Planetary formation
Observational evidence

In the last decades observational evidence has accumulated that stars are born surrounded by circumstellar disks.

Infrared excesses & circumstellar disks

Infrared excesses

• The infrared excess is defined as an excess of the stellar infrared emission with respect to the black-body spectrum expected from the stellar effective temperature.

In the far infrared the emission can be orders of magnitude more intense with respect to the expected stellar emission.

Origin of the infrared excess

• The infrared excess is interpreted as due to thermal emission of circumstellar dust present at the epoch of star formation.

• The dust is expected to be only 1% by mass of the circumstellar material, the rest being in gaseous phase.

• Despite its small mass contribution to the circumstellar material, the dust is, by far, the main contributor to the IR emission.

• The dust emits over a large spectral interval, from ~ 2μm to ~ 1 mm, as the result of large gradient of temperature in the circumstellar material located at different distances from the star.
  – From $T \sim 1000$ K in the proximity of the star down to $T \sim 30$ K in the outer regions at hundreds of AU from the star.

• The dust material is expected to be distributed in the form of a circumstellar disk.
Circumstellar disks

- High resolution images have confirmed that the infrared excess is due to the presence of circumstellar disks of dust
  - Sizes
    Comparable to the Solar System size
  - Geometrical characteristics
    Relatively flat disks, thin in the inner regions (< 50 AU), they become gradually thicker in the outer regions
    The edges are truncated

Recent examples of observations of circumstellar disks

Imaging in the far IR of η Corvi obtained with the instrument PACS on board of the Herschel satellite

Lisse et al. (2012)

The disk - infrared excess connection

Recent examples of infrared excesses

Measurements of the infrared excess of η Corvi in the far IR, obtained with the instrument PACS on board of the Herschel satellite

Lisse et al. (2012)

Surface density and sizes of circumstellar disks

- Surface density (gas+dust; g cm\(^{-2}\)) versus radius for circumstellar disks in Ophiucus
  Based on fitting an analytical law to the IR spectral energy distributions
  The dark gray rectangular regions mark the surface densities required to build up Saturn, Uranus and Neptune
  Surface densities and sizes are in the same scale of those estimated for the solar nebula

Andrews et al. (2009, 2010)
Dust masses are calculated from (sub)millimeter wavelength observations of dust

- Mass in dust:
  \[ \sim 10^{-4} - 10^{-3} \, M_\odot \]
  The mass in dust is sufficient to produce 10 times more planets than those of the Solar System

- Total mass (dust+gas):
  \[ \sim 0.01 - 0.1 \, M_\odot \]
  The total mass is in the range of the mass of solar nebula that gave birth to the Solar System

The total mass is then estimated by adopting a gas-to-dust ratio by mass of \( \sim 100 \)

- Mass distribution of disks compared with the range of masses of the Solar Nebula
  Beckwith & Sargent (1996)

By comparing the mass of circumstellar dust with the age of the star, evidence for evolution is found: the mass in dust tends to decrease with time

Interpretation: the solid component is being gradually consumed

The decrease of the mass of circumstellar dust is interpreted as an effect of dust coagulation and accretion of the solid component in protoplanetary and planetary bodies

Even though, in principle, different effects can be invoked, such as dust sublimation or astration (accretion by the star) of the solid component

All the observational evidence, including masses, surface densities and sizes, is consistent, also from a quantitative point of view, with the hypothesis that the solid component in circumstellar disks is the material that gives rise to planetary formation

- For this reason circumstellar disks are also called protoplanetary disks

Almost all the disks around stars with masses in the range 0.04 to 10 \( M_\odot \) lie within the gray shaded area, \( \pm 1 \) dex about the median \( M_{\text{disk}}/M_\ast = 0.01 \)

Exceptions are O stars, where no disks are detected at (sub)millimeter wavelengths, indicating either very short disk life times, or a very different star formation scenario

(Williams & Cieza 2011)
Classification of Young Stellar Objects (YSOs)

- Young Stellar Objects are classified in classes
  - Class 0, I, II e III
  - The classification is mostly based on the slope of the emission spectrum in the infrared and (sub)millimetric spectral bands

