Stellar and planetary formation

Observational evidence

Planets and Astrobiology (2023)

G. Vladilo and S. Ivanovski

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 year 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

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 Blok 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

Globules without stars

Lada et al. (2007; PPV)

- Observational techniques
  - Stellar counts
  - Near infrared colour excesses

    H (1.65 μm) and K (2.2 μm) 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)

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 azimutal average of the 2D map, one then calculates a radial profile of extinction

Globules without stars

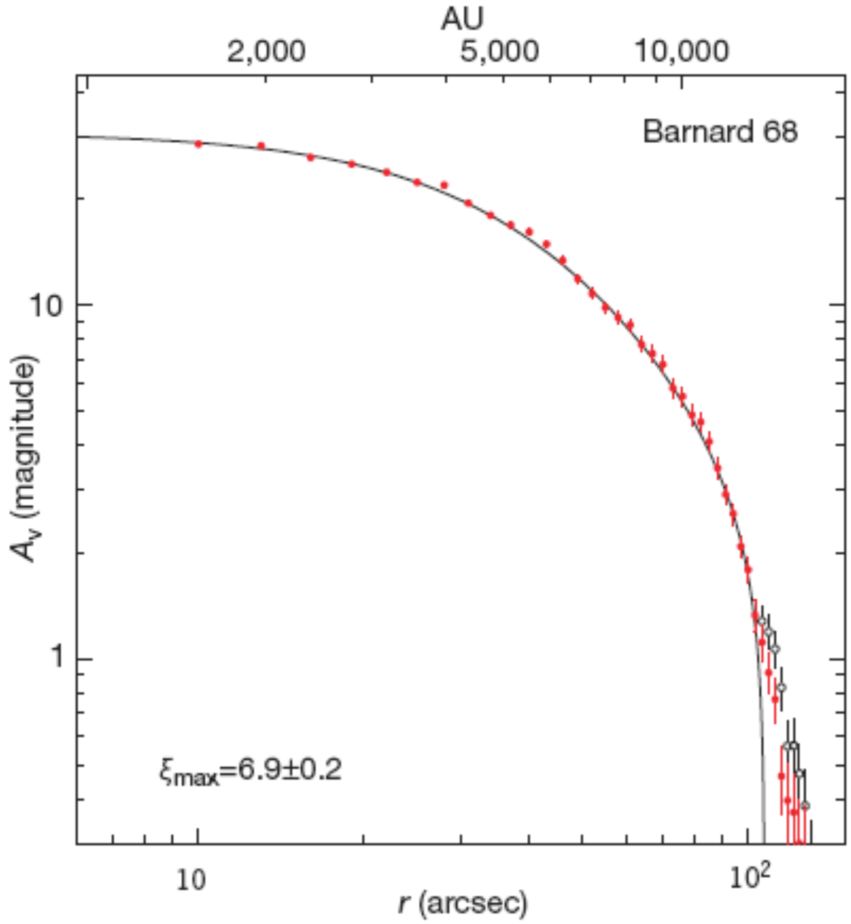
- Structure of the core B68

  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



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

Early stages of star formation

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

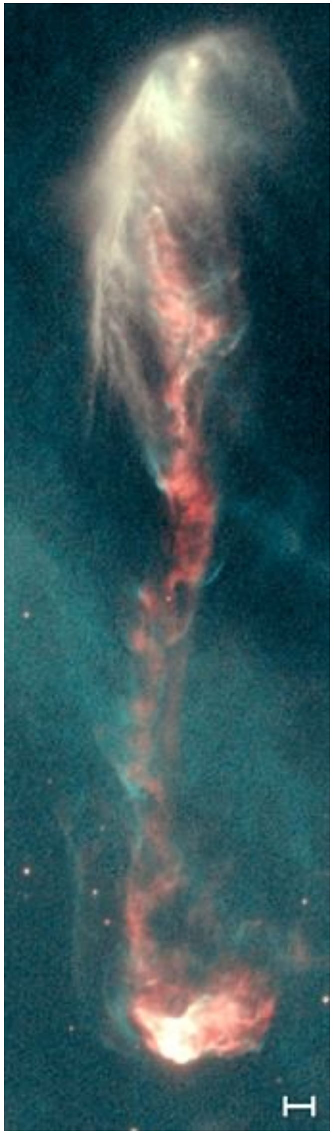
    HH objects are peculiar nebulosities located in the vicinity of dark clouds in regions of recent star formation

