Properties of YSOs

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A671

Protostellar disks in Orion, HST image
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Young Stellar Objects (YSOs)

- YSOs = stars in the earliest stages of development
- Majority form from “clumps” or “cores” in Giant Molecular Clouds (GMCs) in the ISM and Galactic Nuclei
  (Some YSOs may also be found in Bok globules and diffuse (or translucent) molecular clouds)
- Typically form in pairs or clusters
- Life of YSO can be divided into two main stages:
  1. “Protostar”
     - Embedded in infalling envelope of gas & dust; optically thick disk
     - SED peak in submm & FIR
  2. “Pre-main sequence star”
     - Decrease in accretion; envelope shed/dissolved; optically thin disk; “T Tauri star”
     - SED peak in visible & NIR
- Five Observational Classes (for low- to mid-mass YSO):
Class 0: massive infalling gas and dust envelope, deeply embedded protostar, main accretion phase, molecular outflows, FIR and submm emission

Class I: infalling envelope (∼10⁴ AU) + optically thick disk (∼ a few 100 AU), luminosity from disk accretion shock, bipolar outflows, infrared emission

Class IIa: optically thick disk, residual envelope, strong stellar wind, disk accretion, outflows, NIR and MIR excess, strong Hα emission

Class IIb: “classical” T Tauri star (sometimes “weak-lined” T Tauri star), optically thin disk, decrease in accretion, stellar wind, strong surface magnetic activity; start of planet formation?

Class III: naked T Tauri star (post T Tauri phase), very little gas and dust in disk, contraction towards main-sequence

(diagram adapted from Wilking, 1989, PASP, 101, 229) (Slide adapted from a presentation by Elise Furlan)
Molecular Clouds (MCs)

Properties of GMCs

- Optically thick ($a_v > 1$) $\Rightarrow$ shields H atoms from UV radiation
  - Due to dust (also provides good site for H atoms to bond)
  - Due to HI shell (PDR) (when $N_{HI} \sim 10^{21}$ cm$^{-2}$)
- Cold (10-30K)
  - Atoms bond into molecules
  - Coldest objects in the Universe
- Chemical composition similar to Sun:
  - $\sim$75% H$_2$ (difficult to observe, CO used as tracer)
  - $\sim$23% He
  - $\sim$2% dust (including PAHs), CO, H$_2$O, & many others (radio observations have detected over 50 different molecules in ISM)
- $n \sim 100 - 300$ cm$^{-3}$
- $M \sim 10^5 - 10^6$ $M_\odot$
- $\sim$ 50-100 pc typical size
- 1000s of GMCs known to exist in Milky Way, mostly in spiral arms
Molecular Clouds (MCs)

- GMCs contain regions with hot dense cores (10% of GMC mass)
  - $r \sim 0.05 - 1$ pc
  - $a_v \sim 50 - 1000$
  - $T \sim 100 - 200$ K
  - $n \sim 10^4 - 10^9$ cm$^{-3}$
  - $M \sim 10 - 1000$ M$_\odot$

- Protostars originate in such regions

Diagram from Stacey A671 lecture, 1/25/06
Birth of Protostar: Class 0

- No complete theory of stellar origins
- Protostar forms from gravitational collapse of dense GMC cores
  - Triggered by shock (?) from: supernova explosion; ionized gas expanding around hot star; galactic spiral density wave ?
  - “Jeans Criterion”:

  \[
  \text{Gravitational Energy} > \text{Thermal Energy of a volume of gas} \\
  \equiv \text{Mass of cloud} > \text{Jeans Mass} \\
  \equiv M_c > M_J \approx (5kT / G\mu m_H)^{3/2} (3 / 4\pi \rho_0)^{1/2}
  \]

  \[
  [\mu = \text{mean molecular weight}; m_H = \text{H atomic mass}; \rho_0 = \text{cloud density}] \quad (\text{Carroll & Ostlie 12.7})
  \]

- Ignores effects of rotation (angular momentum), deviation from spherical symmetry, and magnetic fields.
- Is still good “rough” estimate of conditions of gravitational collapse
Birth of Protostar: Class 0

Once Jeans Criterion is satisfied...

