Gone with the wind: The innermost structure of protoplanetary disks

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• Introduction

• The inner disk through continuum observations

• The inner disk through gas tracers

• Conclusions
Introduction

Garufi, Benisty et al. 2017, VLT-SPHERE
This talk definition of inner disk: $R \leq 5$ au
• This talk definition of inner disk: $R \lesssim 5 \text{ au}$
• This talk definition of inner disk: $R \lesssim 5$ au

Garufi, Benisty et al. 2017, VLT-SPHERE
Introduction

- Accretion and winds:
  - Dominate gas dispersal
  - Drive disk dynamics
- Dust particles evaporate at the sublimation front
- UV, optical and IR radiation determine the energy balance of the full disk

Adapted from Dullemond & Monnier 2010
Beam size at 120pc
Indirect tracers of the inner disk: the continuum

Optically thin disk

Optically thick dusty disk

Planck curve + stellar flux

©Kama et al. 2009

©Dullemond & Monnier 2010
Indirect tracers of the inner disk: the continuum

Natta et al. 2001: A reconsideration of disk properties in Herbig Ae stars
Indirect tracers of the inner disk: the continuum

Natta et al. 2001: A reconsideration of disk properties in Herbig Ae stars

See also: Dullemond, Dominik & Natta (2001)
The size-luminosity diagram agrees with the presence of an optically thin disk surrounded by an inner rim.

\[ R_{\text{rim}} \propto L_\star^{1/2} \]

• Prediction: the image of an inclined rim projected on the sky should deviate from point-symmetry.

• Interferometry with at least 3 telescopes: closure phase (CP)
• VLTI-PIONIER (H-band) & GRAVITY (K-band) large program:
  • Variety of morphologies
  • Ring shaped morphologies but very wide
The inner disk: continuum

©Perraut+ in prep.
The inner disk: continuum

- CPs point to a smooth rim

- Isella & Natta (2005), Tannirkulam et al. (2007): curved rim morphology

\[ T_{\text{evap}} \text{ depends on gas density } \rightarrow \text{ more than one } T_{\text{evap}} \]

**Silicates** $r > 1.3 \ \mu\text{m}$

\[ r \sim 0.1 \ \mu\text{m} \]
The inner disk: continuum

©Isella & Natta (2005)
The inner rim shape and composition

VLTI-GRAVITY GTO program

K-band

$T_{\text{dust}} \sim 1560$ K

$T_{\text{sub}}$ (silicates)

$T_{\text{sub}}$ (carbon)

VLTI-PIONIER/GRAVITY

Average rim position

Temperature of the dust environment in K band (K)

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©Klarmann+ to be sub.
The inner rim shape and composition

VLTI-GRAVITY GTO program

K-band

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VLTI-PIONIER/GRAVITY

Average rim position

©Klarmann+ to be sub.
The inner rim shape and composition

K-band

VLTI-GRAVITY GTO program

$T_{\text{dust}} \sim 1560$

Wide and smooth sublimation front consistent with multigrain population

VLTI-PIONIER/GRAVITY
Average rim position

Temperature of the dust environment in K band (K)

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©Klarmann+ to be sub.
The inner inner-disk

- Most of the NIR emission comes from inside $R_{\text{dust}}$

- Possible solutions:
  - Refractory dust grains
  - Inner gaseous disk
  - Dusty wind

Refs: Benisty, Natta+ 2010; Benisty+ 2011; Bans & Königl 2012

© Kluska+ 2014
The inner disk: continuum

Similar study of the gas phase is missing

• VLTI-PIONIER large program (50 sources)
• Accretion and winds:
  • Dominate gas dispersal
  • Drive disk dynamics
• Dust particles evaporate at the sublimation front
• UV, optical and IR radiation determine the energy balance of the full disk

Adapted from Dullemond & Monnier 2010
The inner disk: gas

- Accretion and winds:
  - Dominate gas dispersal
  - Drive disk dynamics
- Dust particles evaporate at the sublimation front
- UV, optical and IR radiation determine the energy balance of the full disk

How is angular momentum transported within the disk?

Adapted from Dullemond & Monnier 2010
Gas dynamics is dominated by accretion, followed by photoevaporation at later stages.

Turbulence: MRI instability

MRI disk “ingredients”: weakly magnetised, angular velocity decreases with distance from the rotation centre, ionisation

(See e.g. Gammie et al. 1996; Ercolano et al. 2017; Najita et al. 2018, ...)

©Armitage et al. 2011
Gas dynamics is dominated by accretion, followed by photoevaporation at later stages.

Turbulence: MRI instability

MRI disk “ingredients”: weakly magnetised, angular velocity decreases with distance from the rotation centre, ionisation

(See e.g. Gammie et al. 1996; Ercolano et al. 2017; Najita et al. 2018,...)
Angular momentum transport

New paradigm: MHD winds

- Non-ideal MHD simulations: MRI supressed, but strong MHD wind is generated.
- Efficiency of angular momentum transport depends on: ionization fraction, magnetic field strength.

(See e.g. Bai et al. 2017 and refs. there in)
New paradigm: MHD winds

- Non-ideal MHD simulations: MRI suppressed, but strong MHD wind is generated. (Adapted from Ercolano et al. 2017)

- Efficiency of angular momentum transport depends on: ionization fraction, magnetic field strength.

