Techniques, Observations, and Diagnostics of Protoplanetary Disks: Inner Disk

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2021 Sagan Summer Workshop
A research astronomer in Tucson, Arizona
- Study star and planet formation, the Milky Way, etc.
- Theory, observations, archival data, storytelling

Staff astronomer at an Observatory (NSF’s NOIRLab)
- NOIRLab is the unification of NOAO, Gemini Observatory, and Rubin Observatory, which is carrying out the Legacy Survey of Space and Time (LSST).
- At NOIRLab, we plan and deliver new facilities, initiatives, instruments, observing modes, data systems and analysis tools...to enable anyone with a good idea to pursue it using forefront capabilities.

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UV/IR, Inner Disks, Planet Formation

Brief sampling of techniques, ideas, science:

• Stellar accretion
  • Inner disk lifetime
  • Nature of transition disks

• Disk structure and substructure
  • Inner gas disk radii
  • Orbiting gaseous circumplanetary disks

• Disk chemistry
  • Probe planetesimal formation (otherwise elusive)

• Disk dynamics
  • Possible accretion in action
Disks in Star and Planet Formation

Molecular cloud cores have finite angular momentum.

When they collapse, disks form.

Stars grow by accretion through disks. Planets also form there.
Exoplanet Populations

High resolution Spectroscopy: Probes planet formation region

Imaging: ALMA, high contrast NIR
The near-stellar environment of T Tauri Stars

Hartmann et al. 2016

Accretion through disks and onto star via a magnetosphere
NUV/Optical Diagnostics

Credit: Alcala in “Accretion & winds/outflows in solar-type YSOs”
FUV Diagnostics

Atomic lines (e.g., CIV): diagnose accretion
Ly $\alpha$: dominates FUV luminosity, affects disk chemistry
$H_2$ fluorescence: probes Ly $\alpha$-irradiated disk
EUV and soft X-rays: disk photoevaporation

Herczeg et al. 2004
France et al. 2012
High res spectroscopy (line profiles)

Nature of stellar accretion (it’s magnetospheres)
Accretion onto Star

Via a boundary layer?

Or a magnetosphere?

Double-peaked profile from a thin annulus
Stellar Accretion via Magnetospheres

See also Calvet & Hartmann 1992; Hartmann et al. 1994; Muzerolle et al. 1998
Low res spectroscopy (line fluxes)

Measuring accretion
Measuring Accretion Rates

**Luminosity method:**

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

Credit: Alcala in “Accretion & winds/outflows in solar-type YSOs”

**Primary indicator:**
Measure UV continuum luminosity.

**Secondary indicators:**
Correlate UV flux with line fluxes (HI lines, CIV, etc)
Accretion demographics

Gas disk lifetime, nature of transition disks
Accretion and gas disk lifetime

Fraction of accreting sources in clusters of different ages constrains gas dissipation time of inner disk

Fedele et al. (2010)

\[ \tau_{\text{acc}} = 2.3 \text{ Myr} \]

\[ \tau_{\text{dust}} = 3.0 \text{ Myr} \]
Accretion and nature of transition disks*

*Protoplanetary disk whose center is optically thin in continuum

- Planetesimal formation
- Low-mass gas giant
- EUV Photoevaporation
- High mass gas giant

IR Spectroscopy and Disks

- Probes of disk
  - Dynamics
  - Structure
  - Chemistry

![Graph showing absorption bands and molecular probes]

- CO \( \Delta v=2 \) at 2.3 \( \mu m \)
- H\(_2\)O \( \Delta v=1 \) at 4.7 \( \mu m \)
- OH, H\(_2\)O, HCN, C\(_2\)H\(_2\), CH\(_4\), NH\(_3\)...

- NeII...
Gaseous Probes of Inner Disks

IR molecular diagnostics probe planet formation region within the snow line

- HCN, CO$_2$
- C$_2$H$_2$, OH, H$_2$O
- H$_2$ UV
- H$_2$O ro-vib
- OH $\Delta v=1$
- CO $\Delta v=1$
- CO $\Delta v=2$

0.1 AU NIR
1 AU MIR
10 AU FIR
>20 AU mm

NeII

CO, HCO$^+$, CS, N$_2$H$^+$, H$_2$CO, CN, HCN, NHC, etc
2.3 µm
High accretors
Probes turbulence!

Najita et al. 2009

4.7 µm
Probes disk (sub)structure!

12-18 µm
Disk chemistry,
Planetesimal formation, solid migration
Disk surface accretion

MIR Water / Organics!

CO Fundamental!

