Protoplanetary Disks
(the dirty job part I)

Leonardo Testi - UniBo
leonardo.testi@unibo.it

- Most of the focus will be on Class II disks
- How we determine the key properties of these systems
- Stellar masses and ages
- Disk physical parameters
- Evolution of the disk and its constituents
From Cores to Planetary Systems
YSO SED classification

- Original classification I-II-III based on IR spectral index
- Class 0 based on FIR-submm
- Many caveats, but still a useful classification scheme
Protoplanetary disks
Flared disks: which observations probe what?

Scattered light

Mid-IR imaging

IR Spectroscopy

PAH Emission

Submm/radio: Entire Disk
Spectral Energy Distributions (SEDs)

The SED shows the energy emitted per logarithmic wavelength interval. Plotting just the flux may be misleading:

Energy: \( F_\nu \, d\nu = F_\nu \, \Delta \nu \)
Spectral Energy Distribution
“flared” disk emission
IR SED slope

**Class I**
- Infrared Protostar
- $\sim 100,000$ yr

**Class II**
- T Tauri (CTTS)
- $\sim 1,000,000$ yr

**Class III**
- Evolved T Tauri (WTTS)
- $\sim 10,000,000$ yr

Time
Statistics and timescales

Evans et al. 2009
Statistics and timescales

Evans et al. 2009
In nearby star forming regions, we can estimate:

- very roughly $t_{II} \sim 5-10$ yr, $t_I \sim 5-10$ yr, $t_0 \sim 10^6$ yr, $\sim 10^5$ yr, $\sim 10^4$ yr
From Cores to Planetary Systems

Inner disk clearing:
e-folding time \( t \sim 2-3 \) Myr

(Hernandez et al. 2007)
Allende meteorite

Calcium-Aluminum Inclusions (CAI)
- Oldest, high-T (≈1700K) processing, short formation phase (≈3x10^5 yr)

Chondrules
- Formed after CAI, high-T (∼2000K) few Myr age dispersion

Matrix
- sub-μm particles, glue together the material
Stellar parameters

- Place star on HR-diagram using Teff and Lstar to read off masses and ages (hoping that the tracks are accurate...)
  - Teff from spectral typing
  - Lstar from magnitudes and extinction

(Manara et al. 2013)
Stellar parameters

~1 Myr

~2 Myr

~0.6 Myr

~0.9 Myr

~5 Myr

~3 Myr

(Testi et al. 2022)
Stellar parameters

- Place star on HR-diagram using Teff and Lstar to read off masses and ages (hoping that the tracks are accurate...)
  - Teff from spectral typing – problems: S/N, extinction and veiling
  - Lstar from magnitudes and extinction – problems: extinction and excess/veiling/variability
Stellar parameters

- Place star on HR-diagram using Teff and Lstar to read off masses and ages (hoping that the tracks are accurate...)
  - Teff from spectral typing – problems: S/N, extinction and veiling
  - Lstar from magnitudes and extinction – problems: extinction and excess/veiling/variability
Place star on HR-diagram using Teff and Lstar to read off masses and ages (hoping that the tracks are accurate...)

- Teff from spectral typing – problems: S/N, extinction and veiling
- Lstar from magnitudes and extinction – problems: extinction and excess/veiling/variability
Accretion

Direct measurement of accretion:
energy released in the collision

Indirect measurement: emission lines from accretion columns

T Tauri star - magnetospheric accretion

~0.1 AU

Stellar magnetosphere

Accretion shock

Accretion columns

Far IR emission

Gas Disk

Dust Disk

Hot continuum

(UV excess)

Near IR emission

Broad emission lines (Hα, Br γ, etc.)

L. Hartmann

Manara+2014

Gullbring+2000
Accretion

- \( L_{\text{acc}} \) measured directly from the UV excess luminosity (with a correction factor for FUV/EUV)

Gullbring 1998

\[
\dot{M}_{\text{acc}} = \left(1 - \frac{R_\star}{R_m}\right)^{-1} \frac{L_{\text{acc}} R_\star}{GM_\star} = \frac{L_{\text{acc}} R_\star}{0.8GM_\star}
\]

\( R_m \sim 5 R_{\text{star}} \)
Accretion rates fall “more or less” where predicted.

Evolution still hard to constrain (need better age/acc measurements).

