Spectroscopic Probes of Turbulence in the Planet Formation Region of Disks

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In this talk...

How “primordial” are protoplanetary disks?

Possible ways to probe turbulence in inner disks (i.e., at < 10 AU)

- Available spectral line diagnostics (molecular)
- #1 Chemical mixing (challenging?)
- #2 Heat signature
- #3 Turbulent motions
- Constraints on disk winds?
Evolutionary Stages of Star Formation

**Embedded object:**
Star assembling its mass; has a disk, outflow, envelope.

**Classical T Tauri star:**
Star essentially formed; has a disk.

**Weak T Tauri star:**
Little/no accretion, gas, and dust
Possible planetesimals for later debris production

What is a protoplanetary disk?
When do planets form?

A. Isella
How Do Planets Form?

The Story of Core Accretion

Once upon a time…

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…tada!

The End
Birth of Planets Revealed in Astonishing Detail in ALMA’s ‘Best Image Ever’

- Flat-spectrum source (Class I.5)
- What’s the situation for most disks?
Synthetic (Monte Carlo) Exoplanet & Debris Disk Populations

![Graph showing the cumulative fraction of planets and debris disks in different classes.](image)

- Class I disks
- Class II disks (s)
- No 5-30 M\(_E\) microlensing planets
- Planets + DD (10-100 M\(_E\))

Najita & Kenyon 2014
Are Protoplanetary Disks Primordial? Not so much.

T Tauri disks: highly evolved as a class
Are T Tauri disks like this....?

Or this....?
Studying Disks Spectroscopically

Clues from disk atmospheres:
- Chemistry
- Heating ($T_g > T_d$)
- Motions
Gaseous Probes of Inner Disks

- HCN, CO
- C$_2$H$_2$, OH, H$_2$O
- NeII
- CO, HCO$^+$, CS, N$_2$H$^+$, H$_2$CO, CN, HCN, NHC, etc

NIR, UV, MIR diagnostics probe planet formation distances
Spectral Line Diagnostics \( \text{NIR} \)

2.3 \( \mu \text{m} \) CO overtone (\( \Delta v=2 \))

- 5-10\% of young stars

4.6 \( \mu \text{m} \) CO fundamental (\( \Delta v=1 \))

- \~\text{All T Tauri stars}

3 \( \mu \text{m} \) H\( _2 \text{O} \) and OH rovibrational

- May be common? (stellar photospheres)

Salyk et al. 2008
Spectral Line Diagnostics \textbf{NIR}

2.3 \(\mu m\) CO overtone \((\Delta v=2)\)

4.6 \(\mu m\) CO fundamental \((\Delta v=1)\)

5-10\% of young stars

3 \(\mu m\) \(H_2O\) and OH rovibrational

\sim All T Tauri stars

Rarely this dense

Doppmann et al. 2011
Spectral Line Profiles NIR

Line profiles used to infer emission radii, physical conditions in the atmosphere

CO fundamental emission from disk truncation radius (0.05 AU) to ~ 1AU

Brown et al. 2013
S/N ~ 250
Atomic lines [NeII], HI
Molecules C$_2$H$_2$, HCN, CO$_2$, H$_2$O, OH

See also Salyk et al. 2008
Spectral Line Diagnostics

Organic Molecules and Water in a Protoplanetary Disk

Spitzer Space Telescope • IRS

NASA / JPL-Caltech / J. Carr (Naval Research Laboratory)
**Line Profiles for Water and Organics**

MIR Spectra from TEXES on Gemini

- **Water** (high quality profiles)
- **Organics – HCN, C$_2$H$_2$$^{*}$ (10x weaker, challenging)

R = 100,000
$\lambda \sim 12\mu$m

MIR line profiles locate emission in the **terrestrial planet region** (< few AU)

Najita et al., in prep
Emission from Disk Atmospheres

Hot Atomic Layer
4000K

Hot/warm Molecular Layer
400-2000K

Cool Molecular Layer
< 400K

Emission from gas disk atmosphere
$T_g > T_d$

Heated by stellar UV (and accretion)

Najita & Adamkovics in prep
Gaseous Probes of Inner Disks

**Hot Molecular**
- \( T_g \approx 1000-2000 \text{K} \)
- \( \text{Organics L-band} \)
- \( \text{H}_2 \text{ UV} \)
- \( \text{H}_2\text{O ro-vib} \)
- \( \text{OH } \Delta v=1 \)
- \( \text{CO } \Delta v=1 \)
- \( \text{CO } \Delta v=2 \)

**Warm Molecular**
- \( T_d \approx 300-800 \text{K} \)
- \( \text{HCN, CO}_2 \)
- \( \text{C}_2\text{H}_2, \text{OH, H}_2\text{O} \)

**Hot Atomic**
- \( \text{NeII} \)

**Dust Temperatures**
- \( T_d \approx 300-800 \text{K} \)
- \( \approx 125-300 \text{K} \)

**Wavelengths**
- \( 0.1 \text{ AU NIR} \)
- \( 1 \text{ AU MIR} \)
- \( 10 \text{ AU FIR} \)
- \( >20 \text{ AU mm} \)
Young stars accrete...and more slowly with age

Still accreting after all these years...

How do they do it?

Sicilia-Aguilar et al. 2010
Magnetorotational Instability?