- Initially MC is optically thin to FIR & submm such that gravitational potential energy can be radiated away
  ⇒ *Isothermal* dynamical collapse

  \[ L_{\text{accretion}} = \frac{GM_\star \dot{M}}{R_\star} \]
  \[ \dot{M} = m_0 a^3 / G \]

  \[ [ a = \text{effective sound speed}; m_0 = \text{constant} \sim 1 ] \quad \text{(Lada, 2001)} \]

- Collapsing MC is in *freefall*:

  \[ t_{\text{ff}} = \left( \frac{3\pi}{32G\rho_0} \right)^{1/2} = \text{free-fall time} \quad \text{(Carroll & Ostlie 12.16)} \]

  - For typical mean density \((n \sim 10^4 \, \text{cm}^{-3})\), \(t_{\text{ff}} \sim 4 \times 10^5 \, \text{yr}\)
  - Center will collapse faster than exterior = *non-homologous collapse*
Birth of Protostar: Class 0

- **Fragmentation**
  - Mass of infalling envelope within a GMC could well exceed $M_J$ limit
  - Initial inhomogeneities ⇒ sections of collapsing envelope will individually satisfy $M_J$ limit and collapse locally
  - Explains clusters of stars and lack of extremely high-mass stars

- Once core $\rho \sim 10^{-13} \text{ g cm}^{-3}$, the region become optically thick and the collapse becomes adiabatic rather than isothermal (gravitational energy cannot be radiated away, and is conserved)
  - Rate of contraction in core slows & $T$ rises
  - Core is in hydrostatic equilibrium with radius $\sim 5\text{AU}$

⇒ “PROTOTSTAR” is born
Birth of Protostar: Class 0

- **Rotation**: as envelope collapses, the core begins to spin
  - Initial envelope has some total angular momentum (L) which = sum of individual L’s of constituent molecules
  - Collapse + conservation of L \(\Rightarrow\) rotation
- **Bipolar molecular outflows** (“jets”)
  - Very energetic flows of cold molecular gas (discovered via mm observations in 1970s and 80s)
  - Two spatially separate lobes moving diametrically away from an embedded YSO at hypersonic speeds, \(\perp\) to rotation plane
  - Origin uncertain: manifestation of underlying primary wind generated by protostellar core
Birth of Protostar: Class 0

- Protostellar core is extremely extinguished and embedded
  - SED has width similar to single-temperature BB function with very low temperature (~30K); peaks in submm

- Class 0 YSOs are extremely rare (~10% of embedded sources)
  ⇒ lifetime \(~ 10^4\) yr. (consistent with dynamical estimates of their associated outflows)
Class I

Above adiabatic protostar core, isothermal free-fall accretion continues; core $\rho$ and $T$ continue to increase

When free-falling material meets hydrostatic core, a supersonic shock front develops

Primary stellar winds increase

- Bipolar Jets mass $>$ YSO mass $\Rightarrow$ Jet consists of swept-up material, not ejecta; Jets extend $\sim$ 1 pc, hypersonic velocity
- Herbig-Haro objects: clumps of shock-excited gas from collision of primary wind with dense ambient cloud material; can extend up to 1 pc
- Circumstellar Jets: very close to protostellar object ($<$50AU); most common manifestation of primary wind; contain hot ionized gas, shaped like extended bow shocks that frequently terminate at Herbig-Haro objects
- H$_2$O masers: small dense areas where microwave transitions in H$_2$O are nonlinearly amplified by stimulated emission
**Class I**

- Rotation increases $\Rightarrow$ circum-protostellar disk forms
  - Optically thick
  - $\sim$ few 100 AU

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Class I YSO

Herbig-Haro object in HH555 in the Pelican Nebula (NOAO: http://www.noao.edu/outreach/pres/s/pr03/pr0308.html#sb-return)
Class I

- SED is broader than single-T BB function and shows MIR & NIR excess
  - Excess IR comes from large amounts of circum-protostellar dust
  - 10 um silicate absorption feature clearly present
  - ~50% of Class I sources exhibit atomic emission lines in NIR, but otherwise spectra are featureless and heavily veiled.