L. Hartmann

Manara 2014
Accretion

- Accretion rates fall “more or less” where predicted
- Evolution still hard to constrain (need better age/acc measurements)

L. Hartmann

Testi+2022
• Accretion rates fall “more or less” where predicted

• Evolution still hard to constrain (need better age/acc measurements)

L. Hartmann

L. Testi+2022, see also Manara et al. 2023
Early accretion

- Accretion highly variable in the early phases of disk evolution
- Hard to measure directly: hope from infrared lines

Hartmann & Kenyon 1996
Rigliaco+2015
Young stars ages

- Uncertainty from stellar accretion history
- Do we know “relative” ages?
- Early accretion history very uncertain, but potentially critical

Baraffe+2010/2012
SED for a locally isothermal disk

\[ F_\nu = \frac{\cos \theta}{D^2} \int_{r_i}^{r_o} B_\nu(T_d)(1 - e^{-\tau_\nu}) 2\pi r dr \]

\[ T_d \sim r^{-q} \]

\[ \tau_\nu \propto \Sigma(r) \kappa_\nu \quad \Sigma(r) \propto r^{-p} \quad \kappa_\nu \propto \kappa_0 \nu^\beta \]

\[ \tau_\nu \ll 1 \quad F_\nu \propto \Sigma(r) B_\nu(T_d) \kappa_\nu \]

\[ \tau_\nu \gg 1 \quad F_\nu \propto B_\nu(T_d) \times M_d \]

If \( \tau_\nu \ll 1 \):

If \( \tau_\nu \gg 1 \):
Consequence: SED signature for Transition Disks

\[ n \frac{(4q-2)}{q} \]

\[ n^{3+\beta} \]

\[ n \alpha \]

\[ n^\beta \]

\[ n \gamma \]

\[ n \delta \]

\[ n \epsilon \]

\[ n \zeta \]

\[ n \eta \]

\[ n \theta \]

\[ n \iota \]

\[ n \kappa \]

\[ n \lambda \]

\[ n \mu \]

\[ n \nu \]

\[ n \xi \]

\[ n \omicron \]

\[ n \pi \]

\[ n \rho \]

\[ n \sigma \]

\[ n \tau \]

\[ n \upsilon \]

\[ n \phi \]

\[ n \chi \]

\[ n \psi \]

\[ n \omega \]

\[ n \alpha \]

\[ n \beta \]

\[ n \gamma \]

\[ n \delta \]

\[ n \epsilon \]

\[ n \zeta \]

\[ n \eta \]

\[ n \theta \]

\[ n \iota \]

\[ n \kappa \]

\[ n \lambda \]

\[ n \mu \]

\[ n \nu \]

\[ n \xi \]

\[ n \omicron \]

\[ n \pi \]

\[ n \rho \]

\[ n \sigma \]

\[ n \tau \]

\[ n \upsilon \]

\[ n \phi \]

\[ n \chi \]

\[ n \psi \]

\[ n \omega \]
SED of a locally isothermal disk

\[ F_\nu = \frac{\cos \theta}{D^2} \int_{r_i}^{r_o} B_\nu(T_d)(1 - e^{-\tau_\nu})2\pi r dr \]

\[ T_d \sim r^{-q} \]

\[ \tau_\nu \propto \Sigma(r)\kappa_\nu \quad \Sigma(r) \propto r^{-p} \quad \kappa_\nu \propto \kappa_0 \nu^\beta \]

Beckwith+ 1991
SED for a locally isothermal disk

Beckwith et al. (1991)

\[ F_\nu = \frac{\cos \theta}{D^2} \int_{r_i}^{r_o} B_\nu(T_d)(1 - e^{-\tau_\nu})2\pi r dr \]

\[ T_d \sim r^{-q} \]

\[ \tau_\nu \propto \Sigma(r)k_\nu, \quad \Sigma(r) \propto r^{-p}, \quad k_\nu \propto k_0 \nu^\beta \]

Viscous heating provides a poor fit of protoplanetary disc temperature: real disks are warmer than expected in the outer regions!
“flat” passive disk

Irradiation flux:

\[ F_{\text{irr}} = \alpha \frac{L_\ast}{4\pi r^2} \]

The flaring angle:

\[ \alpha \equiv \frac{0.4 r_\ast}{r} \]

\[ T = \left( \frac{0.4 r_\ast L_\ast}{4\pi \sigma r^3} \right)^{1/4} \]

\[ T \propto r^{-3/4} \]

