Astr 2310 Thurs. March 23, 2017

Today's Topics

- Chapter 16: The Interstellar Medium and Star Formation
        - Interstellar Dust and Dark Nebulae
    - Interstellar Dust
        - Dark Nebulae
        - Interstellar Reddening
        - Interstellar Polarization
        - Reflection Nebulae
        - Properties of Interstellar Grains
    - Interstellar Gas
        - Interstellar Optical Absorption Lines
        - Emission Nebulae: H II Regions
        - Supernovae Remnants
        - Planetary Nebulae
        - Radio Emission Lines
    - Star Formation
        - Basic Physics
        - Molecular Outflows
        - Birth of Massive Stars
        - Birth of Intermediate-Mass Stars
        - Observational Evidence

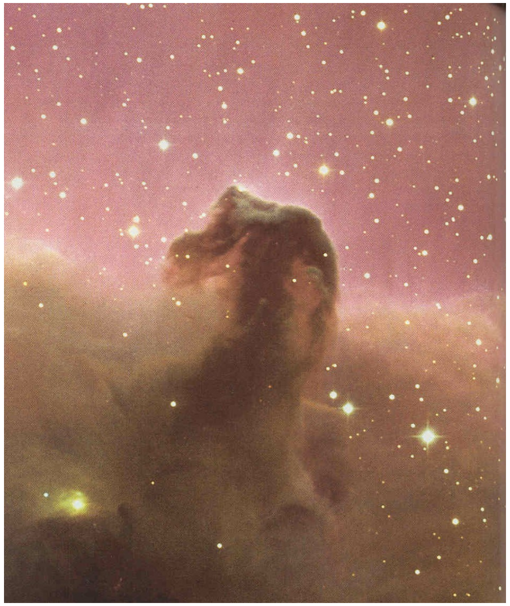
Chapter 16 Homework

Chapter 16: #2, 3, 7, 9

(Due Tues. April 4)

Interstellar Medium Overview

- All available data indicate the composition of the interstellar medium is similar to the Sun's. Cosmic abundance:
- Broadly composed of gas and dust:
  - 73% H, 25% He, 2% "metals" (mostly C, N, O)
  - Gas: detectable via emission lines or absorption lines in stellar spectra
  - Dust: detectable via absorption of starlight, scattering (reflection & polarization), and thermal emission ($\lambda \sim 100\ \mu$m)
  - Gas/Dust is approximately constant.



Dark Nebulae: Compact Dust Clouds

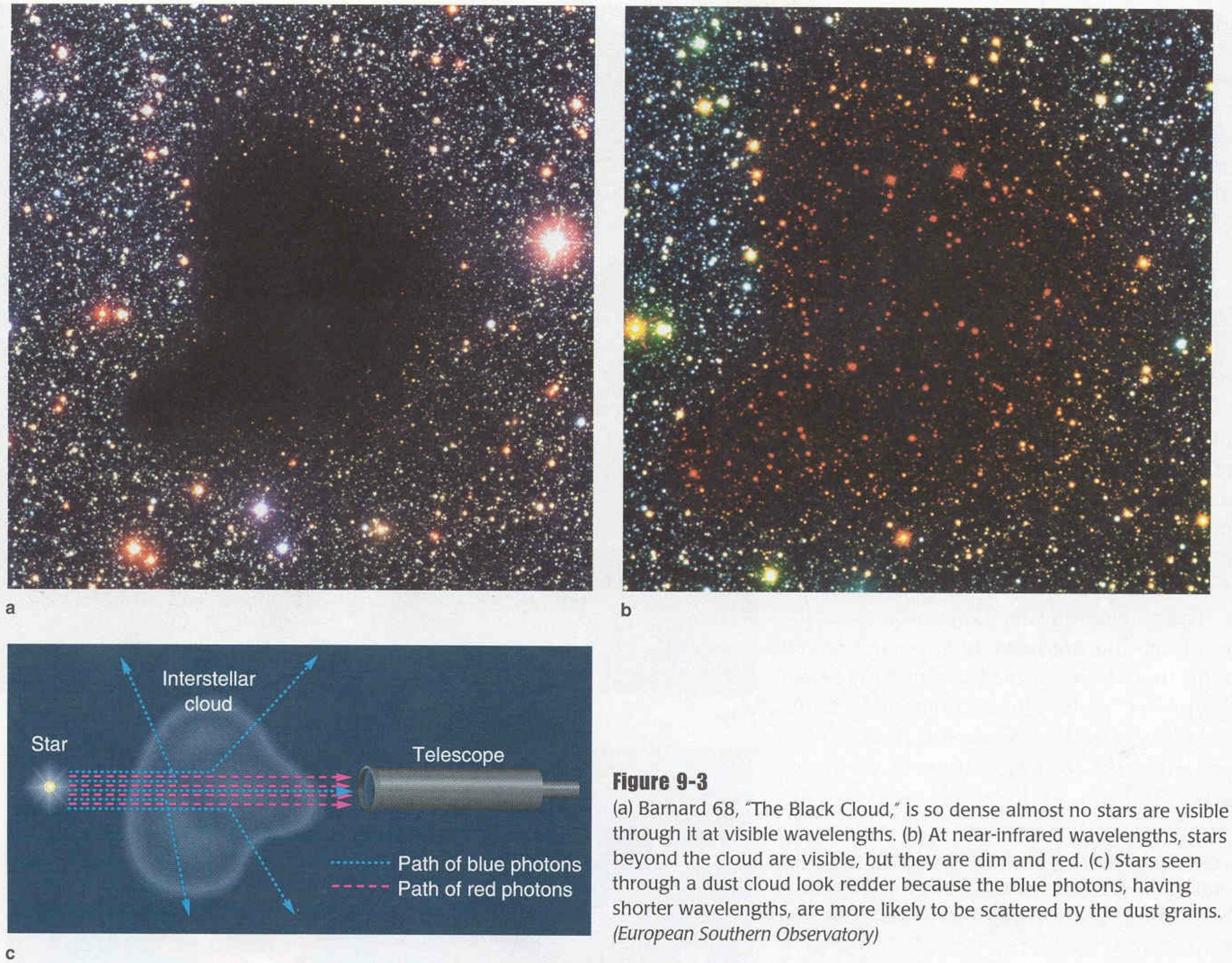


Figure 9-3
(a) Barnard 68, "The Black Cloud," is so dense almost no stars are visible through it at visible wavelengths. (b) At near-infrared wavelengths, stars beyond the cloud are visible, but they are dim and red. (c) Stars seen through a dust cloud look redder because the blue photons, having shorter wavelengths, are more likely to be scattered by the dust grains. *(European Southern Observatory)*

