Protoplanetary Disks

UNM Planetary Astrophysics
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Guest Lecture by Dr. Dana Anderson

Image Source: Luis Calcada
I study chemistry in planet-forming “protoplanetary” disks around young stars.

Using a combination of observations and computational models.
Q1: What are protoplanetary disks?

Q2: Why do protoplanetary disks form?

Q3: How do we know protoplanetary disks exist? (& How do we study them?)

Q4: How do protoplanetary disks relate to the planets that form from them?

Q5: What happens to protoplanetary disks?
Q1: What are protoplanetary disks?
FORMING A STAR AND PLANETARY SYSTEM

~10s of Myr

~100s of kyr

~1-20 Myr

> Myr - Gyr
DUST
1% OF THE TOTAL MASS, INITIALLY MICRON-SIZED

PRIMARILY MOLECULAR HYDROGEN H₂
92%

HEL IUM
8%

OTHER DOMINANT GASES INCLUDE CO, N₂

T~10-100 K  n~10⁶-10¹² cm⁻³

ICES (H₂O, CO₂, NH₃)

Slide modified from Cleeves
Dust plays an important role in temperatures as well as radiation propagation, including shielding the disk from stellar UV and X-rays.
Q2: Why do protoplanetary disks form?
Start with a spherical, rotating cloud of gas

Gravity causes the molecular cloud to shrink

Rotation slows collapse in the direction perpendicular to the axis of rotation

As the cloud shrinks, the conservation of angular momentum causes it to spin faster
Multiple stages of disk formation and evolution

Gray = Cloud or envelope material
Orange = Disk
Blue = Outflow

Most often the term “protoplanetary disk” refers to the Class II evolutionary stage
What is the physical origin of angular momentum transport in disks?

- Molecular viscosity is insufficient to cause disk evolution on the observed < 10 Myr timescales

- Instead, it is often assumed there must be macroscopic mixing of disk gas at neighboring radii, disks are “turbulent,” but the physical origin of this turbulence is unclear

- Potential mechanisms of angular momentum transport in disks include:
  1) Magnetorotational instability
  2) Gravitational instability
  3) Magnetically driven outflows

- Ultimately, this is still an open question!
Q3: How do we know protoplanetary disks exist? (& How do we study them?)
The “nebular hypothesis” for the solar system dates back to the 18th century.

The protoplanetary disk that used to surround the Sun is referred to as the “solar nebula”.

*Many comets exist outside the orbital plane.*
Silhouettes of disks against background emission from the Orion Nebula.
Resolved images show a rotating gas disk
Observations at different wavelengths probe different regions of the disk

[Simplified version]
IR = disk surface closer to the star (0.1 – 10s of au)
sub-mm = larger distances and deeper into the disk
Different molecules and spectral lines also probe different regions of the disk

**Diagram: Kamp et al. (2017)**
Questions?
- The size scale we can resolve is proportional to the wavelength of light \((1.22 \lambda/D)\).
- Hubble-like resolution at \(\lambda\sim\text{mm}\) requires 10 km-sized telescopes.
- Interferometry allows a series of smaller telescopes (an array) to act as one larger telescope.
RESOLVING PLANET FORMATION: 1999

Facility: Plateau de Bure Interferometer (PdBI)
As of today, 253 resolved disks known! Many more unresolved.
Atacama Large Millimeter/Submillimeter Array (ALMA)

Chajnantor plateau, Atacama Desert, Chile (5000 meters)

Credit: ESO/B. Tafreshi (twanight.org)

Slide modified from Cleeves
Unprecedented collecting area...

And spatial resolution!