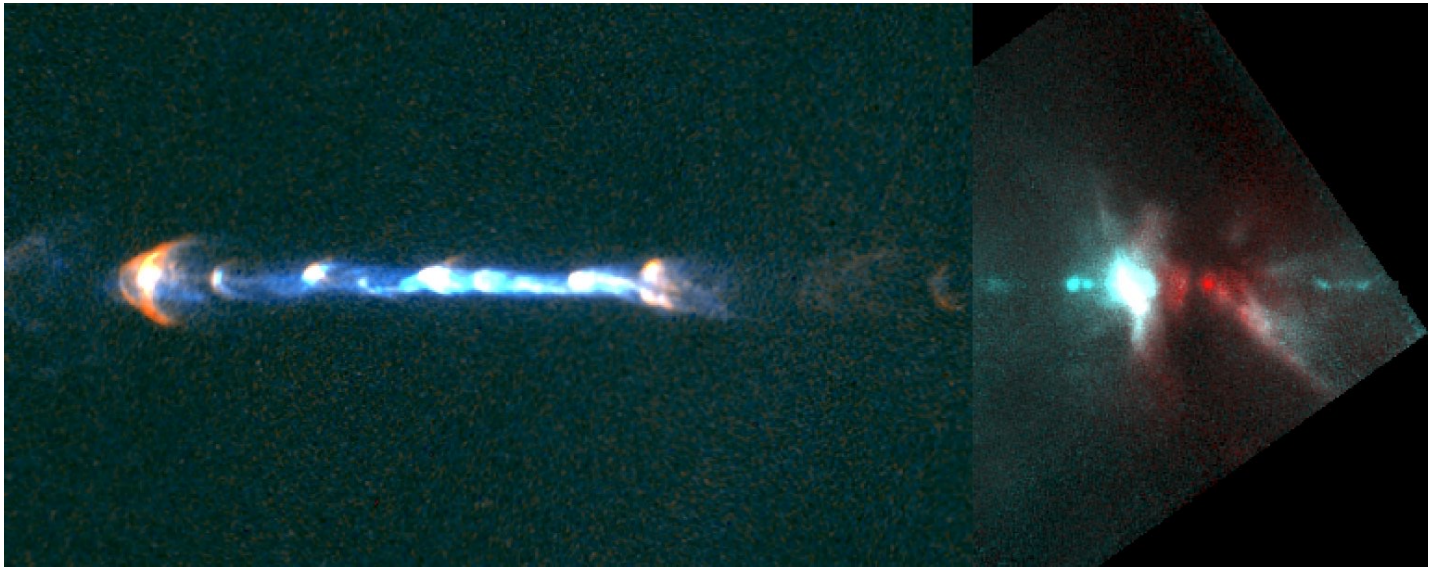
    Evidence for collisional shock waves were found from the analysis of HH spectra in the 1970's

    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)





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

Observational properties of molecular jets

- Velocity

  In the order of ~ 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

  ~ 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

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

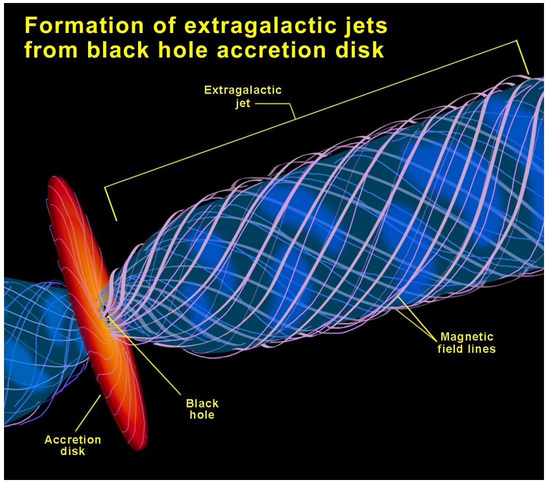
- The physical mechanism that provides energy to the jets is related to the conservation of angular momentum in presence of an accretion disk

