Kinematic evidence for embedded protoplanets in circumstellar discs

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Figure 1. Synthesized images of the 1.33 mm continuum with a Briggs weighting of robust. The image dimensions and intensity scales, see Huang et al. (2018a) and Kurtovic et al. (2018). The dynamic range (accentuate fainter details without over-saturating the bright emission peaks). For more quantitative details regarding scalebars are shown in the lower left and right corners of each panel, respectively. All images are shown with an asinh stretch to reduce.

Figure 2. Radial intensity profile along disk major axis for the 12 selected disks with dust substructures, in the same order as in Figure 1. The noise level is shown by the dashed line.

Figure 3. A resolved ring or fitted intensity profile along disk major axis for the 12 selected disks with dust substructures, in the same order as in Figure 1. The noise level is shown by the dashed line.

Are (some of) these gaps carved by planets?

Taurus survey
Long et al. 2018
Chemical layers in a discs

Three layers of chemistry:

- **Hot atomic layer (PDR)**
- **Warm molecular layer** → probed by ALMA
- **Cold icy mid plane** → dust pebbles probed by ALMA
Pinte et al. 2018

ALMA 1.3mm + $^{12}$CO
0.3” 0.1km/s

SPHERE H band DPI  ~ 0.05”

IM Lup

Avenhaus et al. 2018

i = 50 deg
\(^{12}\text{CO} \ (2-1)\)

\[ \begin{array}{ccc}
\begin{array}{c}
\text{dv}=−1.28\text{km/s} \\
1''
\end{array} & \begin{array}{c}
\text{Upper surface} \\
\text{Lower surface}
\end{array} & \begin{array}{c}
\text{Upper surface} \\
\text{Lower surface}
\end{array} \\
\begin{array}{c}
\text{dv}=−0.96\text{km/s}
\end{array} & \begin{array}{c}
\text{dv}=−0.64\text{km/s}
\end{array} & \begin{array}{c}
\text{dv}=−0.32\text{km/s}
\end{array} \\
\begin{array}{c}
\text{dv}=−0.00\text{km/s}
\end{array} & \begin{array}{c}
\text{dv}=0.32\text{km/s}
\end{array} & \begin{array}{c}
\text{dv}=0.64\text{km/s}
\end{array} \\
\begin{array}{c}
\text{dv}=0.96\text{km/s}
\end{array} & \begin{array}{c}
\text{dv}=1.28\text{km/s}
\end{array} & \begin{array}{c}
\text{dv}=1.28\text{km/s}
\end{array}
\end{array} \]

\( \text{Tb} \ [\text{K}] \)
\( ^{12}\text{CO} \ (2-1) \)

Upper surface

Lower surface

\( dv = -0.64 \text{km/s} \)
\[^{13}CO\ (2-1)\]

\[
\begin{array}{ccc}
1'' & \text{Upper surface} & \text{Lower surface} \\
\text{dv}=\text{-1.28km/s} & \text{dv}=\text{-0.96km/s} & \text{dv}=\text{-0.64km/s} \\
\text{dv}=\text{-0.32km/s} & \text{dv}=\text{-0.00km/s} & \text{dv}=\text{0.32km/s} \\
\text{dv}=\text{0.64km/s} & \text{dv}=\text{0.96km/s} & \text{dv}=\text{1.28km/s} \\
\end{array}
\]
Reconstructing the altitude, velocity and temperature of the CO emitting layers

\[
r = \sqrt{(x - x_\star)^2 + \left(\frac{y_f - y_c}{\cos i}\right)^2}
\]

\[
h = \frac{y_c - y_\star}{\sin i}
\]

\[
v = (v_{\text{obs}} - v_{\text{syst}}) \frac{r}{(x - x_\star) \sin i}
\]

\[
T_b = T_{\text{ex}} \left(1 - e^{-\tau}\right)
\]

Assuming Keplerian rotation and circular orbit
The CO layers

The brightness temperature of points on the disc lower surface is higher than the gas kinetic temperature for optically thin emission, and as long as the emission fills the vertical extent of the disc. This is the case for the 12CO and 13CO layers. For optically thick lines, the peak brightness temperature is lower than the excitation temperature, which can be measured from the ratio of the line brightness temperature to the gas kinetic temperature. For optically thick emission, and as long as the emission fills the vertical extent of the disc, the excitation temperature is approximately equal to the gas kinetic temperature. To reconstruct the disc Keplerian velocity and reduces correspondingly the range over which we can accurately measure the CO layer altitude.

Each channel probes a range of distances from the star, defined by the radius of the beam, which depends on the beam size and the resolution of the telescope. A proof is presented in this section, as well as estimate an altitude. This is very likely the result of UV interstellar radiation field (see for instance Fig. 5 d), allowing gas CO to exist even in the midplane, and to emit from a vertically extended region.

