Structure in Protoplanetary Disks: a signpost of planet formation?

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Giant planets form when gas is present. We are observing the gas-rich stages commensurate with timescales for giant planet assembly - there are some planets here....
Will focus on results from ALMA which trace emission from \(~\text{mm}-\text{sized pebbles}\) in planet-forming midplane of the disk, but....
Protoplanet Direct Emission

- Limitations of direct detection
  - hot start (Baraffe+2003; Burrows 1997) vs cold start (Marley+2007; Fortney+2008)
  - episodic accretion (Brittain et al. 2020)
  - ice giants remain difficult to detect

see also ALMA detection of circumstellar disks: Isella et al. 2019

VLT/SPHERE 2018-02-24

K-band (2.1 microns)

An Accreting Planet Within a Disk Gap

Müller et al. 2018
Kepler et al. 2018

20 au

Wagner et al. 2018

Blue: Infrared
Red: Hα (accretion)

PDS 70

b
Models of Planet-Disk Interaction

- Gap width appears to depend on planet mass
- Change in dust surface density larger than gas
- Note: depends on assumptions regarding disk viscosity parameter ($\alpha$) and B field - see recent work by Kanagawa et al. 2016; Fung and Chiang 2016; Dipierro and Laibe 2017; Bae et al. 2017; Dong and Fung 2017; Meru et al. 2017; Dipierro et al. 2018; Dong et al. 2018a; Fedele et al. 2018; Forgan et al. 2018; Facchini et al. 2018; Bae et al. 2019
INFERRING PLANETS WITH ALMA

Isella+ 2016

**Dust**

- $0.1 \, M_J$
- $0.3 \, M_J$

**Gas**

- Orbit radius (AU)
0.1 $M_{\text{Jup}}$ planet @100 au in low viscosity disk can also foster gaps at 60 au and 40 au (Zhang+ 18; Dong+18; Bae+ 17)
INFERRING PLANETS WITH ALMA

Isella+ 2016

\[ \Sigma_{\text{dust}}(R) \propto \frac{l_\nu(R)}{K_\nu} \]

\[ \Sigma_{\text{gas}} = \Sigma_{\text{CO}}(R) / x(\text{CO}) \]

\[ \Sigma_{\text{CO}}(R) \propto l_\nu(R) \]

Pinilla & Youdin 2017

Aikawa+ 96
Reboussin+ 15
Schwarz+ 17, 19
Yu+ 17
Bosman+ 18
DEVIATIONS FROM KEPLERIAN ROTATION

\[ \frac{v_{\text{rot}}^2}{r} = \frac{GM*r}{(r^2 + z^2)^{3/2}} + \frac{1}{\rho} \frac{\partial P}{\partial r} \]

Isella +18
MEASURING EMISSION SURFACE

\[
\frac{v_{rot}^2}{r} = \frac{GM*r}{(r^2 + z^2)^{3/2}} + \frac{1}{\rho} \frac{\partial P}{\partial r}
\]

image resolution: 3.8 au x 4.8 au

Teague, Bae, and Bergin 2019 (Nature)

CONFIRMED $\text{H}_2$ GAS PRESSURE GRADIENTS

Teague + 2018

Teague, Bae, and Bergin 2019
Kinematical Detection

Pinte et al. 2018
Kinematical Detection

Pinte et al. 2018
Kinematical Detection

Data

Model

Pinte et al. 2018

Best fit by 2 M\(_{\text{Jup}}\)

Pinte et al. 2019

- Analysis of DSHARP data finds 9 localized disturbances in velocity structure in 6 systems.
- Localized disturbances coincide with gaps.
- See also Casassus & Perez (2019) “doppler flip”
the viscous evolution of gas into gaps and a disk wind?

@30 AU $c_s \sim 600 \text{ m/s}$
@400 AU $c_s \sim 300 \text{ m/s}$

Teague, Bae, and Bergin 2019 (Nature)
MERIDIONAL FLOWS

Szulágyi+ 2014
Morbidelli+ 2014
Fung & Chiang 2016
Dong, Liu, & Fung 2019
ALMA & PLANET FORMATION

Current State:

- Case for planets in HD 163296 is strongest

  ➡ Mismatch between planet mass estimates from surface density structure and from dynamics

  ➡ Dynamical mass estimates garnered by matching 2D/3D hydro to gas kinematics - gives masses a factor of 3 - 10x higher (Pinte et al. 2018, 2019; Teague et al. 2018)

  ➡ Lodato et al. 2019 - tracks migration of the observed planets.
ALMA & PLANET FORMATION

Statistics -

DSHARP has 85% occurrence rate of rings and gaps (Huang et al. 2018), but these are the brightest systems.

Long et al. 2020
Taurus survey (Long et al. 2018) finds 38% occurrence rate.

Disk frequency is 75% (Luhman et al. 2009) so occurrence rate is ~28%

Giant Planet occurrence rate from 1 - 100 au and 0.1 - 20 M\(_{\text{Jup}}\) is 26.6% (Fernandes et al. 2019)

- M. Meyer (priv. comm.) from 0.1 to 1000 au and 1 - 10 M\(_{\text{Jup}}\) occurrence rate is 21% (higher if down to lower mass).

Consistent if each source has 1 ring - but, many disks have > 1 ring

- single planets can induce multiple rings
- need smaller mass planets (< 0.1 M\(_{\text{Jup}}\)) in low viscosity disks to be source of rings (e.g. TW Hya; Mentiplay et al. 2019)
- recall tension between dynamical mass estimates and from surface density structure.
ALMA & PLANET FORMATION

- Current ALMA data sets have been optimized for dust continuum and not gas kinematics (requires many more hours). Urgent need for deep and high resolution kinematic data.

- Need to better characterize dust emission structures in smaller disks (e.g. Long et al. 2020), which requires different techniques (Zhang et al. 2016).

- Have not discussed fantastic results from GPI and SPHERE (see, e.g., Villenave et al. 2019).

- Possibility exists to search for chemical signatures of planets (Cleeves et al. 2015) - and new ALMA large program “The Chemistry of Planet Formation” (PI: Öberg, Aikawa, Guzman, Walsh, Bergin) will search for these signatures and provide better data for kinematic studies.

- Planets are there - we also need to find them by, e.g. direct detection where possible.
Thank You!

“The Chemistry of Planet Formation” (PI: Öberg, Aikawa, Guzman, Walsh, Bergin)