CO Overtone!
UV/IR, Inner Disks, Planet Formation

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High res spectroscopy (line profiles)

Studying inner disk structure

e.g., Carr 2007; Hoadley et al. 2015
High Spectral Res: Surrogate for High Ang Res

(See Smak 1981)

Graphics Credit: Sean Brittain
Inner Disk Radii and Exoplanet Orbital Radii

CO fundamental line profiles of Classical T Tauri stars

Carr 2007

Inner Gas Radius

Extra-Solar Planets Orbital Radii

Carr 2007
FUV H$_2$ emission

**Inner and outer radii from H$_2$ line profiles**

### Table

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<th>LkCa15</th>
<th>V4046 SGR</th>
<th>UX Tau A</th>
<th>SU Aur</th>
<th>GM Aur</th>
<th>DM Tau</th>
<th>CS Cha</th>
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**Rich H$_2$ fluorescence spectrum**

- AA Tau
- V4046 Sgr / 4
- GM Aur
- LkCa19

**Flux (10^{-18} ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$)**

**Wavelength (Å)**

- Lyα
- CI
- CII
- SiⅢ
- CIV
- HeⅡ

**References**

- Hoadley et al. 2015
- France et al. 2012
Exoplanet Populations

Gas giants can migrate into the inner disk edge
Spectroastrometry

Detecting forming planets and circumplanetary disks (birthplaces of moons)

Pontoppidan et al. 2008; Brittain et al. 2010, 2015, 2019; Whelan et al. 2021
Circumplanetary Disk in HD100546

After Ayliffe & Bate 2009

Credit: NOIRLab/NSF/AURA/P. Marenfeld
Fun with high s/n spectroscopy

CO fundamental emission from HD100546, a young intermediate mass star

Brittain et al. (2009): shows transitions of
CO $v=1-0,\ldots,7-6$
$^{13}$CO $v=1-0, 2-1$
C$^{18}$O $v=1-0$
Super-Resolution with Spectroastrometry

(See Whelan & Garcia 2008)

- Magic: spatial centroid more accurate than ang res $\Delta x \sim 0.4$ FWHM / SNR
- Good for simple velocity fields

Graphics Credit: Sean Brittain
Circumplanetary Disk in HD100546

Credit: NOIRLab/NSF/AURA/P. Marenfeld
Spectroastrometry

Brittain et al. 2014
Spectroastrometry

Excess emission consistent with size of CPD

Brittain et al. 2014
Spectroastrometry

Brittain et al. 2014
Spectroastrometry

Brittain et al. 2014
Circumplanetary Disk in HD100546

Position, velocity, and emitting area of orbiting CPD.

After Ayliffe & Bate 2009

Brittain et al. 2019
IR Spectroscopy: Structure and Sub-structure

High spectral resolution as a surrogate for high spatial resolution

• E.g., measure inner disk radii.

Spectroastrometry enables super-resolution

• E.g., detect orbiting gaseous circumplanetary disk.

Credit: Galileo Project/Voyager Project/NASA’s JPL
MIR molecular spectroscopy

Chemical Fingerprint of Planetesimal / Protoplanet Formation

e.g., Carr et al. 2011; Najita et al. 2011, 2013; Banzatti et al. 2020
Story of Core Accretion

Grains ($\mu$m) grew…

Planetesimals (km) that grew…

Protoplanets (~1000s km) that grew…

Giant planets ($10^5$ km)

5-10 $M_{\text{Earth}}$ core
accretion of gaseous envelope

Remnant disk cleared…The End
What is a signpost of core accretion?

- Core accretion makes planetesimals and protoplanets
- Are these abundant at epoch of planet formation?

Core Accretion

Gravitational Instability

Mayer et al. 2004
What do planetesimals look like?

Hale Bopp: Wikimedia Commons

67P: ESA/Rosetta/NAVCAM
Solid aerodynamics and C/O of inner disk

Planetesimal (~1 km) and protoplanet (~$M_{\text{Mars}}$) formation dehydrates and enhances C/O of inner disk.

1 µm grains

- CO Gas
- H$_2$O ice

Gas, dust accrete together; no enhancement

1 m

- CO Gas
- H$_2$O ice

Ice migrates faster than gas; super-hydrated inner disk, low C/O

1 km

- CO Gas

Large bodies don’t migrate; dehydrated inner disk, high C/O; enhanced organics?