Coincidentally, same profile as an viscously heated disk : not good!

\[ F_\nu = \frac{\cos \theta}{D^2} \int_{r_i}^{r_o} B_\nu(T_d)(1 - e^{-\tau_\nu})2\pi r dr \]

\[ T_d \sim r^{-q} \]

\[ \tau_\nu \propto \Sigma(r)\kappa_\nu \]

\[ \Sigma(r) \propto r^{-p} \]

\[ \kappa_\nu \propto \kappa_o v^\beta \]
"flared" passive disk

Irradiation flux:

\[ F_{\text{irr}} = \alpha \frac{L_*}{4\pi r^2} \]

The flaring angle:

\[ \alpha = r \frac{\partial}{\partial r} \left( \frac{h_s}{r} \right) \rightarrow \frac{\xi}{r} h_s \]

\[ T^4 = \frac{\xi}{\sigma} \frac{h_s L_*}{4\pi r^3} \]

\[ h_s = \chi h \]

Can work...

...depending on \( h_s(r) \)

\[ F_\nu = \frac{\cos \theta}{D^2} \int_{r_i}^{r_o} B_\nu(T_d)(1 - e^{-\tau_\nu}) 2\pi r dr \]

\[ T_d \sim r^{-q} \]

\[ \tau_\nu \propto \Sigma(r) \kappa_\nu \]

\[ \Sigma(r) \propto r^{-p} \]

\[ \kappa_\nu \propto \kappa_0 \nu^\beta \]
Flared disks: detailed models

... consists of vertical slices, each forming a 1D problem. All slices are independent from each other.

[K. Dullemond]
Including viscous heating
Including viscous heating

\[ \dot{M} = 1 \times 10^{-7} \]
\[ \dot{M} = 5 \times 10^{-9} \]
\[ \dot{M} = 2 \times 10^{-10} \]
\[ \dot{M} = 0 \]

\( T [K] \)

\( z/r \)

\( r = 1 \text{ AU} \)

\( (M_{\text{acc}} \sim 10^{-8} M_{\odot}/\text{yr @ 1 Myr}) \)
Resolving disk structure

- $10\text{AU} @ 140\text{pc} = 0.14\text{ arcsec}$
- Diffraction: $0.14\text{arcsec} @ 1\text{mm} \Rightarrow 1.5\text{km}$
- Need to use interferometry
The ALMA Revolutions

Beam size

Sensitivity

1 mJy/beam

0.1 mJy/beam

10 μJy/beam

0.01"

1"

(slides thanks to M. Tazzari)
The ALMA Revolutions

sensitivity

1 mJy /beam

0.1 mJy /beam

10 μJy /beam

beam size

0.01”

1”

(slide thanks to M. Tazzari)
Small digression on interferometry

- Interference pattern of the signal from two antennas separated by a baseline $b$
- After correction for the optical path delay each pair of antennas measure the fringe visibility corresponding to the baseline $b$ (as seen from the source)

$$V(u, v) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} P(x, y) I(x, y) \exp(-2i\pi (ux + vy)) dx dy$$

$(x,y)=$Sky   $(u,v)=$baselines plane   $V(u,v)=$Measured visibility
$P(x,y)=$Antenna power pattern   $I(x,y)=$Brightness distribution on Sky
Analysis of interferometric data

Models solve for the self consistent structure, given Sigma (and star)

See also Isella+2007;2009

\[ \Sigma(R, t) = \Sigma_t \left( \frac{R_t}{R} \right)^\gamma \times \exp \left\{ -\frac{1}{2(2-\gamma)} \left[ \left( \frac{R}{R_t} \right)^{(2-\gamma)} - 1 \right] \right\} \]
galario: a Gpu Accelerated Library for Analysing Radio Interferometry Observations

Marco Tazzari\textsuperscript{1*}, Frederik Beaujean\textsuperscript{2} and Leonardo Testi\textsuperscript{2,3}

\textsuperscript{1} Institute of Astronomy, University of Cambridge, Madingley Road, CB3 0HA, Cambridge, UK
\textsuperscript{2} Excellence Cluster Universe, Boltzmannstr. 2, D-85748 Garching, Germany
\textsuperscript{3} European Southern Observatory, Karl-Schwarzschild-Str. 2, D-08574 Garching, Germany