Extinction of Background Starlight

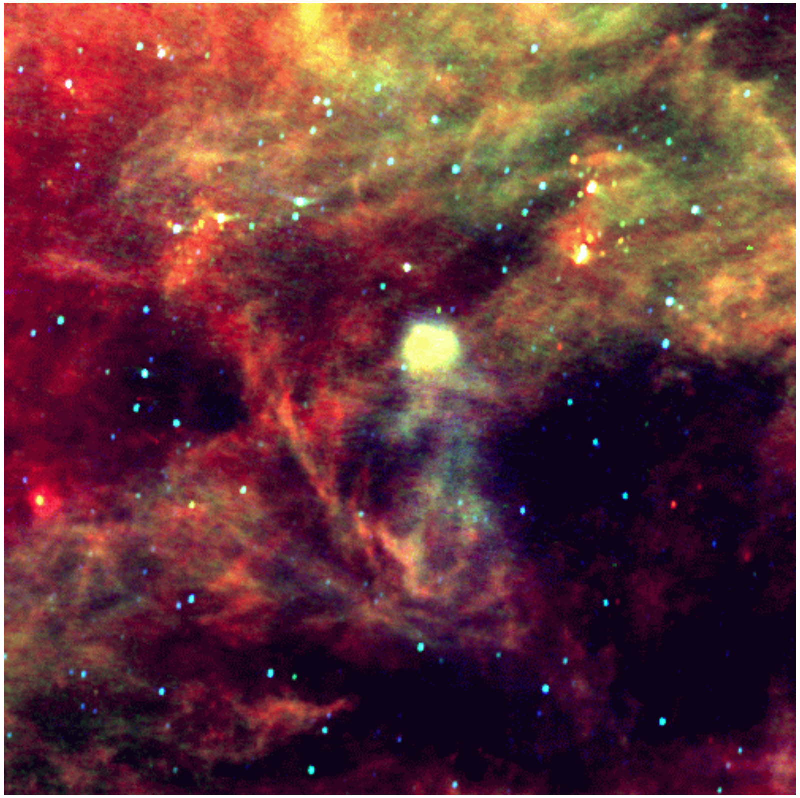
Interstellar Reddening of Background Stars

Interstellar Dust - II

- Interstellar Dust
  - Diffuse Dust
    - Size of Star Clusters vs. Apparent Magnitudes of Stars
    - Must Fill Interstellar Space
    - $m_\lambda - M_\lambda = 5\log(d) - 5 + A_\lambda$
    - A_λ measured via Color-Excess:
      $E(B-V) = (B-V) - (B-V)_0$ and $A_V = 3.1\ E(B-V)$
  - Interstellar Polarization
    - Light is polarized as it traverses the ISM
      - » Dust grains are non-spherical
      - » Magnetic fields align the grains
  - Reflection Nebulae
    - Scattered starlight from nearby stars (polarized)

Direct Detection via Thermal Emission

From our text: Horizons, by Sees



- **Infrared "Cirrus"**
  - **Direct emission from cool dust (far-infrared)**
  - **Multi-wavelength data yields temperature and optical depth**

Nature of Dust Grains

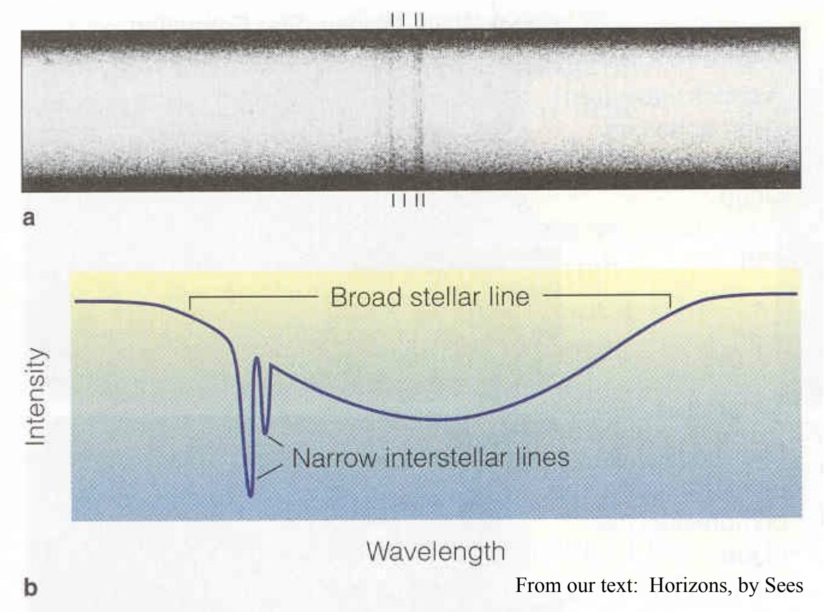
- **Extinction vs. wavelength can constrain size distribution and composition:**
  - **Dust is likely graphite core with silicate and/or icy mantle (infrared absorption and emission)**
  - **PAH: Poly-cyclic Aeromatic Hydrocarbons**

    (Benzene-like rings)
  - **Size: extinction vs. wavelength requires a broad range of wavelength: 0.01 – 0.2 μm in radius**
  - **Origin: Dust can condense at T ~ 1000 K and some cool, luminous giant stars show silicate and carbon absorption features.**

Interstellar Gas

- Interstellar Gas
  - Interstellar Optical Absorption Lines
    - Absorption lines from interstellar gas
    - Hydrogen lines in UV (Lyman lines)
    - Narrow, low ionization “metal” lines in hot stars
      - Velocity difference wrt star
      - Stationary lines in spectroscopic binaries
  - Emission Nebulae: H II Regions, Planetary Nebulae, etc.
    - Hydrogen recombination lines
    - Forbidden lines
  - Radio Emission Lines
    - HI 21-cm lines
    - Molecular Lines

