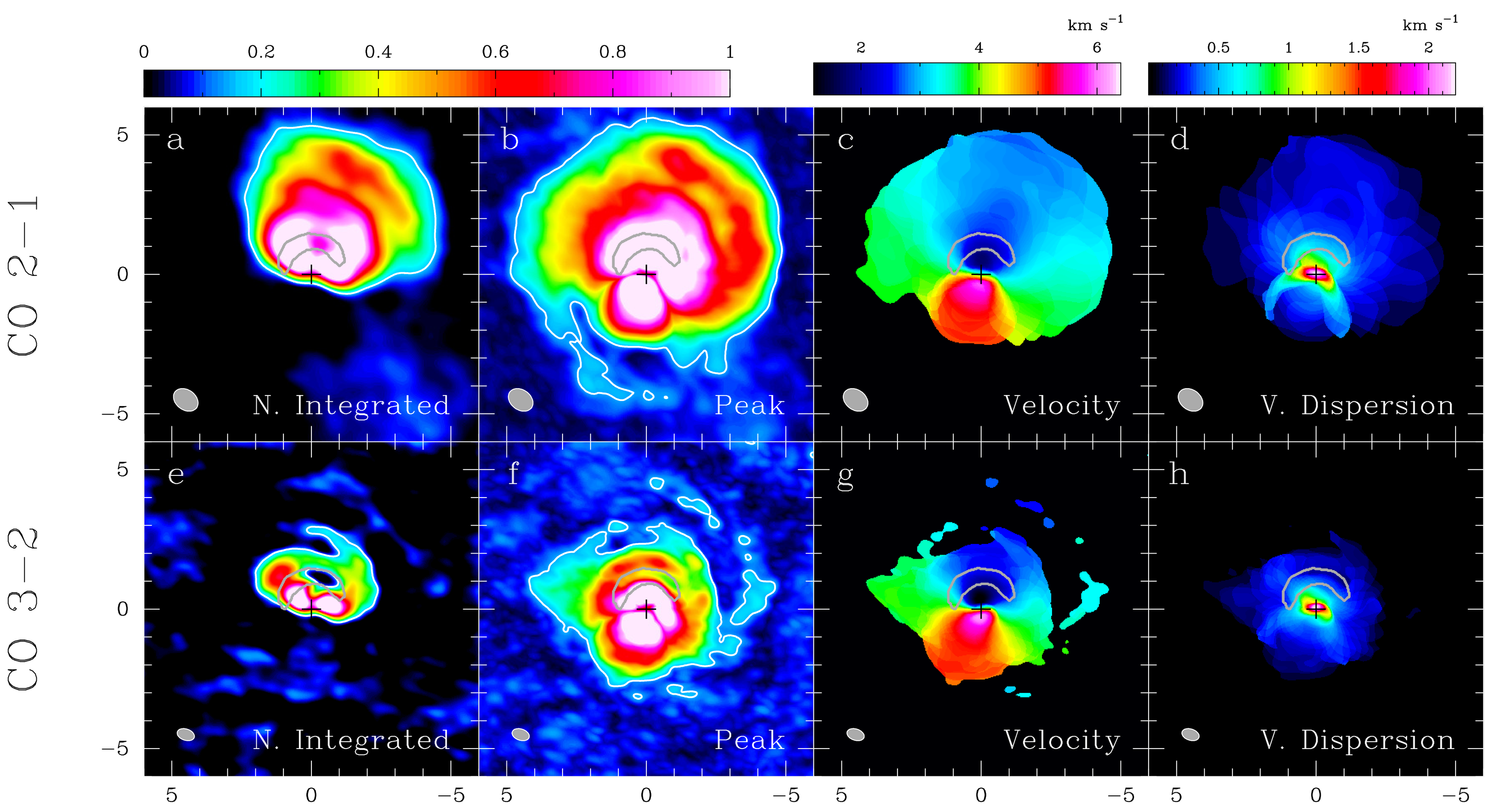

Figure 1: *Moment maps computed for CO 2-1 and CO 3-2 respectively: Integrated specific intensity map in the north (**a** and **e**); I_{peak} map over all channels (**b** and **f**); Velocity profile (**c** and **g**); Velocity dispersion (**d** and **h**). White contours correspond to 3-σ significance. A continuum contour at 180 mJy beam^{-1} (half-maximum) from Casassus et al. (2013) is overplotted in dark gray.*