- The classification is interpreted in terms of an evolutionary sequence
  - Representative of the early evolutionary stages of solar-type stars
  - There is a gradual transition between subsequent classes

- The classification provides:
  - an evolutionary interpretation for a variety of observational evidence (collimated jets, T Tauri stars, infrared excesses, protoplanetary disks)
  - a reference frame for understanding the process of planetary formation

Class 0: young protostars

A collapsing envelope with radius $10^3 - 10^4$ AU hides the protostar. The dust in the envelope is too cold (~30 K) to irradiate in the IR. Only millimetric emission can be detected.

A central disk with radius 200-300 AU starts to form.

The accretion rate of the protostars is $10^{-5} - 10^{-6} \, M_\odot$/yr.

An intense collimated jet is generated.

Class I: evolved protostars

The envelope is still optically obscure, but becomes more tenuous.

The envelope becomes warmer and emits intensely in the IR. Accretion persists. The protostar is fed by an accretion disk with a radius of a few hundreds AU.

Molecular jets are still present, but less collimated.

This stage lasts for about $10^5$ yr.
Class FS: Flat spectrum

Class FS is intermediate between Class I and Class II and is characterized by a flat IR spectrum.

Class II: classic T Tauri stars

The envelope disappears, star accretion has finished and the protostellar phase ends.
The protostar has become a classic T-Tauri star.
The infrared excess and circumstellar disk are still present.
Molecular jets diminish and disappear.

Class III: weak-line T Tauri stars

The star has characteristics of a weak-line T-Tauri star.
The infrared excess and circumstellar disk disappear on a short time scale (~10^5 yr).
The Class III stage lasts for about 10^6 - 10^7 yr.
Molecular jets are completely absent.

Transition disks

Williams & Cieza (2011)

• In some cases, SEDs do not fit the YSOs classification scheme
  – Weak or absent near infrared excess; significant excess above 10μm
  – The properties are somehow intermediate between Class II and Class III
Transition disks
Williams & Cieza (2011)

• SED modeling of transition disks provides evidence for central holes

• Long baseline interferometric measurements confirm the existence of central holes in the dust distribution

• CO gas has been found inside the holes in some cases

Planetary formation in the context of stellar evolution:
evolution in the HR diagram
Beckwith & Sargent (1996)

ALMA observations of protoplanetary disks

• ALMA (Atacama Large Millimeter/submillimeter Array)
ESO + international collaboration

• Altitude: in large part > 5000 m above sea level
Low water vapour absorption

• Antennas: 54 x 12.0 m and 12 x 7.0 m

• Possibility of interferometric mode, with baselines from 150 m to 16 km

• Max angular resolution in interferometric mode: ~ 10^{-2} arcsec

• Thanks to the classification of YSOs we can understand how stellar jets are related to circumstellar disks
  – “Paradox” of star formation:
  in order to accrete mass, the star has to lose mass
  About 10% of the mass accreted from the disk is estimated to be ejected through the jets
  – To explain this phenomenology magneto-hydrodynamic models are invoked, where magnetic fields play an important role to transfer part of the accreted material along the rotation axis
  – The energy source would be driven by stellar rotation
ALMA observations of protoplanetary disks: HL Tau
ALMA partnership Brogan et al. (2015)

- Millimetric continuum emission of HL Tau
- Unprecedented resolution of a few AU at a distance of 140 pc
- A pattern of bright and dark rings observed at all wavelengths
- Several characteristics of these rings, including an increase in eccentricity with radius and numerous resonances, suggest that the dark rings are gaps arising from the process of planet formation
- Opening of a new era in the study of protoplanetary disks that promises to unearth the architecture of extrasolar multi-planetary systems during their epoch of formation

ALMA observations of protoplanetary disks: HD163296
Isella et al. (2017)

- The gas-to-dust ratio varies across the disk
- The middle and outer rings could be due to the gravitational torque exerted by two Saturn-mass planets orbiting at 100 and 160 A.U. from the star