Observations of Protoplanetary Disks: An Overview

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Observational Evidence for the Existence of Disks

- IR excess: circumstellar dust present
- Observed $A_V < A_V$ for a spherical dust shell
- Polarization measurements
- Direct imaging (near-IR, thermal-IR, sub-mm)
Direct Imaging: Disk Shadows


Bally et al. 2000, AJ 119, 2919
Direct Imaging: Visual (scattered light)

HD 100546 in the visual (0.2-1.0 μm)

Grady et al. 2001, AJ 122, 3396
Direct Imaging: Thermal IR

HD 100546 @ 24.5 μm

Direct Imaging: (sub-)mm

Disks Are Everywhere!

- **T Tauri Stars** (0.1—2.0 \( M_\odot \))
  (e.g. Bertout et al. 1988; Edwards et al. 1992)

- **Herbig Ae/Be Stars** (2—10 \( M_\odot \))
  (Hillenbrand et al. 1992; Mannings & Sargent 1997; Fuente et al. 2003)

- **Brown Dwarfs** (< 0.1 \( M_\odot \))
  (Comerón et al. 2000; Apai et al. 2002; Pascucci et al. 2003)

- **Binaries, triple systems, …**
  (Jensen et al. 1996; Mathieu et al. 2000; Prato et al. 2001)
Disk Dispersal Timescales

- Fraction of systems with disks decreases with time
- Oldest PP disks: ~ 10 Myr
- Stochastic process

Observed Disk Properties

- Disk Sizes
- Disk Composition
- Disk Structure
**Disk-Size Distribution**

- Typical disk size in scattered light: a few hundred AU
- Similar sizes derived from (sub-)mm continuum and line data
- Smaller in Thermal IR (20-30 AU)

Disk-Size Distribution Orion Trapezium Cluster

Vicente & Alves 2004
Disk Composition: Gas

- UV/Optical/IR emission lines
- (Sub-)mm emission lines
- Absorption studies (UV, optical)
- Free-Free emission (radio)
(Sub)-mm Emission Lines from Protoplanetary Disks


Disk Composition: Dust

- Amorphous Silicates
- Crystalline Silicates
- Iron-Sulphide
- Polycyclic Aromatic Hydrocarbons (PAHs)
Amorphous Silicates

Observed in virtually all PP Disks

Crystalline Silicates

Interplanetary Dust Particle

Bradley et al. 1999, Science 285, 1716

Observed in only a small fraction of PP Disks; homogeneous in appearance

Iron-Sulphhide

FeS
Fe$_{1-x}$S
PP Disk
PP Disk
IDP
IDP

Polycyclic Aromatic Hydrocarbons (PAHs)

Observed in ~50% of Herbig Ae/Be Stars

Polycyclic Aromatic Hydrocarbons (PAHs)


Acke & van den Ancker 2004

Differences in PAH size, chemistry and/or ionization within the group of Herbig Ae/Be stars
Evidence for Grain Growth

- Extinction Studies
- IR spectroscopy
- (Sub-)mm continuum measurements
Evidence for Grain Growth


No dependence of disk size on wavelength
⇒ Grey extinction!
Evidence for Grain Growth

Evidence for Grain Growth

Testi et al. 2003, A&A 403, 323

CQ Tau disk is optically thin at $r > 8$ AU: (sub-)mm slope indicates large grains!
Disk Structure of Herbig Ae/Be Stars

- Near-IR excess: rather uniform
- Large differences in mid-far-IR (20-100 micron) excess
- Disks with puffed-up inner rim with various amounts of flaring

Observational Correlations with M01 Classification

- PAH emission is much stronger in M01 Group I sources
- Consistent with the idea that PAH emission originates in the surface layers of a flared disk

Acke & van den Ancker 2004
Observational Correlations with M01 Classification

- UXOR behaviour is limited to Group II sources
- Consistent with the idea that a self-shadowed disk geometry is necessary to see the central star

Observational Correlations with M01 Classification

- Group II sources have a different (sub-)mm SED slope than Group I sources
- Amount of disk flaring correlated with grain size

Conclusions

- Great advances in our knowledge of the size and composition of PP disks over the last 10 years
- As of yet lacking in observational evidence: information on radial distribution of matter (gaps!)
The Future

- Spitzer ➔ Extend dust inventory to lower-mass objects
- VLTI ➔ Radial dust/gas distribution
- JWST, ALMA ➔ Direct imaging of radial dust distribution