

## Stellar and planetary formation

### Observational evidence

Planets and Astrobiology (2018-2019)  
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## Stages preceding star formation

- The star formation process is associated with the presence of interstellar gas in molecular form
- Molecular gas that drives star formation can be found:
  - inside large complexes of molecular clouds
  - in isolated dense cores (known as Bok globules)
- Dense molecular cores can be associated with:
  - Cores without stars
    - indicative of the stages that precede star formation
  - Protostellar objects
    - indicative of the early stages of star formation

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## Challenges posed by the study of stellar/planetary formation

### Observational challenges:

Transient and (often) hidden event, difficult to observe  
In the case of the Solar System the event has taken place in a remote past, and must be reconstructed using present-day evidence. Only in recent years astronomical observations have become able to cast light on the stages of stellar and planetary formation

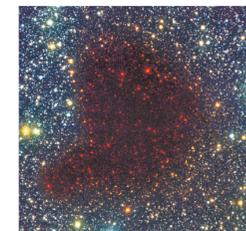
### Theoretical challenges:

Process that takes place in multiple stages,  
each one dominated by different physical processes,  
and involves interactions between a large number of components

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## Globules without stars

- Lada et al. (2007; PPV)
- **Observational techniques**
    - Stellar counts
    - Near infrared colour excesses
      - H (1.65  $\mu\text{m}$ ) and K (2.2  $\mu\text{m}$ ) bands
  - **Example in the figure**
    - ESO image of Globule Barnard 68 in the optical (top) and infrared (bottom) bands
    - The cloud is completely opaque in the optical range and relatively transparent in the infrared
    - This behaviour reflects a general property of the interstellar medium, which is more transparent at longer wavelengths than at shorter wavelengths
- Alves et al. (2001)



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## Globules without stars

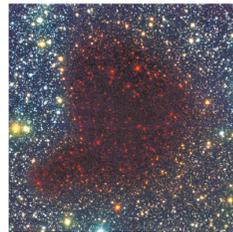
Alves et al. (2001)

- Study of the internal structure of globules

- From the stellar counts one can estimate the extinction at each location of the core

$$A_\lambda \text{ (mag)} = -2.5 \log_{10} (I_\lambda / I_{\lambda 0})$$

- In this way one can build a map of extinction values as a function of position
- From an azimuthal average of the 2D map, one then calculates a radial profile of extinction



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## Molecular cores in equilibrium

- Similar results of equilibrium between pressure and self-gravitation have been found in other isolated globules and molecular cores without stars
  - Such equilibrium configurations are believed to represent the initial conditions that characterize dense cores before the onset of star formation
  - Sizes of globules are in the order of several thousands AU, still much larger than the typical size of planetary systems

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## Globules without stars

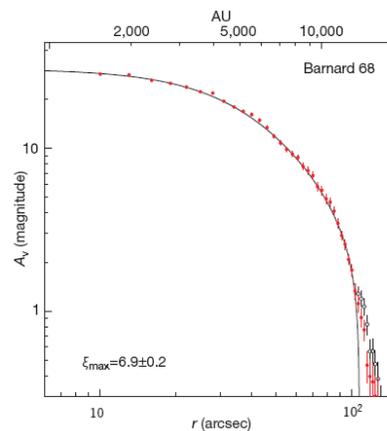
- Structure of the core B68

Alves et al. (2001)

- The radial profile is well fitted by a “Bonnor-Ebert” sphere

Isothermal gas sphere with internal pressure in equilibrium with self-gravitation and external pressure

- This result indicates that the globule is in an equilibrium configuration, rather than in a transient phase



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## Early stages of star formation

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## Outflows and molecular jets

- Outflows from young stellar objects provide one of the signatures of star formation easier to observe
    - The first examples, associated to Herbig-Haro (HH) objects, were discovered around the 1950's
      - HH objects are peculiar nebulosities located in the vicinity of dark clouds in regions of recent star formation
- Evidence for collisional shock waves were found from the analysis of HH spectra in the 1970's
- Later it was found some of the HH objects are associated with outflows beamed into two narrow, oppositely directed jets (bipolar jets)

HST image of Herbig Haro object HH47

The bar at the bottom indicates the scale (1000 AU)

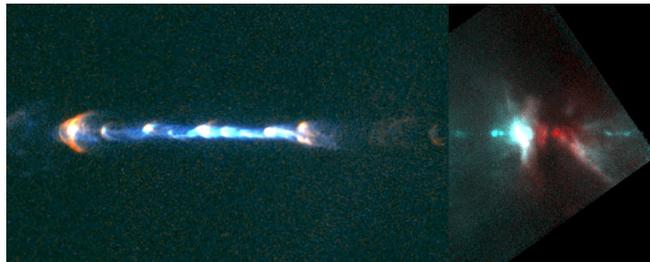


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## Observational properties of molecular jets

- **Velocity**
  - In the order of  $\sim 50$  km/s, but wavelength-dependent
  - Primary jets with the highest velocities are observed in the most energetic spectral bands (e.g., in the X band)
  - Secondary fluxes with lower velocities are observed in spectral bands of lower energy
- **Evolution**
  - The density of the gas tends to decrease with time
  - The jet velocity tends to increase
- **Sizes**
  - $\sim 10^4$  AU (much larger than the globules)
- **Associated stellar objects**
  - Often not detected in the optical band
  - In some cases, T Tauri stars have been found

