Zooming into planet-forming zones of disks with ALMA

Ewine F. van Dishoeck, Leiden Observatory / MPE
23 years ago: Iconic HST images of disks

HST/NASA/ESA
O’Dell et al. 1994
Iconic ALMA image of young disk 20 years later...

ALMA 20 milli-as (few AU resolution)
HL Tau

ALMA partnership, Brogan et al. 2015
New era of observational planet formation

Not yet clear what is causing these rings, gaps, dust traps...

HL Tau young disk
ALMA partnership et al. 2015

ALMA TW Hya

Orbit of Neptune

ALMA: van der Marel et al. 2013, 2016

ALMA: Pinilla et al. 2017

VLT-Sphere, Gemini
Stolker et al. 2016
Subaru-SEEDS
e.g. Muto et al. 2012

1 AU gap=
Earth scale

ALMA:
Fedele et al. 2017

IRs48

ALMA: van der Marel et al. 2013, 2016

B9
From disks to planets
From icy grains to planetesimals to embryos to planets

Grain, rocks < meters

Planetesimals kilometers

This may happen fast, even in the embedded stage; assisted by dust traps

Water ice accelerates coagulation

Planetary embryos
Lunar (1 AU)-to-Mars (2 AU) sized

J. Lunine
How were ‘we’ formed 4.5 billion years ago?

Chondritic Meteorites

Rosetta

Comet

Stardust

Deep impact

Messengers from the early solar system
Atacama Large Millimeter Array (ALMA)

54x12 m + 12x7 m antennas
84-900 GHz; 0.3-3 mm

*Lines*: rotational transitions of molecules; *continuum*: cold dust
Outline

• Introduction

• Disks around pre-main sequence stars
  – Surveys, dust statistics
  – Gas/dust ratios, carbon and oxygen depletion
  – Snowlines, rings

• Transitional disks

• Conclusions

Thanks to many students, postdocs, collaborators

Nienke van der Marel
Megan Ansdell
Anna Miotello
What I will not talk about: Disks in the embedded phase

VLA1623A
Murillo et al. 2013

L1448 triple
Tobin et al. 2016

Elias 2-29
L. Perez et al. 2016
Disk evolution and planet formation

a) Massive flared disk
b) Settled disk
c) Photoevaporating disk
d) Debris disk

ALMA can characterize and quantify each of these steps

Williams & Cieza 2011
What sets exoplanet characteristics?

- Lots of SuperEarths
- Few giant planets
- Increase with stellar mass

Planet population synthesis
ALMA measures the bulk of the gas and dust in disks and can observe bulk of molecules
Pre-ALMA: handful of disks

Large gas  Small dust disk

ALMA

Walsh et al. 2015, Facchini et al. 2017

Small dust disk naturally arises from low optical depth of continuum emission; Also evidence for grain growth and radial drift
From detailed studies of a few disks to large samples
PI: Jonathan P. Williams (IfA)

Juan M. Alcalà (INAF),
Megan Ansdell (IfA, UC Berkeley),
Stefano Facchini (MPE)
Greta Guidi (INAF),
Michiel Hogerheijde (Leiden Obs.),
Carlo F. Manara (ESA, ESO),
Geoff S. Mathews (IfA),
Anna Miotello (Leiden Obs., ESO),
Antonella Natta (INAF, DIAS),
Marco Tazzari (IoA),
Leonardo Testi (ESO, INAF),
Leon Trapman (Leiden Obs.),
Nienke van der Marel (IfA, UVic)
Ewine F. van Dishoeck (Leiden Obs., MPE),
Sierk van Terwisga (Leiden Obs.).

Publications
Ansdell et al. (2016)
Manara et al. (2016)
Miotello et al. (2017)
Tazzari et al. (2017)
Unbiased survey Lupus disks

J.P. Williams, PI

2''x2''

330 GHz Cont
1-2 min Each
20 AU resolution
Gas + dust

Ansdell et al. 2016

65 / 98 sources detected in continuum, only 30 in $^{13}$CO

- $F_{\nu} \sim M_d T_d \kappa_{\nu}$
Cumulative dust mass distribution

Most disks do not have enough dust mass for core accretion model to form a giant planet

Assumes $\kappa_\nu^{\text{dust}}=100$ cm$^2$ gr$^{-1}$ at 1000 GHz, $\beta=1$
Declining dust distribution

- Disks that can form giant planet cores (10 $M_{\text{Earth}}$)
  - 1-3 Myr: 25%
  - 3-5 Myr: 13%
  - 5-10 Myr: 5%

- Giant planet formation well underway early?
- Giant planet formation rare?
  - Most disks lack sufficient dust
  - Consistent with exoplanet statistics
Dust mass increases with $M^*$

- Consistent with giant planets more frequent around higher-mass stars
Link planet formation theories with disk evolution

Planet population synthesis

Benz et al. 2014
Dust

Lupus
1.3mm
CO lines are weak, much weaker than expected

Ansdell et al. 2016
σ Orionis disk survey

Only 37 / 92 disks detected in continuum
Only 6/92 detected in lines

Weak CO emission is common

Pascucci et al. 2016 (Cha), Barenfeld et al. 2016 (upper Sco), Eisner et al. 2016 (ONC1), Cazzoletti et al. (R Cra)
Determining gas masses

- Most disks not enough gas to form Jupiter
- Most disks gas/dust $<< 100$ assuming $[\text{C}]/[\text{H}]=10^{-4}$

Ansdell et al. 2016
Miotello et al. 2017
Weak CO emission: Low gas/dust ratios or low volatile carbon?