The presented framework also requires sufficient signal in the CO emission at large scales (a few 1000 au). As already noted by Cleeves et al. (2016), the CO emission is partly optically thick (e.g. for 13CO and C18O emission is partly optically thick in regions where the emission is located). The red and blue dashed lines show the expected Keplerian velocities derived from the C18O position-velocity curve, taking into account the altitude of the 12CO and 13CO layers. The black full line represents the Keplerian velocity for a 1 M_{\odot} central star, derived from the C18O position-velocity curve.
For optically thick emission, and as long as the emission fills the beam, the observed brightness temperature $T_b$ is equal to the gas kinetic temperature $T_k$. Low $J$ transitions are not optically thick, so that an altitude dependence of the gravitational field (Fig. 4, central panel). The black full line represents the Keplerian velocity for a 1 M$_\odot$ star (Fig. 4, right panel and Fig. 6). In the lower surface, on the gas orbit. The radius and velocity are less a face through the disc, we are looking at the emitting CO layer. The di-phology of the channel maps is not a photo-evaporation.

2 Note that this mainly a dilution by irradiation from the local (weak) external radiation field. Haworth et al. (2016), such a photo-evaporative wind can also explain why the deviations from Keplerian rotation seem to start closer-in at high altitude, where the density is lower, also requires su-fer in which $\Delta \tau_h$ might be at play.

As already noted by Cleeves et al. (2016), such a photo-evaporative wind could be applied to estimate an altitude. This is very likely the result of UV photo-desorption of the CO by external irradiation from the surrounding protostellar envelope. Interestingly, as shown by Facchini et al. (2016) and this prevented a measurement of the higher spatial resolution observations. This behaviour is not also requires su-fer in which $\Delta \tau_h$ might be at play.

Vertical velocity gradient and sub-Keplerian rotation

$\frac{v^2}{r} = \frac{GM_\star r}{(r^2 + h^2)^{3/2}} + \frac{1}{\rho_{\text{gas}}} \frac{\partial P}{\partial r}$

$\Delta T$ is the temperature gradient, which is calculated as a function of radius $r$ for the CO layers (see Fig. 4). The central channels of $^{12}$CO and $^{13}$CO and we only plotted the upper surface for clarity.
Mapping the vertical snow line

![Diagram showing the vertical snow line in a protoplanetary disc](Image)

- **Upper surface**
- **Lower surface**

**dv = -0.64 km/s**

**Graph showing the maximum temperature distribution**

- **$T_{\text{max}}$ [K]**
- **r [au]**

- **$12\text{CO upper surface}$**
- **$13\text{CO upper surface}$**
- **$C^{18}\text{O upper surface}$**

- **Flux dilution**
- **$T = 21$ K**

See also Schwarz et al. (2016)
The very similar temperature profiles, despite a typical factor of 10, explain why we observe the gas $^{13}$CO in the dense region just above the freeze-out region. This is reinforced by the measured brightness temperature of the $^{13}$CO on the upper surface, which is extremely close to the $^{12}$CO brightness temperature on the lower disc surface. The C$^{18}$O emission has a brightness temperature of $21 \text{ K}$, this means that the C$^{18}$O optical depth is of the order of 0.5.

With a typical abundance ratio of 70 in abundance, indicate that the lines remain optically thick to decrease (as measured by both $^{12}$CO and $^{13}$CO) with distance from further away along the line of sight. If the temperature of the reduced densities.

The results are so far in agreement with the broad picture of how we understand protoplanetary discs, with a tapered-edge structure passively heated by the central star. The accuracy of our measurements is currently limited by the spatial resolution can come optically thin (while $^{12}$CO remains optically thick) due to geometrical considerations were applied to IM Lupi. Because these measurements are performed directly on the ALMA channels of our measurements is currently limited by the spatial resolution can come optically thin (while $^{12}$CO remains optically thick) due to geometrical considerations.

Comparison with models of irradiated protoplanetary discs at intermediate inclination. These simple stages of planet formation.

We have presented a general framework to measure directly the vertical CO snow line as a function of radius.

**5. Concluding remarks**
CO layers vs scattered light layer

IM Lup

Avenhaus et al, 2018
HD163296 in dust and gas

Gas=Blue, Dust=Red

Isella et al 2016
12CO layer of HD163296

Circular orbits and/or Keplerian velocities assumption not valid anymore
$^{12}$CO layer of HD163296

Circular orbits and/or Keplerian velocities assumption not valid anymore
The basic feature of the channel maps can be explained with a simple model assuming emission from two infinitely thin emitting surfaces. Figure 3 shows the expected emission arising from such a model, showing the butterfly signature from the disc. Asymmetries of the line emissions.

We embedded a single planet in the disc orbiting at the estimated planet location is marked by a cyan dot, assuming it is located in the midplane. The channel width is the expected location of the isovelocity curve on the upper surface of a disc with an opening angle of 15°.