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Example: Herbig-Haro object HH111

Superposition of HST images in the optical (left) and infrared (right) spectral bands

The source of the jet is deeply embedded in a molecular cloud and cannot be observed in the optical band

The jet is associated with young stars of low mass

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## Outflows and molecular jets: interpretation

- Jets were not predicted to exist by theories of star formation
- The observations, as well as theoretical considerations, indicate that collimated jets are oriented along the rotation axis of the protostar and obtain their energy from accretion
  - The presence of a bipolar outflow indicates that the (unseen) protostar is accumulating material from the surrounding cloud via an accretion disk
- The physical mechanism that provides energy to the jets is related to the conservation of angular momentum in presence of an accretion disk
- Collimated fluxes of gas have been discovered around much larger astrophysical systems, such as AGNs (Active Galactic Nuclei)
- Despite differences in size, the common physical ingredients are believed to be accretion, rotation, and magnetic fields

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## Young Stellar Objects

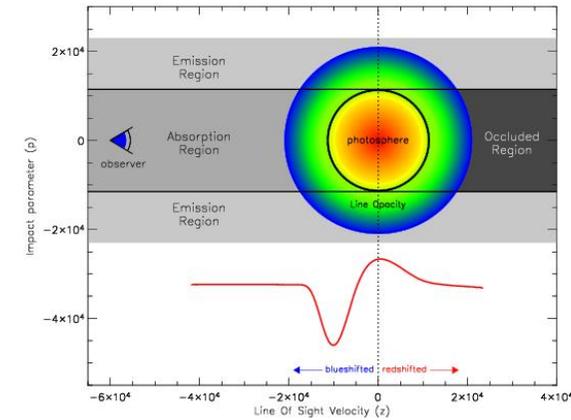
We focus on the early stages of late-type stars  
 ( $M_* \sim 0.2 - 2 M_{\odot}$ )

A similar phenomenology also exists for Ae/Be stars,  
 the early stages of more massive stars

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## P-Cygni profiles

– Signatures of stellar gas outflows (stellar winds)



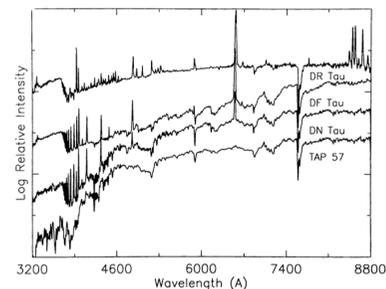
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## T Tauri stars

- T Tauri stars are found in Galactic regions of star formation  
 Sometimes they are associated with jets and HH objects
- The optical spectra of T Tauri stars indicate that they are late-type stars, with a series of peculiar characteristics

Strong emissions of  $H\alpha$ , CaII H & K  
 Suggestive of intense chromospheric activity

P-Cygni profiles  
 Suggestive of strong stellar winds



Spectra of T Tauri stars  
 Bertout (1989)

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## T Tauri stars

- Signatures of young age

High rotational velocities,  $V \sin i$

In the early stages after star formation, stars are characterized by high rotational velocity, resulting from conservation of angular momentum of the accreting disk

Rotational rate is damped with time, probably as a result of magneto-hydrodynamical effects that dissipate rotational energy

Strong Li lines

Lithium nuclei, produced in the Big Bang nucleosynthesis, can be destroyed in stellar interiors, even at relatively low temperatures

The external, convective layers of late-type stars drive surface lithium in inner regions where it is destroyed

As a result, the Li abundances decrease with time and strong Li lines are a signature of young age

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## T Tauri stars

- Observations in other spectral bands confirm the peculiar nature of T Tauri stars
  - They often show infrared excess (1-10  $\mu\text{m}$ )  
Indicative of cold dust
  - They emit in the X-ray band  
Indicative of coronal gas with very high temperature ( $\sim 10^6$  K)
- There are two types of T Tauri stars:
  - Classic T Tauri stars
    - Strong H $\alpha$  emission line
    - Infrared excess (1-10  $\mu\text{m}$ )
  - Weak-line T Tauri stars
    - Discovered in X rays
    - Weak H $\alpha$  emission
    - Without infrared excess

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## T Tauri stars

- The location in the HR diagram confirms that T Tauri stars are very young objects

Overluminous with respect to main-sequence stars of the same spectral type

Pre-main sequence stars

Figure: HR diagram of T Tauri stars

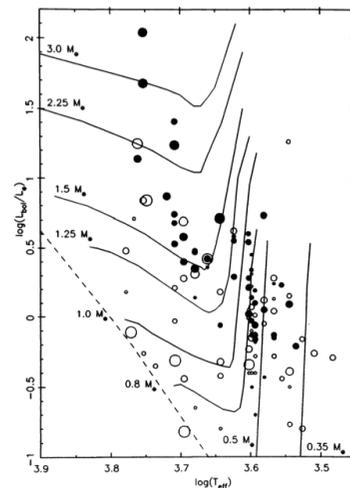
Filled circles: classic T Tauri

Empty circles: weak-lines T Tauri

The symbol size scales with the star rotational velocity,  $V \sin i$

Solid lines: pre-main sequence evolutionary track for stars of different masses

Dashed line: zero age main sequence



Bertout (1989)

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