2.2 Spiral arms

The spiral arms extend in projected angular distances (resp. deprojected physical distances):

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

2.2.1 Physics in the spirals

- Brightness temperatures: $T_b(S1) \sim 20$ K and $T_b(S2) \sim$ 11-15 K [assumes $\tau >> 1$];
- Excitation temperatures: $T_{ex}(S1) \sim$ 22-27 K and $T_{ex}(S2) \sim$ 13-15 K [assumes LTE];
- CO gas is detected below the freezing temperature ($\sim$20 K)
  => either dust depletion, dust settling in the mid-plane, or efficient CO desorption.
  (e.g. Dullemond & Dominik 2004, Hersant et al. 2009);
- Inserting T_b in equations of sound speed and scale height (H) for protoplanetary disks
  => $H_{S1} \sim 38-44$ AU and $H_{S2} \sim 66-76$ AU [assumes isothermal vertically]
  => aspect ratio: $h_{S1} \sim h_{S2} \sim 0.12-0.13$.

2.2.2 Modelling of the spirals

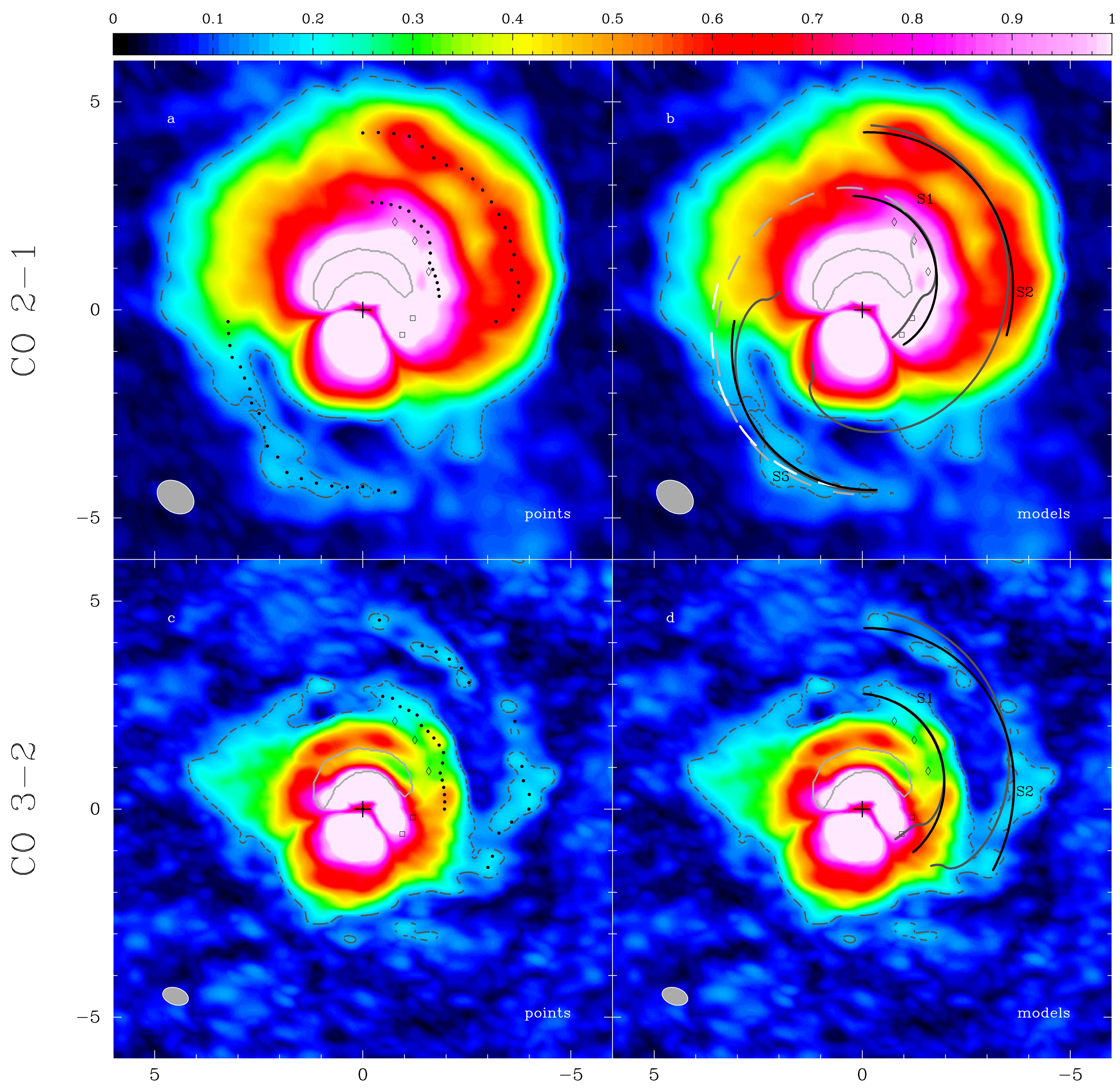

Figure 2: *CO 2-1 and CO 3-2 I_{peak} maps. **(a)**: Points tracing the spirals used for the modelling. **(b)**: Modelling of the spiral arms following Kim et al. 2011 (solid black lines), and Muto et al. 2012 (solid dark gray lines). The dashed white (resp. dashed light gray) curve represents the axisymmetric of model S2 in black (resp. in dark gray) with respect to the star. **(c)** and **(d)**: Identical to (a) and (b) but with the CO 3-2 I_{peak} map. Diamonds: the H-band spiral arm (Fukagawa et al. 2006). Squares: Ks-band most prominent spiral's outer end (Casassus et al. 2012).*

- Points tracing the spirals: local maxima in the radial profile of I_{peak} in 1° azimutal slices;
- Spirals (independent) modelling: least-square fit between the coordinates of the points and two different approximate equations based on spiral density wave theory:
  1) Spirals with an inflection point at the location of the planet, 5 parameters (Muto et al. 2012):

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

  2) Archimedes spirals, 2 parameters (Kim 2011):

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

- Values of χ^2 for the best fit parameters to Eq. (1) and (2) are higher for S2 and S3 than S1 => Other origin involved?