Spectral Absorption Lines



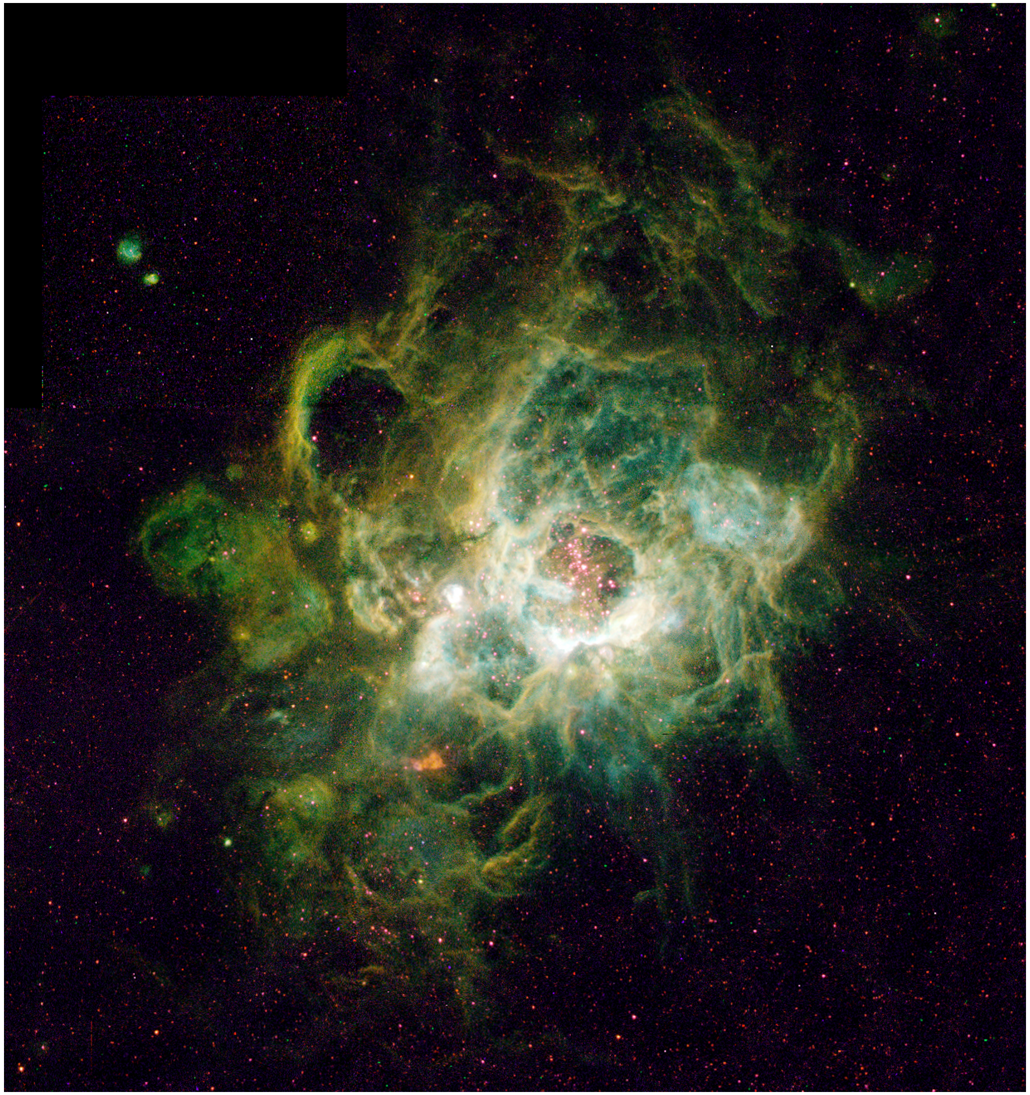
From our text: Horizons, by Sees

- Preset in spectra of stars
- Broad stellar lines (high gas pressure)
- Very narrow (low pressure) lines from interstellar gas
  - This one Ca II $= Ca^{+1}$
- Stronger in more distant stars (larger path length)
- Often seen as distinct interstellar gas clouds with different velocities
- Seen as stationary lines in spectroscopic binaries

- Hydrogen hard to measure (mostly in ground state)

Emission Nebulae: H II Regions

- Hydrogen ionized by UV from bright stars
  - Recombination cascade produces emission lines
  - Other elements can be collisionaly excited
  - Forbidden lines from “meta-stable” states (very low probability transitions) escape nebula
  - Temperature and density sensitivity provide diagnostics
  - Physical conditions of gas
  - UV output of stars