Low ionization in disk midplane – is the disk dead at planet formation distances?

How can we look for evidence of MRI in action?

- Chemical mixing
- Mechanical heating
- Turbulent motion
#1 Chemical Mixing

Migration of icy grains and gas in turbulent medium
• Vertically
• Radially

Looking for something chemically out of place…
Molecular Diagnostics of Chemical Mixing

- Chemical timescale is generally short in atmosphere, long at large r and small z.
- History is lost, for known diagnostics within few AU.

- Need observable chemical species with long chemical lifetimes...
- Or look at effects from changes to elemental abundance ratios.
#1 Chemical Mixing

- Seems challenging.

Questions:
  - How much mixing is predicted?
  - What is a useful probe?

Molecular probes: Looking for molecules with long chemical timescales to serve as probes of turbulent mixing

Elemental abundance probes: Does mixing affect elemental abundance ratios in an observable way? (e.g., planetesimal formation example)
Gas temperatures of IR spectral line diagnostics (500-2500K) exceed dust temperatures in the same region of the disk. → Are elevated temperatures powered by mechanical heating?
More dissipation at disk surface with MRI (current sheets, shocks) than with classical $\alpha$ disk

Turbulent heating rate equiv to $\alpha \sim 1$
- Is atm heated mechanically?
- Need to rule out other possibilities.
Model Disk Atmospheres with FUV (Lyα + Continuum) and Accretion Heating

Hot Atomic

Hot/warm Molecular (Lyα + mechanical)

Cool Molecular (mechanical)

At 0.5 AU

$L_{\text{FUV}} = 0.0025L_{\text{sun}} + \text{Lyα}$

$\alpha_h = 0.5$

$a_g = 0.7$

Najita & Adamkovics in prep
Warm Molecular Columns: Observation & Theory

- Ly$\alpha$ + mechanical
- with Ly$\alpha$
- with mechanical

Observations best fit with Ly$\alpha$ + mechanical heating, but Ly$\alpha$ does much of the heavy lifting

- Ly$\alpha$ important for hot molecules
- Mechanical heating enhances H$_2$O, HCN, CO$_2$
Heat Signature of Accretion in Protoplanetary Disks

- FUV (Lya + continuum) impacts the hot/warm molecular layer where most of the known diagnostics arise.
- Look below the FUV-heated layer, in cool molecular layer, for evidence of accretion-related heating.
#2 MRI Heating

Looks like:

- Known diagnostics do not provide strong evidence.
- Heat signature of accretion below the FUV-heated layer?

Caveats:

- How strong is accretion heating (what is \( \alpha_H \)?)
- Does detailed Ly\( \alpha \) radiative transfer (scattering + absorption) change this picture?
Turbulent Line Broadening

Turbulent velocity fluctuations rise with height, reaching ~ sound speed in the disk atmosphere.
Probing Turbulent Broadening in Spatially Unresolved Disks

2.3 μm CO overtone emission

Emission spectrum if no disk rotation

Line profile for a rotating disk (single line)

Convolution fits the data

Carr 1995
Probing Turbulent Broadening in Spatially Unresolved Disks

2.3 µm CO overtone emission

Range in interline spacing probes line broadening

Rotation and excitation/broadening separable because of large number of lines and spacing

Carr 1995
Turbulent Line Broadening

CO $v=2-0$ bandhead: $\Delta v \sim$ sound speed 
($T_g > 1000$K, $r < 1$AU)

Ringberg June 2011

Magnetorotational instability

Qualitatively: plausible we have dead zone
(Gammie 1996)

But:
- details are sensitive to dust size distribution
- role of Hall effect is not fully understood

Armitage (2011)

see Natalia Dzyurkevich talk
Turbulent Line Broadening at Dead Zone Radii

3 \( \mu \text{m} \) \( \text{H}_2\text{O} \) and rovibrational

- Dense emission spectrum
- Poor line list
- Rich spectra are rare

Atomic lines [NeII], HI, Molecules \( \text{C}_2\text{H}_2 \), HCN, \( \text{CO}_2 \), \( \text{H}_2\text{O} \), OH

MIR transitions?
+ Emission is common
- Need to identify appropriate lines
Winds?

Clues from existing diagnostics:

- **No large velocity offsets from** $v_{\text{star}}$ (winds not molecular?)
- **Massive winds may absorb/scatter** FUV, reducing great agreement between models and observations (would increase need for mechanical heating?)
Summary

Where everyone agrees we should see turbulence, we do
  • Non-thermal broadening within few 0.1 AU (CO overtone)
Where disk may be dead, we don’t (but observations don’t rule out MRI either)
  • Inconclusive heat signature within few AU
  • Line broadening not yet probed
Summary

Evolutionary status of protoplanetary disks
- Highly evolved as a class (from solid mass budget)
- Built planetesimal or larger objects beyond snowline (from C/O)

Chemical signature of turbulence?
- Look for molecules with long chemical timescales
- Any expected changes in elemental abundance ratios?

Heat signature of turbulence?
- No definitive signature from known diagnostics
- Look below FUV-heated layer?

Turbulent line broadening?
- Detected close to star where thermal ionized (CO overtone)
- Search for closely-spaced lines probing larger radii

Winds?
- Not molecular? (large velocity offsets not seen)
- If they absorb/scatter FUV, reinvestigate disk heating