Can we observational constraint the presence of MHD-winds?

(See e.g. Bai et al. 2017 and refs. there in)
### Observational constraints

**MHD winds**

- **HVC**: Jet emission
- **LVC-BC**: $R < 0.5$ au
  - lower inclinations: narrower + bluer line.
  - MHD-wind?
- **LVC-NC**: $R < 5$ au, always observed in TDs
  - photoevaporative wind?

  (e.g. Simon+ 2016; McGinnis+ 2018, Fang+ 2018, Banzatti+ 2019)

See Elisabetta Rigliaco’s talk

(©Simon et al. 2016)
Observational constraints
Spatially resolved observations

NIR/MIR Interferometry

R ≤ 5au

©Dullemond et al. 2011
Observational constraints
Spatially resolved observations

Most interferometers work in the K-band
+ YSOs are red objects

Brγ is our favourite line!!

Can we constraint the origin of this line/associate it with winds/accretion?
Spatially resolved observations

- Emitted in a compact region (few tenths of mas) within $R_{\text{dust}}$

(see e.g. Kraus et al. 2008, Eisner et al. 2009)
Spatially resolved observations
Modelling Brγ emission

\[ V_{\text{line}} > V_{\text{cont}} = R_{\text{line}} < R_{\text{cont}} \]

Photocenter shift of the line vs continuum

HD163296
HD98922

Garcia Lopez + 2015; Caratti o Garatti+ 2015
Spatially resolved observations
Modelling Brγ emission

Contributions:
1) continuum emission: star + disc
2) line emission: disc wind + (magnetosphere)

More details in: Weigelt et al. (2011); Tambovtseva et al. (2014;2016); Garcia Lopez et al. (2015)
Spatially resolved observations

Modelling Brγ emission

Garcia Lopez et al. 2015; Caratti o Garatti et al. 2015
Spatially resolved observations

Modelling Brγ emission

Most of the Brγ line is emitted in a disk wind

<table>
<thead>
<tr>
<th>Disc wind model parameters</th>
<th>HD163296</th>
<th>HD98922</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>10 000</td>
<td>10 000</td>
</tr>
<tr>
<td>Half opening angle (θ)</td>
<td>45°</td>
<td>30°</td>
</tr>
<tr>
<td>Inner radius (ω₁ (Rₖ))</td>
<td>2.0 (0.02 AU)</td>
<td>3.0 (0.1 AU)</td>
</tr>
<tr>
<td>Outer radius (ω₅ (Rₖ))</td>
<td>4.0 (0.04 AU)</td>
<td>30.0 (1 AU)</td>
</tr>
<tr>
<td>Mass loss rate (Ṁ🚶‍♀️ (M☉/yr))</td>
<td>5 × 10⁻⁸</td>
<td>2 × 10⁻⁷</td>
</tr>
</tbody>
</table>

Garcia Lopez et al. 2015; Caratti o Garatti et al. 2015
Can we study the presence of inner winds in a statistical and homogeneous ways across the mass and age spectrum?

- Aim: Statistical study of the gas content in YSO disks to spatially resolve the hot (Brγ) and warm (CO) gas in disks.
- Large sample of YSOs (∼100) spanning a wide range of stellar masses (very low-, high-mass), ages (10⁴ - 10⁷) and disk properties (full and TDs).
Spatially resolved observations

A statistical approach

Pre-Main sequence stars in Taurus–Auriga

Object numbers

Magnitude

© Perraut
Spatially resolved observations
A statistical approach
Spatially resolved observations

A statistical approach

Most Herbiggs show Brγ emission more compact than the continuum

\[ R(\text{Brγ}) < R(\text{cont}) \]

But more extended than the \( R_{\text{trun}} \)

\[ R(\text{Brγ}) > R_{\text{trun}} \]
Spatially resolved observations
A statistical approach

Spatially resolved observations

A statistical approach

S CrA North

Protostellar jet

Bry emitting region 
($R \sim 0.06$ au)

Halo

$R_{\text{trun}} \sim 0.03$ au

Wind

Outer disk

$R_{\text{dust}} \sim 0.11-0.15$ au

Inner disk 
($R \sim 0.11$ au)

Magnetosphere

S CrA binary system

North

$d \sim 1.4^\circ$

$i \sim 28^\circ \pm 3^\circ$

$PA \sim 0^\circ \pm 6^\circ$

South

$i \sim 22^\circ \pm 6^\circ$

$PA \sim -2^\circ \pm 12^\circ$

RU Lup

S CrA N

Velocity (km/s)

Spectra

Flux

Vis. Amp

Wavelength ($\mu$m)

Diff. Phase

Spatially resolved observations
A statistical approach

Brγ might be tracing winds in the innermost regions of (some) low-mass protoplanetary disks.

Conclusions

- Antonella loves infrared interferometry (although she will never admit it)
- Rims exit and they are wide and smooth consistent with a multigrain population.
- Most of the NIR emission is coming from an unknown source within the rim.
- NIR interferometry has came to age.
  - Brγ might be mostly originated in a disk wind, tracing the presence of winds in the innermost disk region.