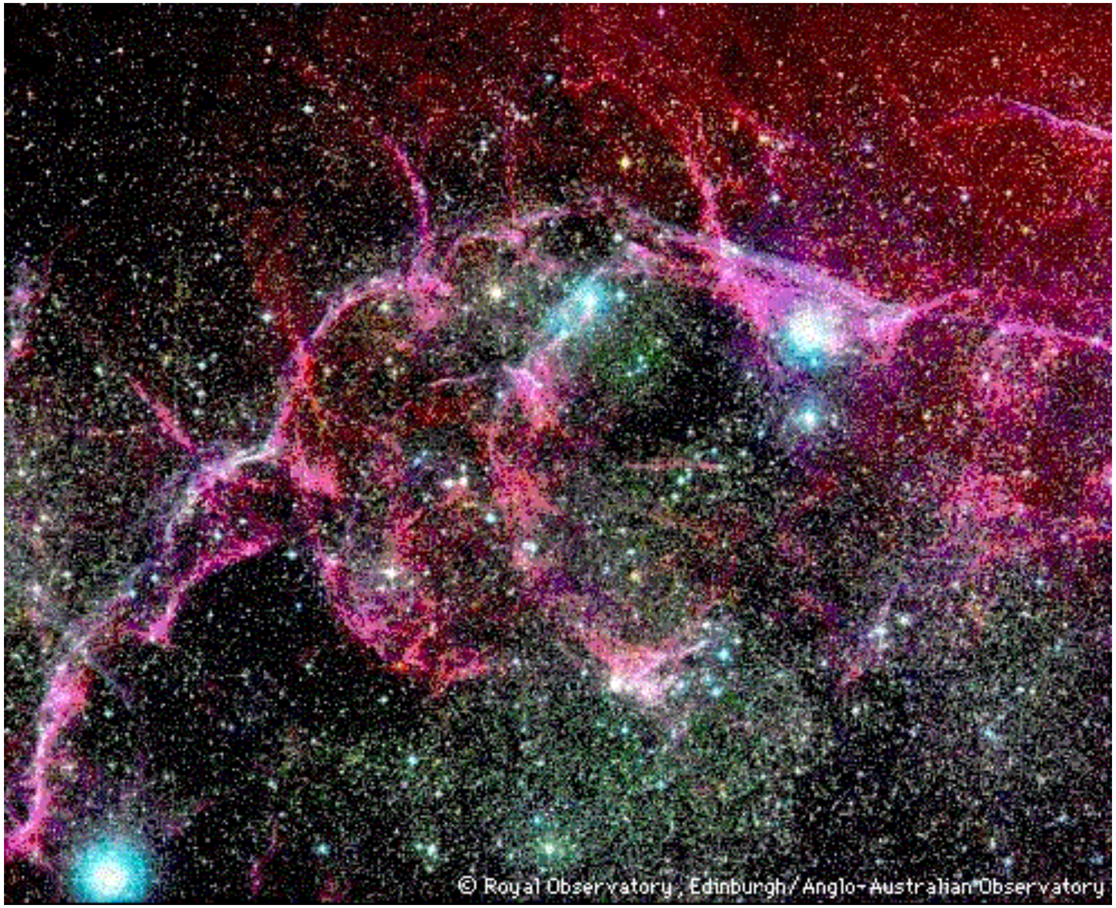


Stromgren Sphere

- Size of an HII region depends on the number of ionizing photons and the density of the cloud.
  - Lifetime of an atom in an excited state is ~ 10^{-8} sec.
  - Most Hydrogen either ionized or in ground state.
  - Cloud is optically thick for $\lambda < 91.2$ nm
    - All these photons absorbed
  - Balmer transitions (n = 2 level) are thus optically thin and can escape
  - Equate number of photoionizations to number of recombinations:
  - $N(UV) = 4\pi/3\ R_s^3 n_e n_H \alpha(2)$ where n_e is the electron density, n_H is the number of protons, $\alpha(2)$ is the recombination rate for the n = 2 level, and R_s is known as the radius of the Stromgren sphere.
  - Thus if the radius and density of the HII region can be estimated we can solve for the number of ionizing photons.

Supernovae Remnants

- Exploding stars (supernovae) produce shock waves
  - Shocks can ionize ISM to high temps
    - X-ray emission
    - High excitation emission lines
  - Enhanced elemental abundances



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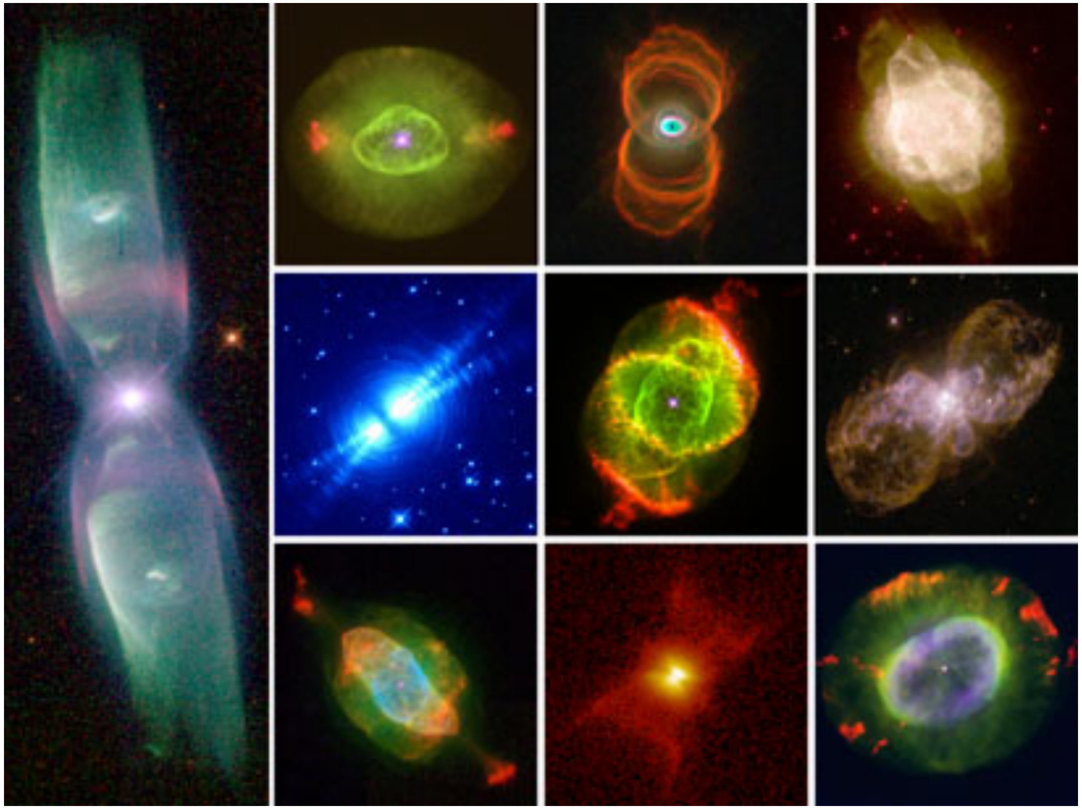
Planetary Nebulae



- Evolved stars can expel their envelopes to reveal their hot cores
  - Intense UV flux from core can ionize expelled envelope
  - Geometry constrains process (binaries, etc.)
  - Ionization models constrain cooling rate

HI 21-cm Emission Line

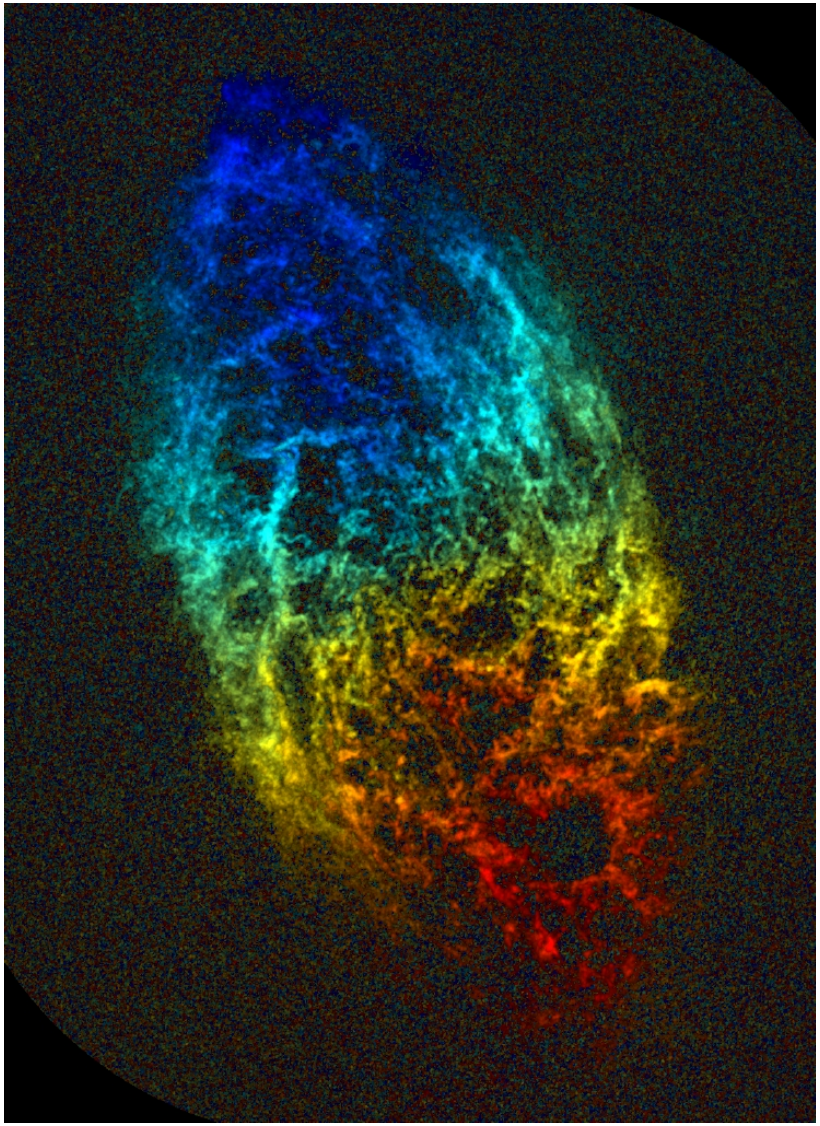
- Protons and electrons have angular momentum (“spin”)
  - Ground state of neutral Hydrogen actually split into two lines
    - Spins parallel has slightly higher energy
    - Spins anti-parallel has lowest energy
  - Collisions can excite Hydrogen atoms
  - Forbidden Transition emits 21-cm photon
    - Characteristic timescale for transition ~ 400 yrs.
    - Low density environments should strongly emit