- Class I sources are rare among YSOs in MCs ⇒ statistical arguments suggest ages \( \sim 1 - 5 \times 10^5 \) yr

Class I SED
Class Ila

- Disk accretion continues
- Optically thick disk is fully developed
- Stellar winds very strong
  - Causes envelope to shed/dissipate
- NIR & Optical excess
  - 10μm feature still visible

Class Ila SED

Class Ila YSO
HR-diagram for $1M_\odot$ Protostar (Classes 0, I, & IIa)

**Figure 12.7** A theoretical evolutionary track of the gravitational collapse of a $1\,M_\odot$ cloud through the protostar phase (times are labeled in years since the development of a hydrostatic core). The dashed line shows the quasi-hydrostatic evolution of a pre-main-sequence star, beginning on the Hayashi track. Also shown is a portion of the zero-age main sequence (ZAMS). Both the Hayashi track and the ZAMS are discussed in Section 12.3. (Figure from Appenzeller and Tscharnuter, *Astron. Astrophys.*, 40, 397, 1975.)
Protostar to Pre-Main Seq Star: Class IIb

- T reaches ~1000K → Dust vaporizes → opacity drops → T rises
- T reaches ~2000K → H₂ dissociates → absorbs energy necessary for hydrostatic equil. → Second Collapse (R drops ~30%) → Second supersonic shock → hydrostatic equil. reestablished
- Strong surface magnetic activity → slows rotation rate through interaction with disk
- By now accretion and stellar winds have removed what is left of envelope → Accretion rate slows due to lack of infalling matter
- Optically thick circum-protostellar disk → Optically thin protoplanetary disk (Proplyd); planet formation starts (?)
- Optical observations possible

Protostar becomes a Classical T Tauri Star (CTTS) (Protostar → Pre-Main Sequence Star)
Protostar to Pre Main-Seq Star: Class IIb

CTTSs show emission from H-Balmer series, Ca II, iron, absorption lines in Li, and forbidden lines of [OI] and [SII] (⇒ low gas densities)

SED
- peaks in visible or NIR, with some UV excess
- broader than single BB function
- >2µm → falls in power-law fashion
  - If disk has concentric annuli with area $2\pi R\Delta R$, spectrum will be series of BB curves with $n \sim T(R) \sim R^{-n}$
  - Luminosity radiated by an annulus is $L_\nu d\nu = 2\pi R dR \sigma T(R) \sim R^{2-3n} d\nu$
    - $\sim \nu^{3-2/n} \Rightarrow \nu L_\nu \sim \nu^{4-2/n}$
  - ⇒ IR excess arises in circumstellar disk, slope directly related to $T$ gradient in disk (values ~ -0.7 to -1.3).

- Age ~ few $10^6$ yr
Protostar to Pre-Main Seq Star: Class IIb

Power law dist of SED (Lada, 2001)

Class IIb SED

Class IIb YSO
Class III

Called Post-T Tauri Star (PTTS) or Weak-lined T Tauri Star (WTTS)

- SED
  - peaks in visible and NIR and > 2μm drops more steeply than Class II.
  - ~ single-T BB ⇒ ~ photoshpere of young star
  - However light could still be substantially extinguished by dust
- Little or no Hα emission (optical astronomers: equiv. width > 10Å = CTTS; equiv. width < 10Å = WTTS)
- X-ray emission: strong variable source
- Age > 5 x 10⁶ yr
- T → 10MK ⇒ H fusion ≡ Main-Sequence Star

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A Note on High-Mass Stars

- Previous discussion applies to stars < 7-8 \( M_\odot \).
- Stars > 7-8 \( M_\odot \) have very different evolution:
  - Timescale for H-burning = Kelvin-Helmholtz time = \( t_{KH} = \frac{GM_\star^2}{R_\star L_\star} \) (Lada, 2001)
    - \( \sim 10^4 \) yr for \( M_\star = 50 \ M_\odot \)
    - \( \sim 3 \times 10^7 \) yr for \( M_\star = 1 \ M_\odot \)
  - Recall typical free-fall time \( t_{ff} \sim 4 \times 10^5 \) yr
  - \( \Rightarrow \) reach main-sequence before termination of collapse of protostellar envelope
References

  (pdf article available on NASA ADS)