- Gas removed quickly from disk (<few Myr)? → *SuperEarths*

- CO transformed to other species? (CO$_2$, CH$_3$OH, hydrocarbons)

- CO and other volatiles locked up quickly in large bodies in midplane?

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Miotello et al. 2017 Lupus
Long et al. 2017 Cha

**13**CO analysis including freeze-out and photodissociation
Where is the volatile oxygen and carbon?

Gas mass from HD factor 100 higher than from CO

Points to carbon and oxygen depletion, not low gas/dust

H₂O
HIFI
Weak!

Disk mass from Herschel-PACS:
HD J=1-0 112 μm

Only 3 disks!

Favre et al. 2013, Schwarz et al. 2016, Trapman et al. 2017


Hogerheijde et al. 2011, Du et al. 2015, 2017

Favre et al. 2013, Schwarz et al. 2016, Trapman et al. 2017

SOFIA
SPICA
Chemistry as tracer of gas and dust evolution

Is most of the chemistry of planet formation hidden from our view?

Icy pebbles
O-rich

Gas with C/O >1 (but overall C depleted)

Small bare grains

UV penetrates deep into disk

Bergin et al. 2016
Birnstiel et al.
Kama et al. 2016
Cleeves et al. 2016
Facchini et al. 2017
Disk structure and snowlines
- Snowline enhances mass of solids → *planet formation*
- Freeze-out changes C/O ratio gas and ice → *planet atmosphere*

Öberg, Bergin et al. 2011
Imaging the CO snowline

\[ \text{TW Hya} \]
\[ \text{Face-on disk} \]
\[ \text{d=68 pc} \]

\[ \text{N}_2\text{H}^+ \quad 4-3 \]

\[ \text{N}_2\text{H}^+ \text{ appears when CO freezes out} \]
\[ \rightarrow \text{Tracer of snowline} \]

\[ \text{Qi, Öberg et al. 2013} \]

\[ \text{N}_2\text{H}^+ + \text{CO} \rightarrow \]
\[ \text{N}_2 + \text{HCO}^+ \]
Another example resolved CO snow line

HD 163296  Herbig star ALMA

- CO freezes out at \(\sim 20 \text{ K} \leftrightarrow 145\pm15 \text{ AU}\)

‘Disk tomography’
DCO⁺ as tracer CO snowline

Öberg et al. 2015
Huang et al. 2017

IM Lup
ALMA DCO⁺

Double rings!

CO photodesorption
Near CO snowline

1”, 150 AU

Öberg et al. 2015
Huang et al. 2017
Snowlines move

Water snowline vs dM/dt

Imaging water snowline (indirect)

Harsono et al. 2015

Cieza et al. 2016

V883 Ori outburst

Quiescent

Burst
Transitional disks

‘Planet formation in action’
Disk evolution

There are multiple paths from protoplanetary to debris disks

Cieza et al. 2007, Merin, Brown et al. 2010
Espaillat et al.; 2014
Transitional disk– dust continuum

Previous SMA Observations

SAO206462 = HD135344B

Just 24 min with ALMA!
Band 9

Brown et al. 2009
L. Perez et al. 2014
Gallery of potential planet-forming disks

Dust traps in transitional disks

ALMA Archive:
Van der Marel 2016, vD et al. 2015
Dust trapping

- Companion generates a radial pressure bump in gas
- Large dust will be trapped and no longer migrates inward
- Dust hole much larger than gas hole $\Rightarrow$ massive companion

Whipple 1972
Pinilla et al. 2012
+ many others
Radial and azimuthal dust traps

- For massive planets (>5 M\textsubscript{Jup}), radial dust trap located at \sim twice \( R\)\textsubscript{planet}.
- If overdensity at edge high + viscosity \( \alpha \) low \rightarrow Rossby unstable \rightarrow long-lived vortex (10\textsuperscript{5} yr).
  - Azimuthal asymmetry.
- Gas edge < dust edge (\sim 5 vs 10 \( R\)\textsubscript{Hill}).