HI Emission in M33

21-cm map of nearby galaxy M33. Color represents the Doppler shift due to galaxy’s rotation.

The HI is distributed throughout the galaxy in the form of filaments and clouds

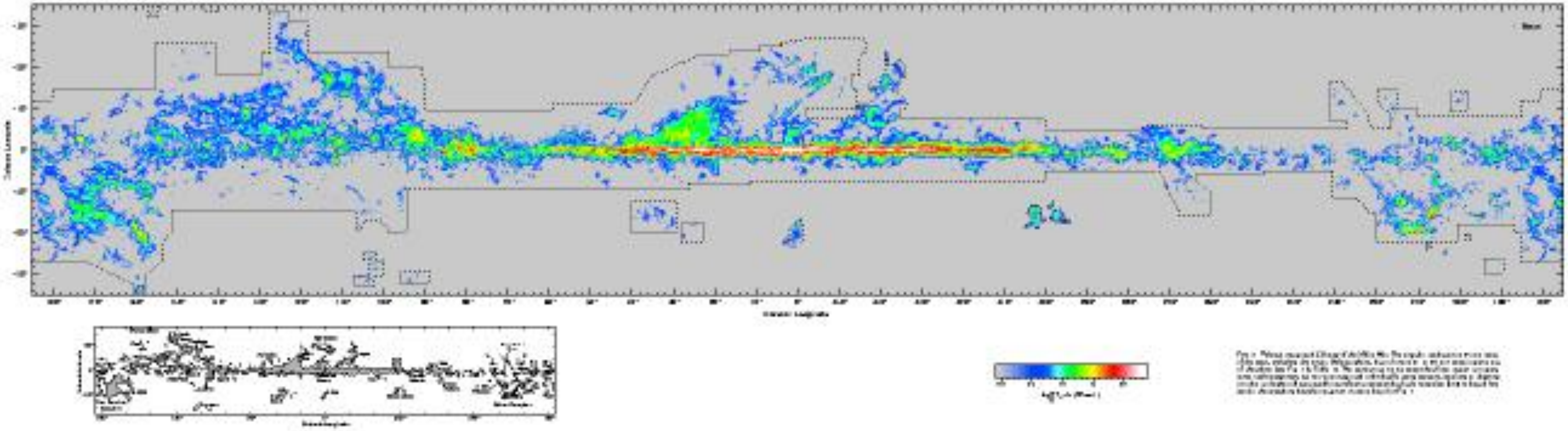
Note the bubble at lower left.

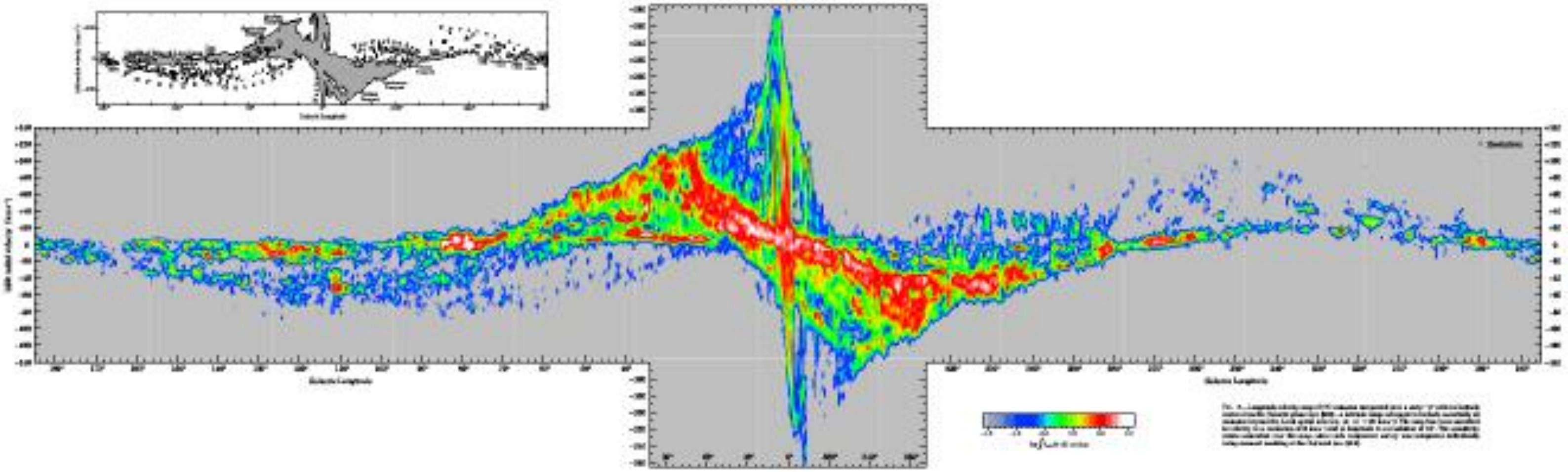


Molecular Emission Lines

- Recall that the quanitization of momentum (quantum mechanics) means molecules can vibrate at only discrete energies
- Molecular vibrations produce rich mm-wave and radio spectrum of emission lines
- H2 is most common but hard to detect (quantum mechanics). CO, OH, CN, CH_3OH, etc. are detectable
  - – Molecular Clouds:
    - Dense: 10^{12} /m^3
    - Cool: T ~ 10 K
    - Masses: $10^4 – 10^7$ M_{Sun}
    - Small scale structure

