Lecture 14
Star Formation II(I): Protostars->ZAMS
14 November 2013
Announcements

• Project Proposals: due NOW
• HW #6 due tomorrow
• HW #7 – last one! – posted on Friday
• Reminder – NO lecture next Tuesday, will be swapped with Discussion Section
  – Q: do you want to have a discussion section on Tuesday (only if Petia is available)?
• First observing lab(s) next Thursday
Lecture 14: Star Formation I:
Protostars & Main Sequence Evolution
14 November 2013

PRELIMS
• Announcements [5 min]

MATERIAL [75 min]
• [15 min] Review
• [30 min] PMS evolution – halt of fragmentation, trajectory onto MS
• [25 min] Protostar classes
• [10 min] Planet formation

DEMONSTRATIONS/EXERCISES

MATERIALS
Review

• threshold for collapse: gravity > thermal pressure => Jeans criterion: 
  \[ M_J \sim 9 \times 10^4 \ T^{-1.5} \ \mu^{-2} \ n^{-0.5} \ M_\odot \]
  
  \[ \text{NOTE: I GOT THIS QUITE WRONG IN CLASS!} \]

• gravity keeps winning! Homologous collapse “free fall” – star has an e-folding time of 300,000 yr

• fragmentation is a major factor here [MOVIE]

• B fields can also influence jean’s collapse – magnetic pressure support (only when the gas gets hot enough!)

Pre-main sequence evolution

• Where is initial starting point?
  
  \[ T = 10 \ \text{K} \ \text{GMC} \]
  
  \[ L = 4\pi(0.1 \ \text{pc})^2 \sigma T^4 \approx 250 \ \text{L}_\odot \]

• When do we stop collapsing?
  
  \[ \text{Had assumed isothermal => perfect release of heat gained from infall => constant } T \text{, declining } L \text{ (as } R \text{ decreases)} \]
  
  \[ \text{Eventually the heat cannot get out (optical depth scales with density)} \]
  
  \[ \text{Consider opposite extreme: adiabatic collapse => energy is distributed through the system} \]
  
  \[ \text{Polytrope: } P \sim \rho^\gamma \Rightarrow T \sim \rho^{1/\gamma} \]
  
  \[ \text{Substitute in Jean’s relation: } M_J \sim \rho^{1.5\gamma^{-2}} \]
  
  \[ \gamma = C_p/C_v = 5/3 \text{ for atomic H gas } \Rightarrow M_J \sim \rho^{1/2} \]
  
  \[ \text{increases as density goes up! } \Rightarrow \text{star can no longer fragment – this is its size} \]

• When does this happen?
  
  \[ \text{Assume } L_{ff} = \Delta E_{ff}/t_{ff} \approx G^{3/2} \ M^{5/2} \ R^{-5.2} \]
  
  \[ L_{\text{rad}} = 4\pi R^2 \sigma T^4 e \text{ <--- efficiency of radiative cooling} \]
  
  \[ \text{Rearrange to solve for mass} \]
  
  \[ \text{We end up with a minimum fragment of } \sim 0.5 \ \text{Msun – this will turn out to be the peak of the mass function} \]
There is a smaller mass scale that limits whether a clump of gas can cool at all – opacity limit, few Jupiter masses – minimum brown dwarf mass?

- Subsequent evolution
  - adiabatic Hayashi track – R declines, T increases – this is our \( n = 1.5 \) polytrope model
  - ignition – radiative core forms, changes to \( n = 3 \)
    - interior polytrop => Henyey track (L constant from rxns, R decreases, T shoots up)
  - eventually settles onto main sequence

Protostars
- Protostellar classes – depends on disk [IMAGES]
  - Why a disk? Conservation of L
  - delineate classes and SEDs
  - Timescales – based on frequency of systems, ages of clusters where found
- Disk structure and emission
  - Optically thick flat & flared disks – why flare?
  - Optically thin debris disks
  - SEDs of disks
- Protostellar jets
  - Herbig Haro objects [IMAGES]
  - Origin – X-wind vs. D-wind,
  - acceleration/collimation by B-fields (still uncertain)
  - Observation in forbidden emission lines
  - “Solves” angular momentum problem (kind of)

Formation of planets from disk
- Incidence of planets in the Galaxy \( \approx 20\% \)
- Evidence of connection
  - Planar distribution (except Pluto)
  - Orbits in same direction as solar rotation
Direct observation of planets in disks [IMAGE OF BETA PIC, FOMALHAUT b]

- Standard model [REF?]
  - temperature gradient – what is “solid”
  - build up of dust->rocks->planetessimals
  - runaway accretion for giant planets
  - spacing – Hill sphere
  - timescales – fast!