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Radial trap

Azimuthal asymmetry

Pinilla, Birnstiel et al. 2013
Couple FARGO output with dust evolution code

Barge & Sommeria 1995
Klahr & Henning 1997
Wolf & Klahr 2002
Meheut et al. 2013,
Birnstiel et al. 2013
Facchini et al. 2017 ......
Dust ring and cavity clearing mechanisms

- Grain growth
- Photoevaporation
- Companion
- Dead zones

→ Need to know the gas and dust distribution inside cavity
Gas cavity smaller than dust cavity

- Gas present inside dust hole
- Gas cavity smaller than that of dust

van der Marel et al. 2015, 2016
Gas and mm dust do not follow each other
Gas cavity < dust cavity

Deep gas drops (factor 100-1000) point to young embedded planets

van der Marel et al. 2016
Press release December 16, 2015
Quantitative CO analysis → Gas mass + surface density

Density structure
Stellar spectrum

Continuum radiative transfer

Dust temperatures

Chemistry: abundance

Excitation levels

Thermal balance

Abundances & gas temperatures

Raytracing molecular lines

DALI

Miotello et al. 2014
Gas mass and surface density

- CO survives in dust-free cavity
- ALMA can probe gas masses down to $1 \, M_{\text{Earth}}$ in 1 hr!

Bruderer 2013
Van der Marel et al. 2015
Facchini et al. 2017
Gas vs dust density structures

- Gas cavity < dust cavity in all cases studied to date

- Gas density drops by factor $100-1000 \rightarrow$ embedded planets


van der Marel et al. 2015, 2016; Bruderer et al. 2014
Cavity clearing mechanisms

- Grain growth
- Photoevaporation
- Companion
- Dead zones
Two regimes of TDs?

- Test photoevaporation scenario with a few disks

Owen & Clarke 2012
Facchini et al. 2017
Can we constrain planet mass?

Hydro-simulations

- Depth of gap depends on mass of planet and viscosity $\alpha$

Need to spatially resolve gaps! $\rightarrow <0.1''$

Pinilla et al. 2012
+ many other groups
Recent work
SR24 binary: large variations

No disk seen in mm around SR 24N, factor $>300$ weaker than S

Pinilla et al. 2017
Double dust rings HD 100546

Outer gas disk > dust disk

Outer dust ring
Main dust disk subtracted
1% of peak flux

Inner dust ring
No circumplanetary disk

Walsh et al. 2014, 2017
C. Wright et al. 2015

ALMA long baselines
Pineda, Szulágyi+ in prep.
Evidence of multiple (sequential?) planet formation?

- Radial drift alone nor a single planet at 10 AU can reproduce the emission from millimeter-sized dust grains + scattered light
- Outer planet must be significantly younger than the inner planet (by > 2.5 Myr)

Pinilla et al. 2015
Double ring in planet-forming disk HD169142

Dust mm continuum

Scattered light

- Deep gas drops in rings point to planets
- But presence protoplanet now being disputed?

Fedele et al. 2017

Quanz et al. 2013
Reggiani et al. 2014
Back to Lupus: TDs

- 10% of disks in Lupus are TDs with >20 AU cavity
- TDs among most massive and largest disks

Problems:
- *Fraction too high compared with exoplanet statistics*
- *No circumplanetary disks detected yet with ALMA*
- *Embedded planets not found by direct imaging*
Summary

- Structure of protoplanetary disks being unravelled by ALMA
  - Gas and mm dust do not follow each other
  - Depletion of dust with age 1-10 Myr
  - Weak CO emission: low gas/dust vs carbon depletion
  - Few disks have enough dust or gas to build giant planet
  - Snowlines directly imaged

- Transitional disks as sites of giant planet formation?
  - Dust traps and gas cavities point to young giant planets
  - Tension with exoplanet statistics?

Next steps: $\Sigma_{\text{gas}}(R)$ large samples
  chemistry
  multi $\lambda$
Extra slides
Disk transport and evolution

Disk winds more important than MRI?

Bai & Stone
Gressel et al.
Armitage
Accretion rate vs disk mass

*testing viscous evolution*

100x$M_{\text{dust}}$ agrees well with viscous evolution for $\sim$3 Myr lifetime

(with considerable scatter)
Lupus dust surface density profiles

\[ \Sigma_d (g \text{ cm}^{-2}) \]

MMSN

All disks

\[ 0.7 < M_*/M_\odot < 1 \]

Tazzari et al. 2017
Disks structures: what do they imply for planets?

- Mm emission is ring + asymmetric trap
- Structures point to giant planet(s), but in different ways
  - Muto, Garufi, Stolker: 2 planets: inner and outer
  - Dong: 1 planet at ~100 AU
  - vdM: 1 planet at ~30 AU
HD135344 spiral scenario

1. A planet is formed at 30 AU

2a. Inner dust trap due to planet gap

2b. Planet triggers spiral arm outwards

3. Secondary vortex dust trap triggered by inner ring

4. Vortex triggers second spiral arm inwards