Milky Way Galaxy in CO





Multi-phase Interstellar Medium

- Interstellar medium is found in multiple phases
  - Pressure balance requires hotter regions to be lower density and vice versa
  - Cold Molecular Clouds (T ~ 10 K)
  - Warm Atomic Hydrogen (T ~ 10^2 K)
  - Hot Ionized Hydrogen (T ~ 10^4 K)
  - Very Hot (T ~ 10^6 K)

Star Formation

- Basic Physics
- Dense Proplyds in Orion
- Molecular Outflows
- Birth of Massive Stars
- Birth of Intermediate-Mass Stars
- Observational Evidence

Basic Physics of Star Formation

- **Size Scale:**
  - **Collapse occurs when gravity overcomes gas pressure (see sec. 15-3 in text)**
  - **Virial Theorm: thermal energy is half the gravitational potential energy:**

$2E_{thermal} = -U$

$E_{thermal} = NkT$, $U = -GMm/R \sim -GM^2/R$

Molecular Hydrogen: $N = M/2m_H$ so:

$2(M/2m_H)kT \sim GM^2/R$

$kT/m_H \sim GM/R$ but $M = (4\pi/3)\rho R^3$ so:

$R \sim (kT/m_H G\rho)^{1/2} \sim 10^7(T/\rho)^{1/2}$ (meters)

So if $T \sim 10$ K and $\rho \sim 10^{-15}$ kg/m^3 then:

$R \sim 10^{15}$ m or 0.1 pc, $M \sim 1$ solar mass

Basic Physics of Star Formation

- **Time Scale:**
  - The time-scale for gravitational collapse is also known as the free-fall time (see sec. 15-3 in text):

$P^2/a^3 = 4\pi^2/GM$

But $M = (4/3)\pi R^3\rho_0 = (4/3)\,\pi(2a)^3\rho_0 = (32/3)\,\pi a^3\rho_0$ so:

$P = (3\pi/8G\rho_0)^{1/2}$

The free-fall time corresponds to half the orbital period so:

$T_{ff} = (3\pi/32G\rho_0)^{1/2}$

Evaluating the constants yields:

$T_{ff} = (6.44 \times 10^4)(G\rho_0)^{1/2}$ (sec)

For $\rho_0 \sim 10^{-15}$ kg/m^3 $\sim 10^5$ years

- **Angular momentum will be conserved so a large collapse implies protostar should have rapid rotation.**

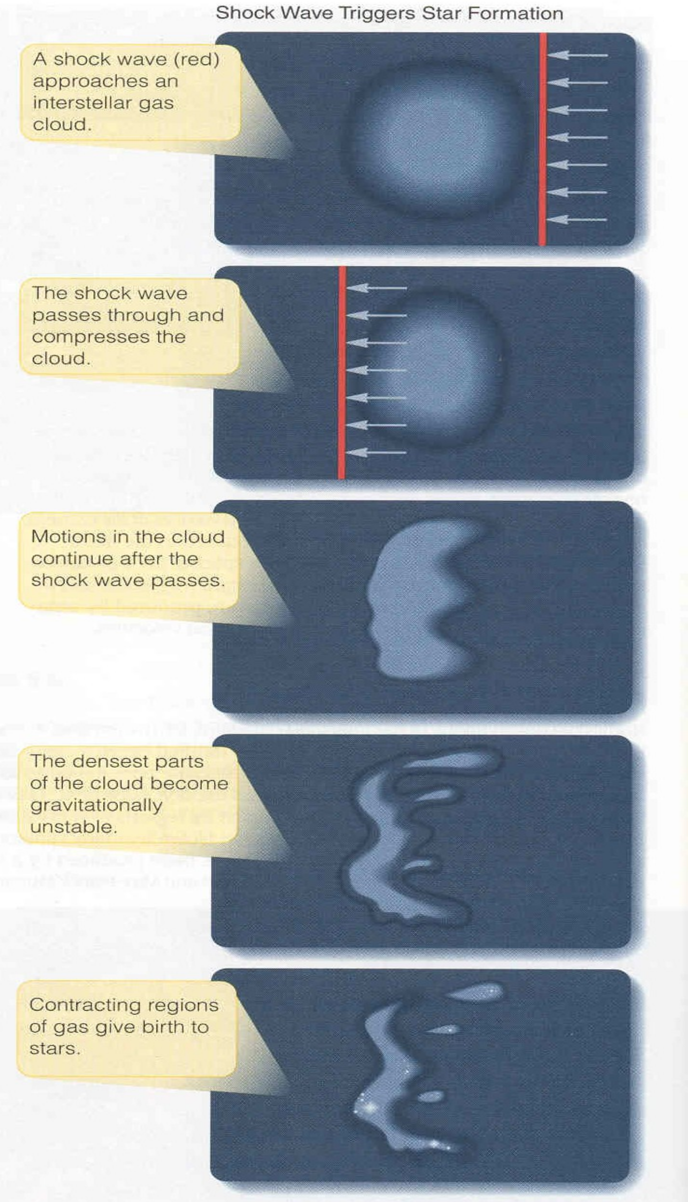
Molecular Outflows from Young Stellar Objects

- Molecular and ionized gas outflows from young stellar objects.
  - Material thought to be collimated by magnetic field associated with accretion disk surrounding young stars
  - Disk may ultimately form planets

Dense Collapsing (?) Clouds in Orion

- Proplyds: Dense clouds seen in HII regions (Orion)
  - Some show dense cores of infrared emission
    - Protostars

Collapse of Molecular Clouds



Shock Wave Triggers Star Formation

A shock wave (red) approaches an interstellar gas cloud.

The shock wave passes through and compresses the cloud.

Motions in the cloud continue after the shock wave passes.

The densest parts of the cloud become gravitationally unstable.

Contracting regions of gas give birth to stars.

Figure 9-6
In this summary of a computer model, an interstellar gas cloud is triggered into star formation by a passing shock wave. The events summarized here might span about 6 million years.

From our text: Horizons, by Sees

- Barely stable against collapse:
- Imagine slightly compressing cloud
  - Gravity goes up because material is packed more tightly (R in $1/R^2$ is smaller)
    - Tends to make cloud want to collapse more
  - Pressure goes up because material is packed more tightly ($P \propto \rho T$) and ρ higher
    - Tends to make cloud want to expand
  - For smaller clouds Pressure wins (stable)
  - For larger clouds Gravity wins (collapse)
- As cloud collapses and becomes denser, smaller and smaller parts become unstable
- Shock wave can also trigger collapse

What will a forming star look like in HR diagram?