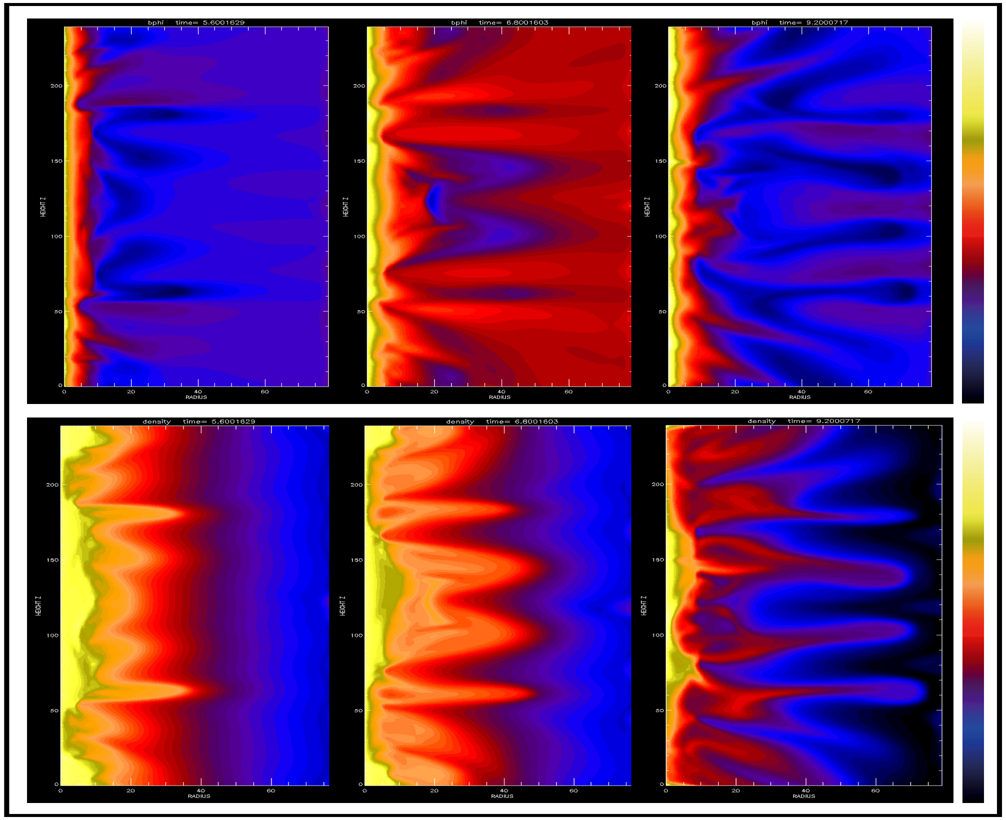
- Collimated fluxes of gas have been discovered around much larger astrophysical systems, such as AGNs (Active Galactic Nuclei)

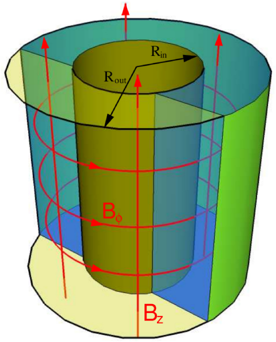
- Despite differences in size, the common physical ingredients are believed to be accretion, rotation, and magnetic fields

Non-linear 3D simulations of current-driven instabilities in jets

Figure 4.1: This image of Centaurus A shows a spectacular new view of a supermassive black hole's power. Jets and lobes powered by the central black hole in this nearby galaxy are shown by submillimeter data (colored orange) from the Atacama Pathfinder Experiment (APEX) telescope in Chile and X-ray data (colored blue) from the Chandra X-ray Observatory. Visible light data from the Wide Field Imager on the Max-Planck/ESO 2.2 m telescope, also located in Chile, shows the dust lane in the galaxy and background stars. The X-ray jet in the upper left extends for about 13,000 light years away from the black hole. The APEX data shows that material in the jet is traveling at about half the speed of light. Credit: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)