- “alternative planets” [IMAGES]
  - Hot Jupiters – migration
  - Close eccentric planets – perturbation from external companion
  - Pulsar planets – remnants of explosion?
  - Wide planets – planets or brown dwarfs?
  - “Tatooine” from Kepler
Pre Main Sequence Evolution

Low, moderate & high-mass stars have slightly different evolutionary stages on their way to being stable main sequence stars. The collapse time, however, is well approximated by the Kelvin-Helmholtz time

\[ t_{KH} = \frac{1}{2} \frac{\Delta m}{L} \approx 20 \text{ Myr for Sun vs. 400 Myr from modeling} \]

The trajectories of stellar RMS evolution can be mapped onto the HR diagram:

Spectral Energy Distributions of young stars reflect both stellar surface contributions and environment – in particular disks & jets are important.

We classify protostars into different classes based on the importance of disk emission in SED.
Class O: object: collapsing protostar

Class I: embedded protostar \((t \sim 10^4-10^5 \text{ yr})\)

Jets clear hole in cloud

Thick disk obscures star

Class II: T Tauri star (protostar with disk) \(t \sim 10^5-10^6 \text{ yr}\)

Class III: debris disk, pre main sequence \((t \sim 10^6-10^7 \text{ yr})\)
adapted from Wilking (1989, PASP, 101, 229)
Emission from a dish

The thermal emission from a circumstellar disk can be approximated by energy balance: flux incident = flux emitted

\[ \text{incident flux} = \sigma T^4 \left( \frac{R^*}{a} \right)^2 \left( \frac{a}{d} \right) \]

for \( d \ll 1 \) (\( a \gg R \))

\[ \text{emitted flux} = \sigma T^4 \]

\[ \Rightarrow T = T^* \left( \frac{R^*}{a} \right)^{1/4} \left( \frac{a}{d} \right)^{1/4} \]

\[ \text{emitted luminosity} = 4\pi d^2 B(T(a)) \]

\[ = 8\pi d^2 \int_{\text{out}} \text{da} \text{ a B}(T(a)) \]

\[ = \alpha L^* \]

In hydrostatic equilibrium, outer disk is more "flared" due to weaker \( T \)-component & gravity (less mass) - this is observed in shadowed disks.

Gaps (a also form in disk from spiral density waves & planet contraception - this also leaves impacts on SED.

\[ * \text{see Chiang + Goldreich (1997)} \]
flared disk & jet  flat disk  debris disk

Time
A critical component of young protostars is the formation of axial jets that punch away the envelope and release material back into ISM. These jets are highly collimated by magnetic fields. There are currently two models to explain the launching of jet material:

**X-model:** Magnetic field at star connects with disk, and the two co-rotate. Material is ejected along open field lines from connection point (X-region)

**D-model:** Material is launched directly from disk along field lines—emission from wide region

These jets extend well away from star; when they slam into surrounding media, they create Herbig-Haro objects (nebulae); these vary on yearly timescales.

The jets and disk interaction also helps shed angular momentum—a cloud must shed 4-6 orders of magnitude of L to create a star that won't break up! (the Sun loses another 100x L through stellar winds)
Protostar HH-34 in Orion (VLT KUEYEN + FORS2)

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ESO PR Photo 406/99 (17 November 1999)
The Initial Mass Function

The product of star formation is a distribution of stars of given mass, each of which has a lifetime set by its mass and composition. This distribution is the mass function, and is distinguished by "birth" $MF = \text{initial mass function}$ at today's $MF = \text{present-day mass function}$.

Historic note: extrapolate Salpeter MF to $\sim 1 \text{M}_\odot$, and you can account for all dark matter in the Galaxy! This was original driving force to find brown dwarfs, but it was clear by 1970s that the MF turned out

Is the IMF Universal? Most indications point to IMF shape being the same for a wide variety of Galactic environments, but might be different in extreme star forming regions (Population III, starburst galaxies). The shape may depend purely on equation of state of gas ($\neq$ universal).