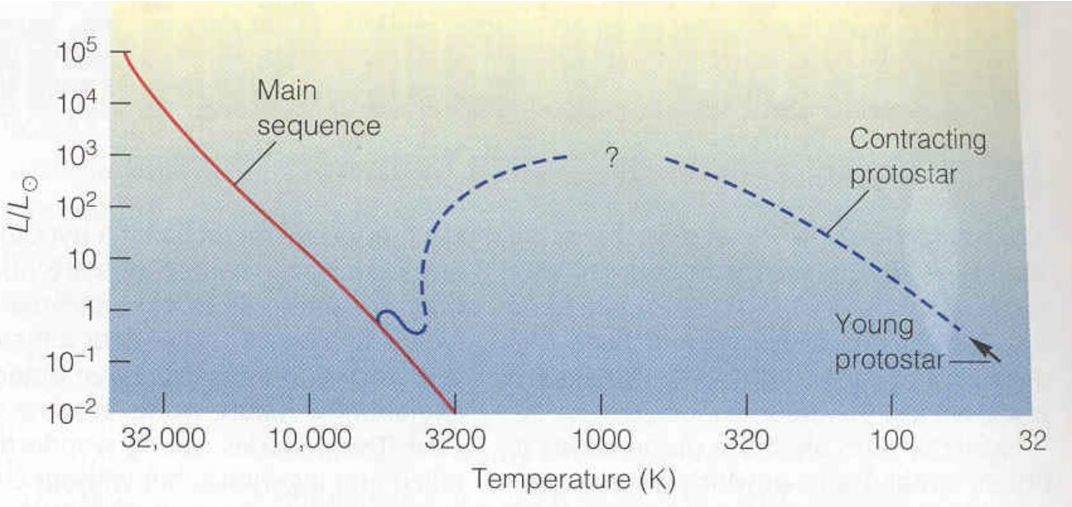
- Temperature changes relatively simple

– Starts out large and relatively cool	Must be on red side of diagram
– It heats up as it contracts	Must evolve towards the blue

- Luminosity more complicated because it depends on T and <u>R</u>

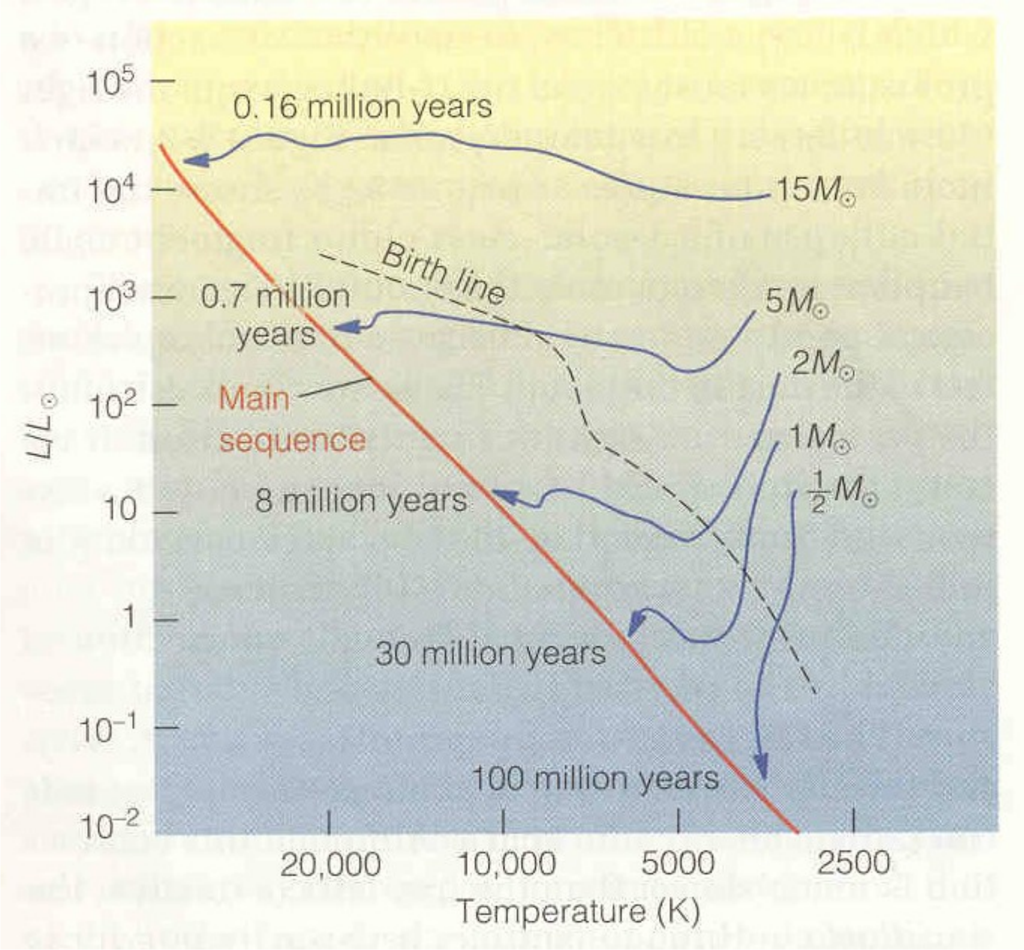
– Not much energy to start with	Luminosity must start out low
– Collapse releases grav. energy	Luminosity will rise
– Fusion begins, releases more energy	Luminosity at a peak
– Collapse slows, only have fusion now	Luminosity declines

- Finally stabilizes on the main sequence



From our text: Horizons, by Sees

How does mass affect collapse?