- Point-symmetric locus of S2 models fits relatively well with S3 => Possibility of a giant two-armed structure?

3. Discussion: Origin of the spiral arms

- Late envelope infall above or below the main disk plane (e.g. Tang et al. 2012 for AB Aur.)?
  No, because the spirals are tightly coiled and in Keplerian rotation (cfr. velocity profile).
- Presence of planet(s)?
  Possible to account for S1 (see location of the inflection point).
  Less probable for S2 and S3 because of the poor quality fit, and very large scale involved.
- Past stellar encounter or bound companion external to the disk (e.g. Quillen et al. 2005)?
  Simulations have shown that two-armed spirals can arise from a past stellar encounter.
  However, they are very transient and last only a few dynamical timescales (i.e. $\sim 10^3$ yrs).
  => The culpit should be seen in the vicinity, but none has been found yet (Fukagawa et al. 2006).
- Gravitational instability (e.g. Boss 1998, G. Dipierro et al. in prep.)?
  Measured by the Toomre parameter Q, approximated with $Q \approx \frac{M_\star}{M_d} h_S$ (Gammie 2001)
  With $M_\star \approx 2\ M_\odot$, $M_d \approx 0.1\ M_\odot$ (Verhoeff 2011) and the aspect ratio $h_S \approx 0.1$ (cfr. sec. 2.2.1):
  $Q \sim 2.0$ => The disk is globally stable, but close to the instability regime.
  Other possibility: higher modes spirals ($m > 2$) are filtered out by ALMA (G. Dipierro et al. in prep.).

4. Summary

- HD 142527 displays a large gap and both near-IR and sub-mm spiral arms.
- Three spiral arms are seen in the CO 2-1 I_{peak} map, two of them in the CO 3-2 I_{peak} map.
- They are modelled separately with two different mathematical formalisms assuming they are generated as pressure waves in the gas due to moving embedded planets.
- The radially inner spiral (S1) could be fit relatively well in the embedded companion picture.
- This is not so for S2 and S3, which may suggest an alternative scenario such as gravitational instability or a past stellar encounter.

Details and references in **Christiaens et al. 2014, ApJL, 785, 12.**

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