We added a 10% deviation in azimuthal velocity north of the planet. We set the accretion radius of the planet to half of the Hill radius (7.05, 8.85, 10.15 and 12 au, respectively), with an accretion radius of 10 au for the planet. We set the accretion radius of the planet to half of the Hill radius (7.05, 8.85, 10.15 and 12 au, respectively), with an accretion radius of 10 au for the planet. We set the accretion radius of the planet to half of the Hill radius (7.05, 8.85, 10.15 and 12 au, respectively), with an accretion radius of 10 au for the planet. We set the accretion radius of the planet to half of the Hill radius (7.05, 8.85, 10.15 and 12 au, respectively), with an accretion radius of 10 au for the planet.

Asymmetries of the line emissions. For illustrative purposes, are evident as small bumps on the lower surface of the disc, and red shows the upper surface. Green shows the emission from the central star. We set the accretion radius of the planet to half of the Hill radius (7.05, 8.85, 10.15 and 12 au, respectively), with an accretion radius of 10 au for the planet. We set the accretion radius of the planet to half of the Hill radius (7.05, 8.85, 10.15 and 12 au, respectively), with an accretion radius of 10 au for the planet. We set the accretion radius of the planet to half of the Hill radius (7.05, 8.85, 10.15 and 12 au, respectively), with an accretion radius of 10 au for the planet.

The inner radius of the disc in our model was set to 50 au (mainly to speed up the calculations as the inner disc is irrelevant), with an initial outer radius set to 500 au. We set the gas mass between those radii to 500 au with a mass of either 1, 2, 3, or 5 M⊙. We set the gas mass between those radii to 500 au with a mass of either 1, 2, 3, or 5 M⊙. We set the gas mass between those radii to 500 au with a mass of either 1, 2, 3, or 5 M⊙. We set the gas mass between those radii to 500 au with a mass of either 1, 2, 3, or 5 M⊙. We set the gas mass between those radii to 500 au with a mass of either 1, 2, 3, or 5 M⊙.

We adopted the gas disc parameters from de Gregorio-Monsalvo et al. (2013). We employed gas-only simulations, ignoring the effects of dust, using 1 million SPH particles and a central mass of 1.9 M⊙. We embedded a single planet in the disc orbiting at 3.5 au with a mass of 0.08 M⊙. We used the sink particles (Bate et al. 1995) to represent the star, which appears as a kink in the line emission. Emission is preferentially seen on the upper surface of the disc due to the higher inclination with respect to the line of sight.

We added a 10% deviation in azimuthal velocity north of the planet, where the wake of the spiral generated by the planet was shown to produce a kink in the emission channel) shows no deviation from the Keplerian rotation around the star, which appears as a kink in the line emission. Emission is preferentially seen on the upper surface of the disc due to the deviation from the Keplerian rotation around the star. The white contour shows the 5-σ level of the continuum map. The dashed line is indicating it is localised in both space and velocity.
Velocity deviation is localised spatially and in velocity.
Figure 4. Left panel: surface density in 3D hydrodynamics simulations of the HD 163296 disc, shown after 35 orbits of a 2 M$_{\text{Jup}}$ planet and viewed at a face-on inclination. Dots mark the star and planet. Right panel: deviation of the azimuthal velocity from Keplerian velocity.

Can massive planets form at a distance of 250 au from the star? The location of giant planets in the outer regions of discs would be broadly consistent with gravitational instability. On the other hand, the timescale for core accretion may also be reasonable given that HD 163296 is a relatively old disc ($\approx$ 5 Myr). The planet may also have undergone outward migration, depending upon the initial profile of the disc. It is beyond the scope of this Letter to speculate further.
Observations vs MCFOST + Phantom models
STIS CORONAGRAPHIC IMAGING OF THE HERBIG Ae STAR: HD 163296

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ABSTRACT

Coronagraphic imaging with the Space Telescope Imaging Spectrograph on board the Hubble Space Telescope reveals a ~450 AU radius circumstellar disk around the Herbig Ae star HD 163296. A broadband (0.2–1.0 μm) reflected light image shows the disk oriented at a position angle of 140° ± 5° and inclined to our line of sight by ~60° ± 5°. The disk includes an annulus of reduced scattering at 325 AU and exhibits a flat trend of surface brightness in to 180–122 AU (1.5–1”), consistent with a cleared central zone. For r ≥ 370 AU the disk surface brightness drops as r to the approximately −3.5 power. The disk cannot be traced beyond 450 AU in our data. The disk is accompanied by a chain of nebulosities at P.A. = 42.5° ± 3.5°, compatible with detection of a Herbig-Haro flow. The HD 163296 disk most closely resembles the disk of HD 141569. As in the HD 141569 system, the dynamical effects of a planet may be necessary to explain the structure in the outer disk.

Subject headings: circumstellar matter — planetary systems — stars: individual (HD 163296) — stars: pre-main-sequence
Concluding remarks

• Measure $T(r,z)$, $v(r,z)$ and map CO surfaces: pressure gradients, snow line

• With high spatial and high spectral resolution, we can detect the kinematic signature of a planet. → planet mass, complementary to direct imaging

• So far, planets detected by kinematic method are located inside gaps. At least some of the gaps are carved by planets.

• Massive planets far out: a few $M_{\text{jup}}$ at 100-300au. How do they form?

• We can estimate Stokes number if planet mass is known