From our text: Horizons, by Sees

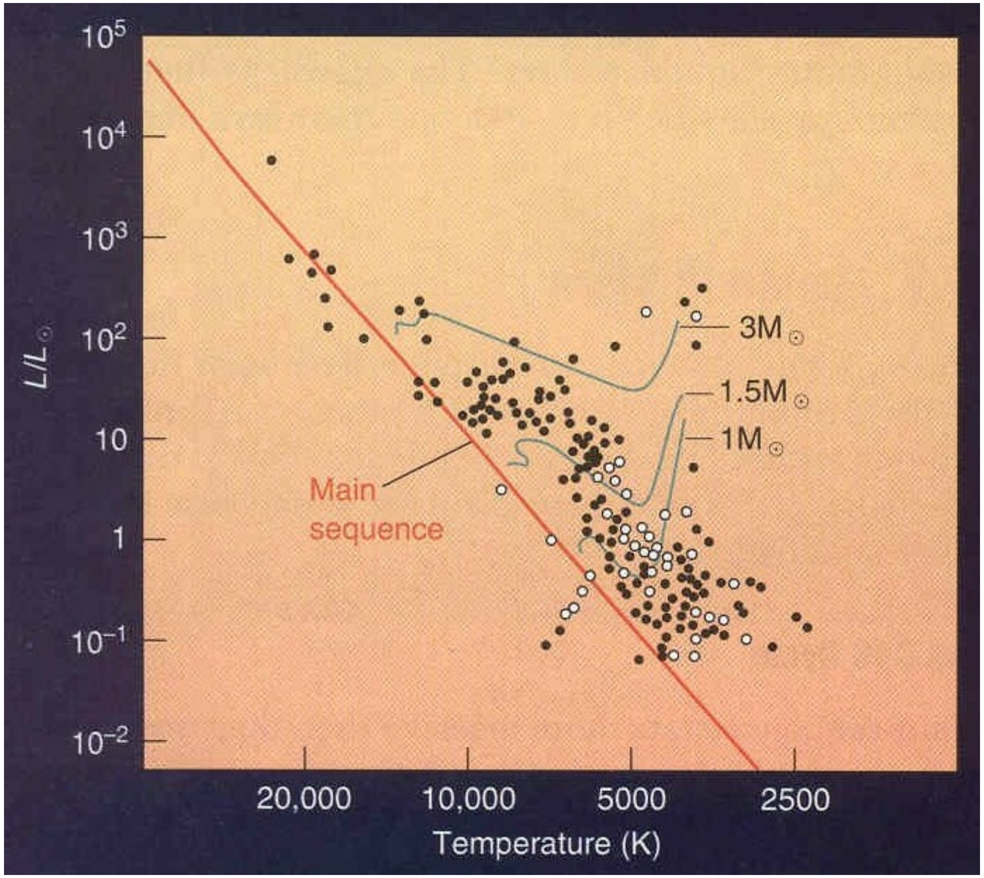
More massive protostars have stronger gravity

Collapse speed will be much faster than for smaller protostars

Fast collapse and short lifetime means massive stars can reach end of lifetime while low mass stars in cloud are still forming

- **Supernova shocks may come from earlier generation of stars**
  - **Sequential Star Formation**
- **Energy from supernova and other effects eventually disrupts cloud – prevents further collapse.**

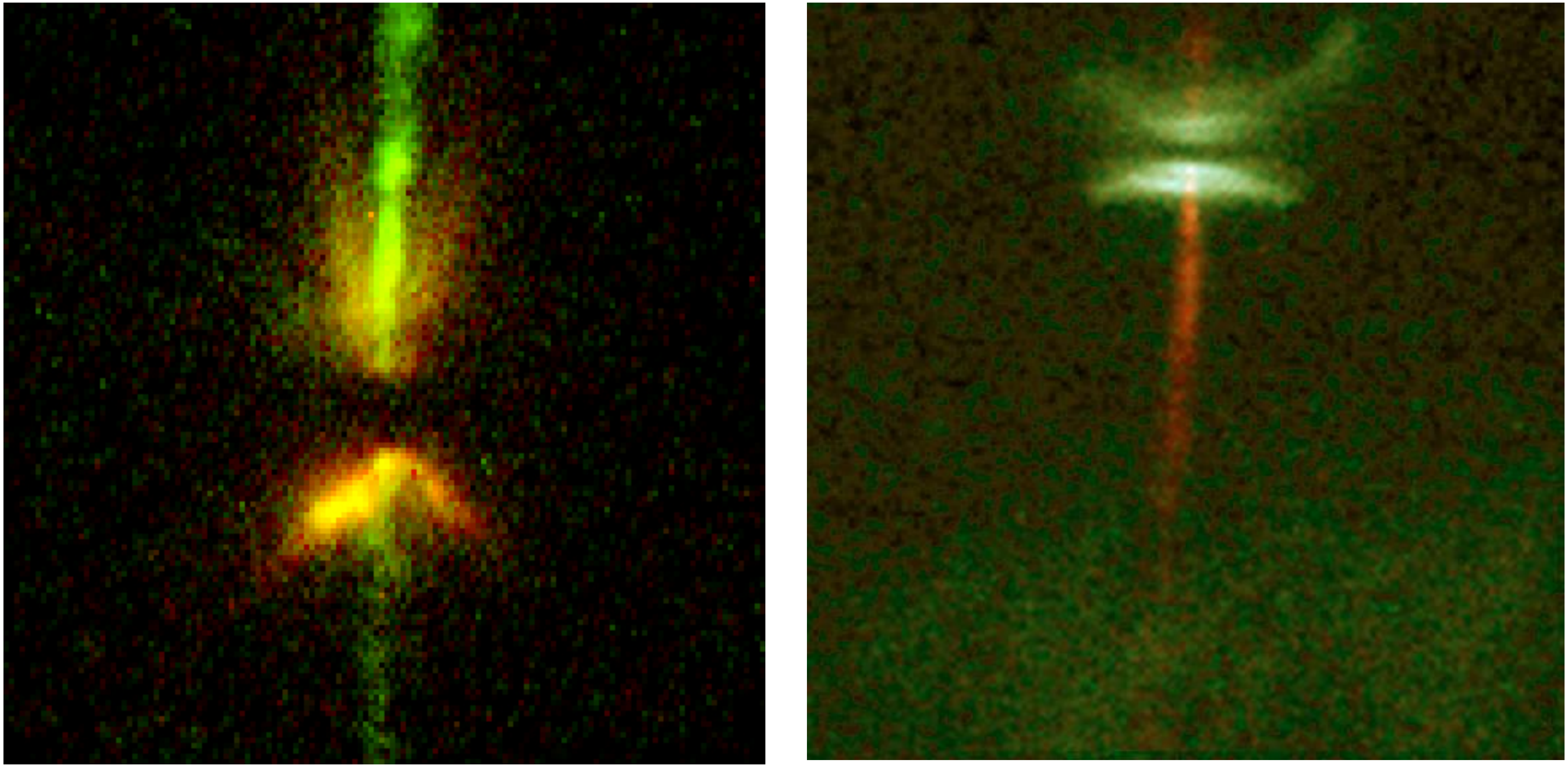
Observations of Young Clusters



From our text: Horizons, by Sees

- **Young cluster "NGC 2264"**
  - **Few million years old**
- **High mass stars have reached main sequence**
- **Lower mass stars are still approaching main sequence**
  - **Known as T Tauri stars**
- **Naming of classes of stars: Usually named after first star in class: T Tauri**
  - **Stars with letters (RR Lyrae) are typically "variable" stars**
- **Earlier stages hidden by dust**

More Herbig-Haro Objects



- **High resolution imaging of young stellar objects reveals accretion disk and polar outflow of gas (HST).**

Chapter 16 Homework

Chapter 16: #2, 3, 7, 9

(Due Tues. April 4)