$r_{in} = 0.1; r_{out} = 1$

$\varphi = 0;2\pi$

$V = 0$

$H/R = 12;$

12 $Bz/B\varphi = 0,0.01,0.02,..,0.4,..$

$Br = 0$

$V_{A\varphi}/cs = 0.1;0.5$

$cs = 10;50$

Ivanovski et al. 2009

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

T Tauri stars

- T Tauri stars are found in Galactic regions of star formation

  Sometimes they are associated with jets and HH objects

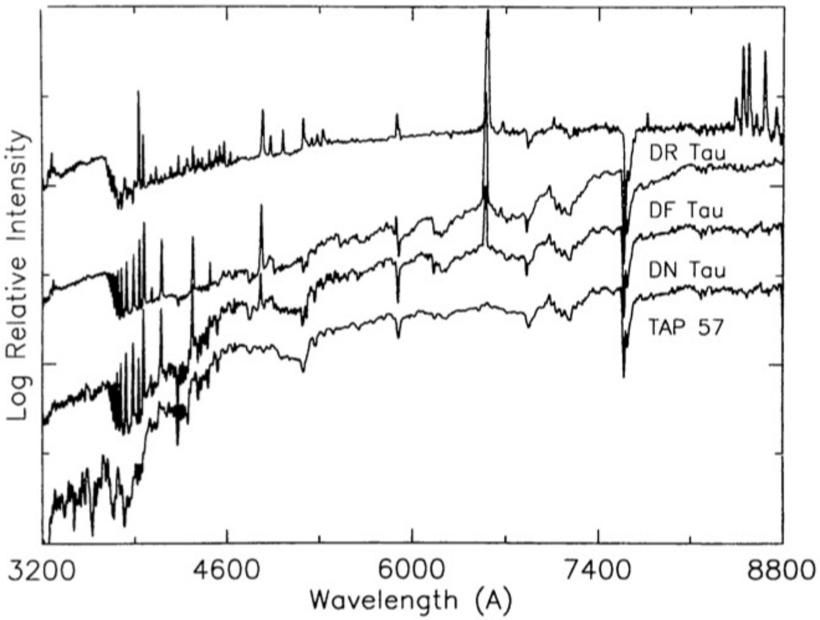
- The optical spectra of T Tauri stars indicate that they are late-type stars, with a series of peculiar characteristics

