Reading: Chapter 21, through 21.3; Chapter 22, Sect. 22.4-22.5
HW 5: Web Reading (due in recitation March 7)
OBAFGKM Contest: a better mnemonic for OBAFGKM? entries due Today

Last time: **How stars evolve and how we know**

- M-L relation tells us that massive stars ‘die’ sooner
- Stellar lifetimes are very long. But what happens when they ‘die?’
- Star clusters reveal what happens to stars as they age and die
- After running out of hydrogen, stars become red giants

**Today: How stars form**

- Clues from observations - planets, young stars, and the ISM in the IR
- Gravity (somehow) overwhelms pressure, causing clouds to collapse
- Young stars shine via gravity, then finally ignite hydrogen
- Pre-main sequence stars are accompanied by disks, forming planets

### Formation of Stars

- **Where to begin?**
  - Evidence from our current Solar System
  - Evidence from the Stars
- **First phases: collapse to star plus disk**
  - interstellar cloud – gravity takes over
  - angular momentum – disk formation
- **The Solar Nebula**
  - mass and composition
  - temperature distribution
- **Planet formation**
  - condensation
  - accretion into planetessimals
  - accretion into planets and satellites
Where to begin?

- Evidence from our current Solar System
  - all planetary orbits are
    - counterclockwise
    - nearly circular
    - in the same plane
  - inner planets are rocky
  - outer planets are gas balls

- Evidence from the Stars
  - there are many other solar systems
  - there are many multiple star systems
  - youngest stars are embedded in dust and gas

Stars from by collapse of interstellar gas & dust

- Average Interstellar medium (ISM) conditions:
  - density: a few atoms / cc (air: $10^{18}$ atoms/cc)
  - temperature ~ 100K
  - composition: 75% hydrogen

- Molecular Clouds: clumps of (ISM)
  - density: up to $10^4$ / cc
  - mass: up to $10^6$ M$_\text{Sun}$
  - radius ~ 10 - 30 pc
  - temperature ~ 10K
  - composition:
    - dust
    - molecules H$_2$, H$_2$O, CO, NH$_2$CH$_2$COOH (amino acids), C$_2$H$_5$OH (ethanol)...
First phase: collapse of interstellar cloud

- To make stars, a cloud must undergo **Gravitational Collapse**

- How do you initiate the collapse?
  - **increase density** (kick the cloud)
    - cloud collisions
    - stellar wind sweeping
    - nearby supernovae
  - **fragmentation**
    - initial collapse of large cloud ($M > 300$ Msun)
    - density increases
    - smaller fragments begin their own collapse
    - a star cluster?
From Cloud to Star - theory

- **Cloud Cores:**
  - Dense knots within fragments; seeds of protostars

- **The Protostar Phase**
  - initial collapse is fast (< $10^5$ yr)
  - core heats up $\rightarrow$ pressure balances gravity
  - slow contraction $\rightarrow$ grav. energy ($10^6$) yr

- **The Pre-Main Sequence Phase**
  - larger (still) than M.S. stars
  - more luminous than M.S. stars
  - cooler than M.S. stars
  - still too cool for nuclear burning
  - $10^7$ yr - core hot enough $>$ H ignition (in pre-Sun)
  - $3 \times 10^7$ years - $1 \, M_{\odot}$ star settles onto M.S.
  - more massive stars reach M.S. faster

From Cloud to Star - observation

- **Mostly seen in IR:**
  - loads of dust in surrounding clouds
  - dust opaque to optical wavelengths
  - dust heated to 1000K: “thermal” IR
  - in optical: dark knots against bright background

- **Collapse $\rightarrow$ Spin-up $\rightarrow$ formation of Disk**
  - consequence of angular momentum conservation
  - bipolar flows of gas
  - HST observations of Orion disks, M16 “eggs”
  - β Pictoris

- **T-Tauri Stars**
  - cool stars with irregular brightness
  - blowing away surrounding dust?
  - evidence of surrounding protoplanetary disk
• **Accretion**
  • grains collide and stick \(\rightarrow\) planetessimals
  • planetesimals grow by further collisions
    • gravity holds them together when big enough
  • some planetesimals eventually become very large
  • final sweeping up into present planets

• **Sun “Turns On”**
  • solar wind blows most of remaining gas away
  • planet growth in protoplanetary disk largely ceases

**Planet Formation - Accretion**

All this took a VERY SHORT time

\[
\text{\textbullet\xspace} \text{less than 100 million years after initial collapse}
\]
HL Tau - a planetary system in formation imaged in sub-mm by ALMA interferometer

Talk at international conference yesterday!

Gallery of Protoplanetary Discs (Radio)

Ojā Panić’s talk: More ALMA results of Herbig Ae/Be stars

Fomalhaut
HST ACS/HRC

Dust ring
Scattered starlight "noise"
Location of Fomalhaut
Coronagraph mask
Fomalhaut b planet

100 AU
13"