Slide modified from Cleeves
Imaging Disks with ALMA: Dust Continuum Emission

DSHARP ALMA
Large Program
PI: Sean Andrews

Slide modified from Cleeves
Imaging Disks with ALMA: Molecular Emission

MAPS ALMA Large Program
PI: Karin Oberg
INFERRING COMPOSITIONS: MODELING

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Models are complex! Many constraints needed.
Laboratory Spectroscopy

Molecules of Interest

Reaction Kinetics, Dynamics, Molecular Parameters

Unidentified Lines

Transition Frequencies and Strengths

Abundance Predictions

Physical Conditions, Molecular Abundances

Observational Astronomy

Astrochemical Modeling

Image credit: Susanna Widicus Weaver
Q4: How do protoplanetary disks relate to the planets that form from them?
From Protoplanetary Disks to Planetary Systems

DSHARP Results: Andrews et al. 2019

Image credits: NASA
Planet Formation in Protoplanetary Disks

Protoplanetary disk

Solids (rocky & icy materials) form dust particles, which collect and grow from pebbles to boulders to planetesimals

Over time, gases end up in the atmospheres of giant planets, accreted by the central star, or dissipate into interstellar space

Planetary system

Image credits: NASA/JPL-Caltech/L. Allen (Harvard-Smithsonian CfA); Buzzle.com; ESA/C. Carreau; McCaughrean; A. Davis, The University of Chicago; NASA; pics-about-space.com; Martin Vargic
Disk Properties Determine Planetary Outcomes

- **Mass**
  - Number of planets
  - Planet masses

- **Composition**
  - Gases $\rightarrow$ Gas giant atmospheres
  - Solids $\rightarrow$ Cores, terrestrial planets, and planetary debris

- **Lifetime**
  - Timescale for gas giant formation
  - Limits gas content
Vertical Structure
3 Main Chemical Regions

I. Photon-dominated layer - ions, neutral atoms, small dust

II. Warm molecular layer - complex molecules, gas-grain interactions

III. Cold midplane - ices coat grain surfaces
Radial Structure Along the Disk Midplane 
Condensation Sequence & Snow lines

Snow line or frost line = distance from the central star at which a particular chemical species freezes out into ice

Temperature diagram showing various species and their condensation temperatures as a function of radial distance from the central star. The species include Ca-Al-Ti Oxides & Silicates, Silicates, Iron Alloys, Sulfides, Hydrated Silicates, Water Ice, NH₃, and CH₄.

Central Region - Only metals and minerals condense into planets
Outside the Soot Line - PAHs exist, allowing forming planets to include condensed carbon compounds
Outside the Frost Line - Low temperatures allow condensing planets to include volatile molecules such as H₂O, NH₃, and CH₄

Baseline expectation: freeze-out changes the chemical environment from which planets accrete.

C/O ratio of disk gas changes with distance from the central star.

Slide modified from Cleeves.
- Motion of disk gas and solids over time
  - Disk gas and small dust grains are turbulently mixed
  - Larger dust grains tend to settle towards the midplane and spiral inward towards the central star

- Time dependence of chemistry & planet formation

- Alteration of planetesimal/planet compositions during assembly and later evolution

- Late delivery of materials via impactors
Reproducing Earth-like Compositions

Reproducing the Earth’s composition requires a yet undetermined disk process that removes carbon from rocky solids.

- **Bulk Silicate Earth**
- **Carbonaceous chondrites**
  - Suggests an early process
- **Comets**
  - Potentially non-uniform throughout the solar system
- **Polluted white dwarfs**
  - Low C/Si
  - Common, widespread process?

Distance from the Sun

- Terrestrial Planet/Asteroid Forming Zone
- Comet Forming Zone
- ISM

This is a current topic of my research!
Questions?
Q5: What happens to protoplanetary disks?
Gas is cleared from the disk mainly by a combination of: accretion onto the central star, accretion into gas-giant planets, and photoevaporation.
Observational constraints on the lifetime of PPDs

\[ f_{\text{disk}} = \exp\left(-\frac{t}{\tau_{\text{disk}}}\right) \]
\[ \tau_{\text{disk}} = 2.5 \text{ Myr} \]

Fraction of stars with disks in star-forming regions of different ages (based on near-IR emission)

But recall that near-infrared observations probe dust from close to the central star

What about the total dust mass?