- Modeling in the uv-plane is demanding (FFT + visibility sampling)
- To exploit ALMA: fast, parallel and scalable analysis tools
- A new implementation for GPUs: fast
  - modular, easy to install/use Python interface
  - ready for large datasets: high resolution, large samples
  - GPU and CPU implementation out-of-the-box
- OpenMP and MPI: multi-CPU/multi-GPU

- Example:

```
from galario import double_cuda, single_cuda
double_cuda.chi2(image, d_alpha, d_delta, uv, obs_vis)
```

- Better angular resolution

https://github.com/mtazzari/galario
GALARIO: a GPU Accelerated Library for Analysing Radio Interferometry Observations

Marco Tazzari\(^1\)*, Frederik Beaujean\(^2\) and Leonardo Testi\(^2,3\)

Easy to use:

- compute \textit{visibilities} from 2D image:
  
  \[ V_{\text{mod}} = \text{sampleImage}(\text{image, dxy, u, v}) \]

- compute \( \chi^2 \) from 2D image:
  
  \[ \text{chi2} = \text{chi2Image}(\text{image, dxy, u, v, ReV, ImV, w}) \]

- compute \( \chi^2 \) from 1D profile:
  
  \[ \text{chi2} = \text{chi2Profile}(l, \text{Rmin, dR, nxy, dxy, u, v, ReV, ImV, w}) \]

Easy to install:

\texttt{conda install -c conda_forge galario}

Fouriously fast:

- up to 150x faster than Python, 40x-90x faster than CPU

- many applications:
  
  - protoplanetary disks
  - debris disks
  - high redshift galaxies
  - massive stars cores

- ready to exploit the ALMA wavelength coverage:
  
  - single-wavelength continuum
  - multi-wavelength continuum
  - gas emission spectral cubes

- single or multiple sources in the FOV

- fast enough for survey analysis

Simple switch to GPU:

\texttt{import galario}
Examples of pre-ALMA results

• Data generally well described, note limited angular resolution

\[ \Sigma(R, t) = \Sigma_t \left( \frac{R_t}{R} \right)^\gamma \times \exp \left\{ -\frac{1}{2(2 - \gamma)} \left[ \left( \frac{R}{R_t} \right)^{2 - \gamma} - 1 \right] \right\} \]

Isella+2009
Examples of pre-ALMA results

- Extract $N$ random samples from “Taurus” applying the same selection biases as expected in the other region. Method first applied by Andrews+2013
Surface density distribution

- First systematic/complete analysis of surface density distribution of solids in disks
- Compact disks (R<50AU) are up to ~30-40% of the population

(Tazzari+2017)
Full fit not always possible: order of magnitude estimates technique

- Initial surveys revealed a gradual decay (factor $\sim 4$ in $\sim 5$Myr)
- Dust content is relatively low
- Estimates rely on simple assumption on temperature structure and dust opacity

(see also Pascucci+2016, Ansdell+2017, Barenfeld+2016, Cazzoletti+2019, Williams+2019, Testi+2022)
Solids in planets and disks

• 1-2Myr old disks do not contain enough solids
  • Consistent with the latest suggestions of Jupiter core growth (Kruijer+2017)
Deficit of solids in BD disks

- Estimated solids mass in BD disks is too low to form the known exoplanets around BDs
HD 163296 as seen by ALMA

- Direct measurement of disk flaring and CO depletion on the mid plane

(deGregorio-Monsalvo+2013)

(Rosenfeld+2013)
CO-based gas masses

- Based on disk thermochemical modelling
- Truly low gas masses or “chemical” model deficit?

(Miotello et al. 2022)
Gas kinematics

- Not exactly Keplerian
- Largest effect is the pressure term 5%, self gravity 0.1-0.5%

Potentially a direct measurement of the disk self-gravity

(Rosenfeld et al. 2013)
Dust mass and disk mass

- Dust emission traces approx 0.01 of the H$_2$ mass

- (by comparison, gas-phase CO emission traces <<<<1e-5, depending on how much of the CO mass is in solids and on the details of chemistry and photodissociation)

- Carefully estimated dust masses are within a factor 2-3 of “robust” disk mass estimates

(Veronesi+2021) (Bergin+2013) (Rampinelli+2022)
HD163296 as seen by ALMA

- Extent of the CO disk is much larger than that of the mm-grains disk
- Qualitative behaviour as expected from viscous spreading and migration of the larger grains

(deGregorio-Monsalvo+2013)