Cf. Cuzzi & Zahnle 2004;
Ciesla & Cuzzi 2007
Planetesimals and C/O of Inner Disk

- Icy planetesimals sequester water and O beyond the snow line
- Efficient formation dehydrates inner disk, raises C/O ratio
Chemical signature of rising C/O

Doubling C/O produces 10 fold increase in HCN/H$_2$O warm column ratio

Najita, Adamkovics, Glassgold 2011
Inner Disk Molecules in Emission

Emission from terrestrial planet region
$T \sim 500 \text{ K}$
Size $\sim 1 \text{ AU radius}$

See also Carr & Najita 2011; Salyk et al. 2008, 2011; Pontoppidan et al. 2010
Planetesimal Formation and C/O

Icy protoplanets form beyond the snowline.

 Raises C/O, \text{org}/\text{H}_2\text{O} ratios within snowline.

MIR molecular emission from here.

More massive disks form protoplanets quicker, have higher C/O ratio?
HCN/H2O Ratio vs. Disk Mass

Single T Tauri Stars in Taurus; disk masses from Andrews & Williams

Najita et al. 2013
Chemical signature of planetesimal formation

MIR molecular emission from here

Not here...

Molecular message from 2013:
Disks are not primordial –
they have formed planetesimals or protoplanets
– a chemical signature of core accretion in action!

...but here!
ALMA Observes HL Tau

Credit: ALMA (ESO/NAOJ/NRAO)
Rings and Spirals in DSHARP

Anders et al. 2018
Chemical signature of planetesimal formation?

- Possibly we’re onto something!
- Chemistry can uniquely illuminate an elusive planet formation process
High resolution MIR spectroscopy

Observing disk accretion in action?

e.g., Najita et al. 2021
Exoplanet Populations

Migration is important
How does matter reach the magnetosphere?

Stars accrete via magnetospheres and transport angular momentum to the inner disk, which is removed in a wind/jet from inner disk.

But how does accreting matter reach the magnetosphere?
How do disks accrete?

- **Qualitatively**: plausible we have a dead zone (Gammie 1996) with ~1-2 orders of magnitude suppressed turbulence.
- **Details** are sensitive to dust size distribution.
- **Role of Hall effect** is not fully understood (Armitage 2011).

**Armitage (2011)**

- **Dead zone**
- **Planet formation region**
- **Resistive quenching of MRI, suppressed angular momentum transport**
- **MRI-active surface layer**
- **Cosmic rays?**
- **Nonthermal ionization of full disk column**
- **Ambipolar diffusion dominates**

**Thermal ionized MRI**

- **Collisional ionization at T > 10^3 K (r < 1 AU)**
- **MRI turbulent**

**Layered accretion**

- **Disk winds?**
- **Something else?**

**Non-thermal ionized MRI**
Inner Disk Molecules in Emission

Emission from terrestrial planet region
$T \sim 500 \text{ K}$
Size $\sim 1 \text{ AU radius}$

Carr & Najita 2008
GV Tau N: Spitzer/IRS molecular absorption
GV Tau N: high resolution line profiles

Redshifted line profiles
- 4-20 km/s
- C2H2, HCN, NH3, H2O
- TEXES/Gemini R=100,000

Measure component equivalent widths and infer
- Temperature T
- Absorption column density N
- Intrinsic line width $\Delta v$
- Filling factor $f$

- Molecular abundances, temperature of inner disks at ~ 1 au
- High column density $\rightarrow$ disk atmosphere viewed edge on
- Supersonic inflow velocities

Najita et al. 2021
Inner disk atmosphere seen edge on

Disk accretion in action through disk atmosphere?

Accretion rate ~ TTS:
$10^{-8} \text{ - } 10^{-7} \mathcal{M}_{\odot}/\text{yr}$
i.e.,
$\dot{M} = 2\pi r_a m_H v_r N_{\perp}$
$N_{\perp} \sim 0.1 \frac{N_{\text{abs}}}{x_{\text{mol}}}$
Disk accretion in a thin atmosphere

Fast current...overlying a “deep ocean” of the disk...hospitable to planet formation?
Summary: UV/Optical Spectroscopy

Rich UV-optical spectrum, long history, well studied

Diverse questions/issues:

• How stars accrete
  • Via magnetospheres not boundary layers

• Demographics of stellar accretion rates bear on:
  • Gas dissipation timescale of inner disk (planet formation, migration)
  • Nature of transition disks (due to planets or not?)
Summary: Infrared Spectroscopy

Many diagnostics available, much less well studied
Fun, powerful techniques (e.g., spectroastrometry)

Diverse questions/issues

• Disk structure and substructure
  • Measure inner gas disk radii (planetary orbital radii)
  • Identify orbiting gaseous circumplanetary disks (birthplaces of moons)

• Disk chemistry
  • Probe planetesimal formation, an otherwise elusive process?

• Disk dynamics
  • Do disks accrete through their atmospheres?