Image credit: Mulders, thesis, University of Amsterdam, adopted from Dullemond et al. 2007
Evolution of the Total Mass of Solids in Protoplanetary Disks

Cumulative dust mass distribution for disks in star-forming regions of different ages:

What about the total mass of gas present in these disks?
Measuring Protoplanetary Disk Gas Masses

$$M_{H_2 \text{ gas}} = M_X \times \frac{H_2}{X}$$

(1) **Dust** Optically-thin (sub-)mm:
- Dust (+ice) aggregates with radii $\geq \text{cm-dm}$ cannot be detected
- Gas-to-dust mass ratios become uncertain over time, both globally and versus distance

(2) **CO** Relatively abundant and emissive under disk conditions, but:
- CO has unknown behavior radially and temporally
- CO may be depleted by 5-100× relative to assumed values

But if we understood their chemistry, we could use additional molecular species to place further constraints on the total H$_2$ gas content and evolving composition of disks

- HCO$^+$
- N$_2$H$^+$
- C$_2$H
- HCN
- CN
- CS
- H$_2$CO

This is a current topic of my research!
Bonus: Hot topics in current protoplanetary disk research
When does planet formation begin?

How does this affect the evolution of the disk and formation of later planets?

Are the substructures seen in disks caused by planets?
Recent observations reveal signatures of protoplanets altering the flow of gas in protoplanetary disks.
When does the gas-rich lifetime of protoplanetary disks end?

Some disks around the age where gas dispersal is thought to occur (around 10 Myr) show emission from CO gas, is this leftover protoplanetary disk gas or gas released from collisions of extrasolar comets?

This is a current topic of my research!
How do protoplanetary disk compositions relate to those of interstellar clouds and solar system bodies?

How much of a disk’s composition is inherited vs. reset within the disk?

Fig. 8.— Comparison between the observed abundances of gas-phase inner disk volatiles derived from Spitzer-IRS spectra (Salyk et al. 2011) relative to those in ices in protostellar clouds (Öberg et al. 2011b; Lahuis and van Dishoeck 2000). Disk abundances are appropriate for the inner disk, as the Spitzer-IRS emission lines originate primarily in the few AU region.

Fig. 2.— The relative CNO abundances in the solar system. The abundances are computed relative to Si, the primary refractory element in the solar system and interstellar space. The abundances are shown as a function of the H/Si ratio which separates the various bodies. The figure is taken and updated from Lee et al. (2010); Geiss (1987). The white dwarf values are for GD 40 (Jura et al. 2012) and are provided with an arbitrary H/Si ratio (since this is unknown).
Summary

Q1: What are protoplanetary disks?
   *Gas & dust that encircle young stars as they form, the birthplace of planets*

Q2: Why do protoplanetary disks form?
   *Disks are the natural outcome of the collapse of rotating molecular clouds during star formation*

Q3: How do we know protoplanetary disks exist? (& How do we study them?)
   *We study disks through a combination of observations, theoretical modeling, and laboratory studies*

Q4: How do protoplanetary disks relate to the planets that form from them?
   *Disk properties determine when and where planet formation can occur and influence planet compositions*

Q5: What happens to protoplanetary disks?
   *Disk gas is cleared from the system over time, leaving behind planets and solid debris*
Want to learn more???

Williams & Cieza 2011, Protoplanetary Disks and Their Evolution
Annual Review of Astronomy and Astrophysics, 49:1, 67-117

Henning & Semenov 2013, Chemistry in Protoplanetary Disks,
Chem. Rev., 113, 9016-9042, dx.doi.org/10.1021/cr400128p

Accretion processes in star formation, 2nd edition, by Lee Hartmann.

Physical Processes in Circumstellar Disks around Young Stars, Edited by Paulo J.V. Garcia.

Astrophysics of Planet Formation, by Philip J. Armitage.

Thanks to Ilse Cleeves for providing several of the slides!