  Strong emissions of Hα, CaII H & K

    Suggestive of intense chromospheric activity

  P-Cygni profiles

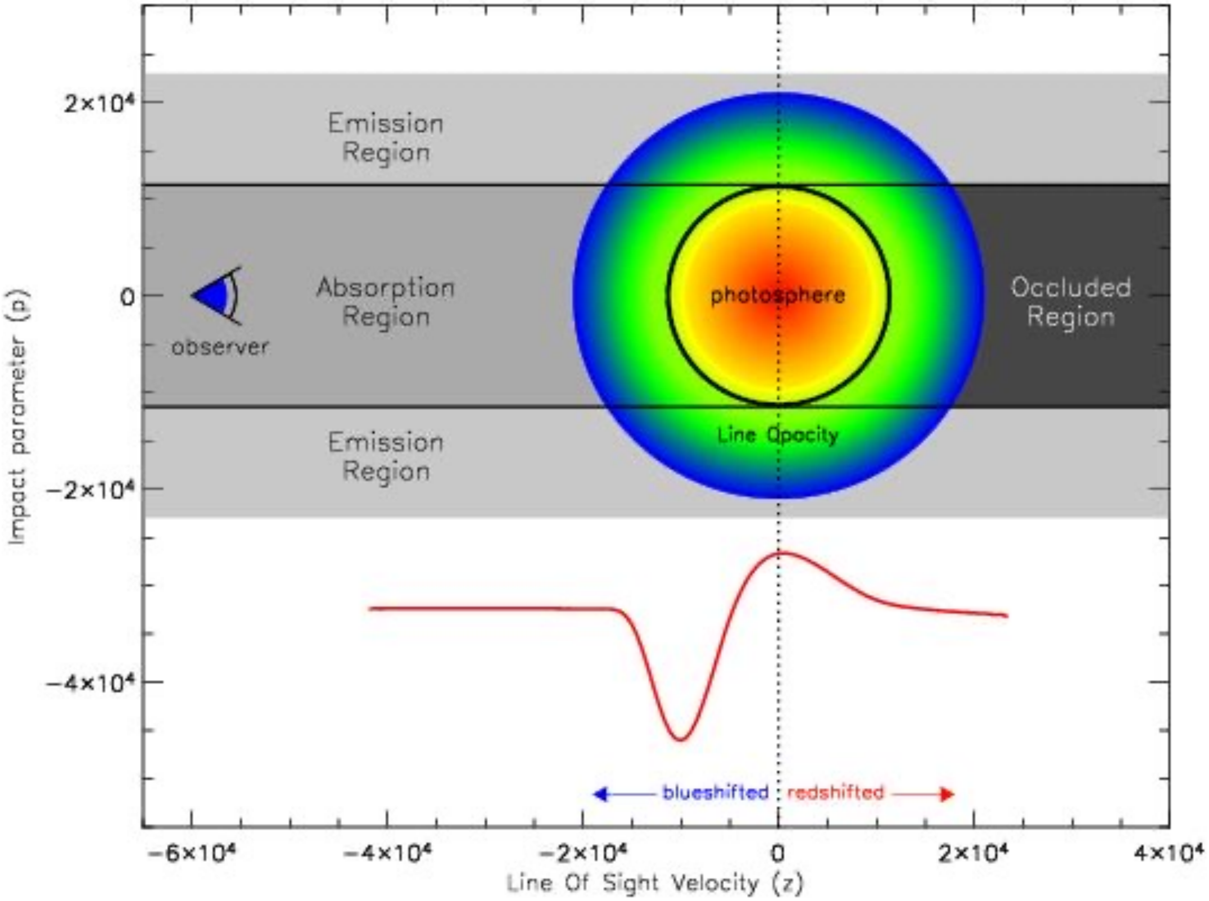
    Suggestive of strong stellar winds



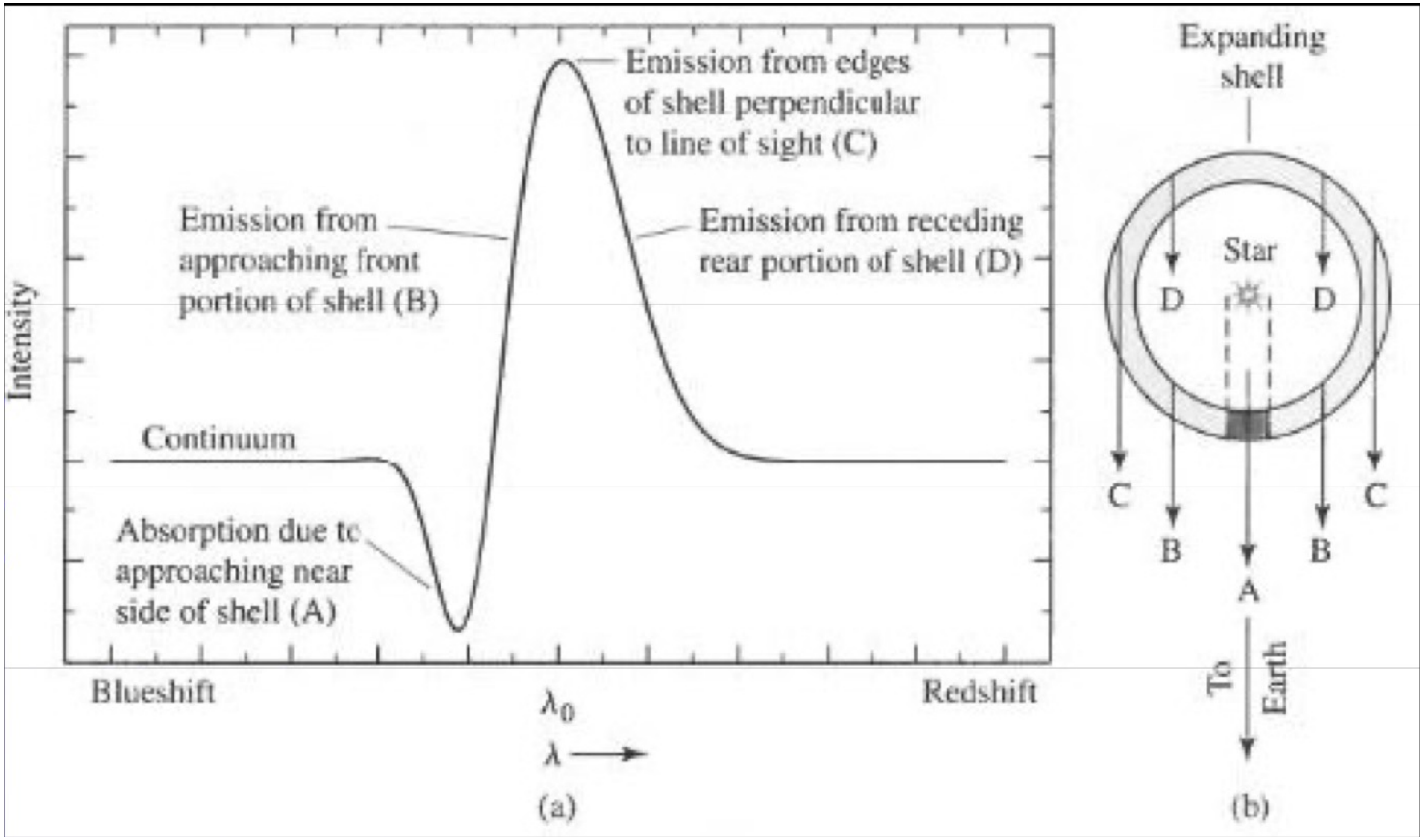
Spectra of T Tauri stars
Bertout (1989)

P-Cygni profiles

- Signatures of stellar gas outflows (stellar winds)



P-Cygni profiles



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 magnetohydrodynamical 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

T Tauri stars

- Observations in other spectral bands confirm the peculiar nature of T Tauri stars
  - They often show infrared excess (1-10 μm)
    - Indicative of cold dust
  - They emit in the X-ray band
    - Indicative of coronal gas with very high temperature (~10^6 K)
- There are two types of T Tauri stars:
  - Classic T Tauri stars
    - Strong Hα emission line
    - Infrared excess (1-10 μm)
  - Weak-line T Tauri stars
    - Discovered in X rays
    - Weak Hα emission
    - <u>Without</u> infrared excess

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

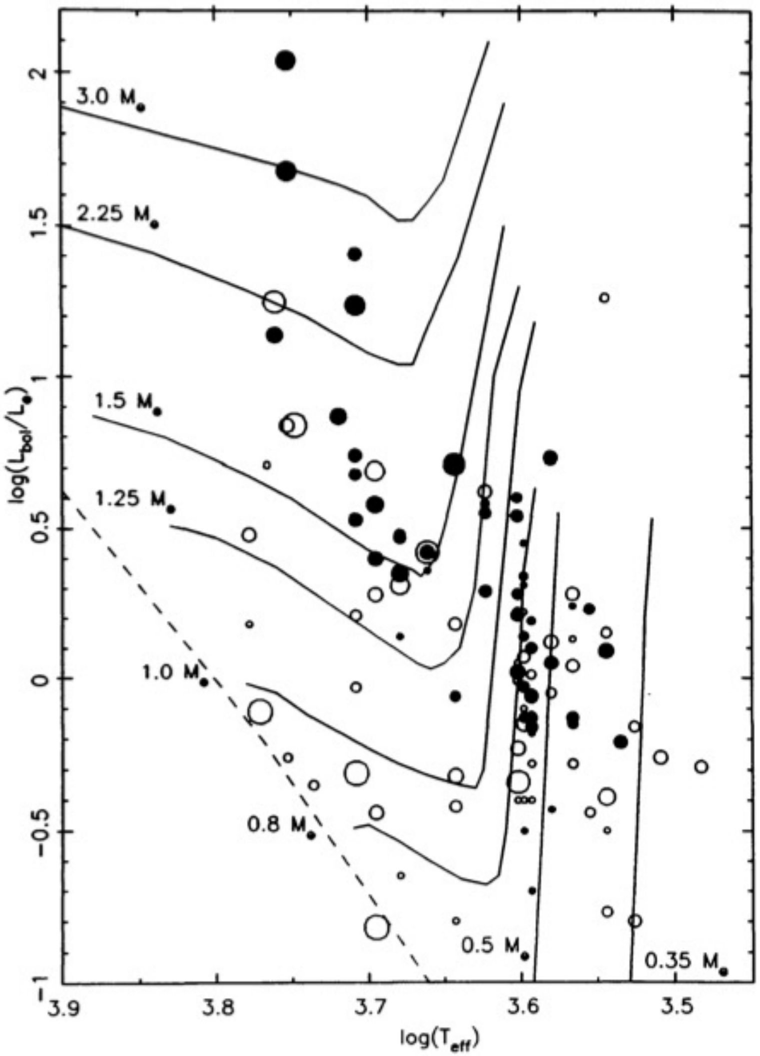
      Filled circles: classic T Tauri

      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)