Handout 21: Chap. 12, star formation

- The sun is known to be 4.6 Gy old
  - Age of oldest rocks
  - Formed ~ 10 My after sun formed
- O and B stars at most 1-10 My old
  - M ~ 10-40 solar masses
  - Lifetime ~ M/L
  - L ~ $M^{3 \text{ to } 4}$
- We see O and B stars
  - i.e. Trapezium in Orion nebula excited by O6 star
- Stars are currently forming out of Interstellar Medium
  - Gas and dust

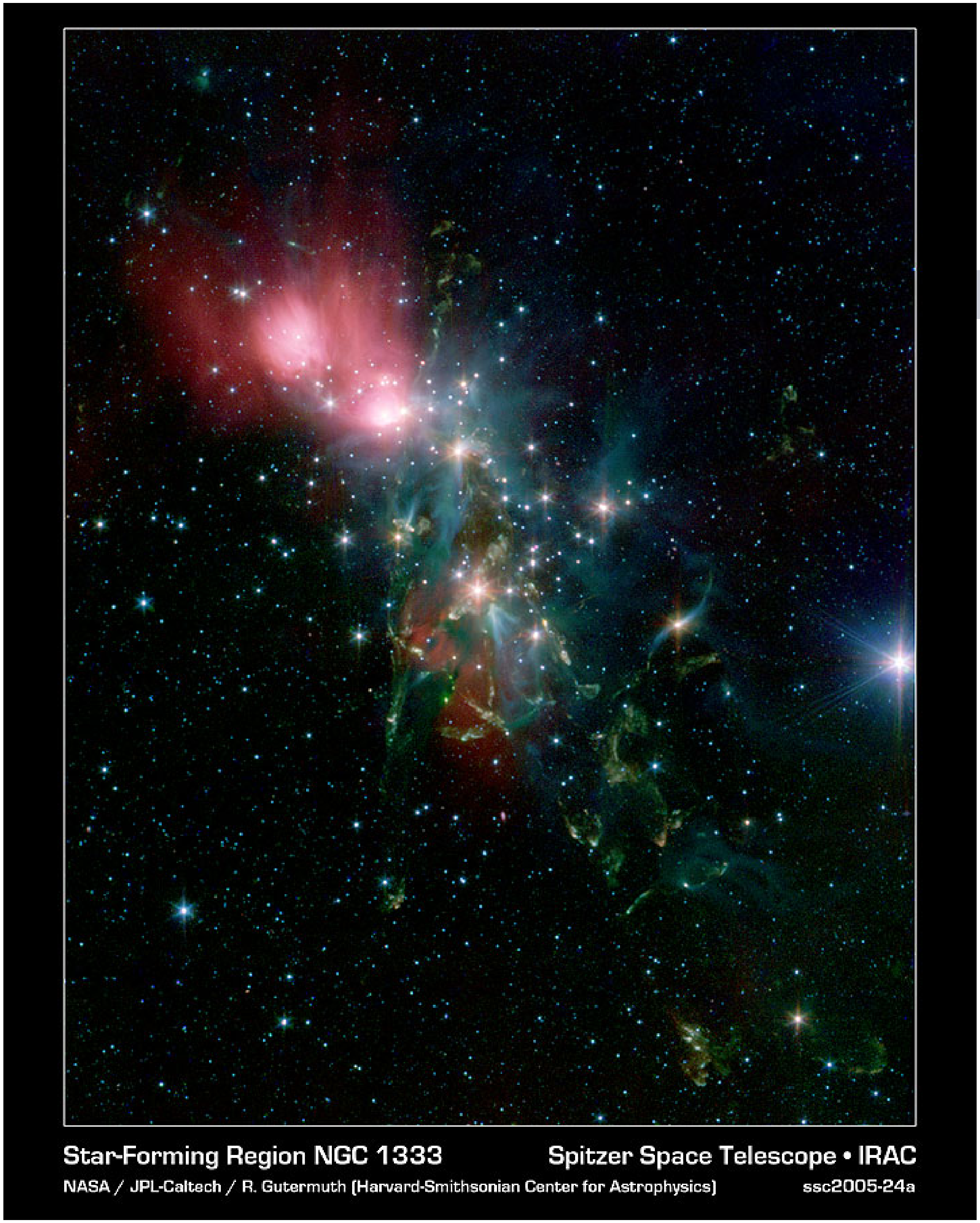
Orion nebula in visible and infrared

Trapezium (cluster of massive O stars exciting the nebula) is at the center.

Blue and green, visible wavelengths. These show stars and gas ionized and excited by UV photons from the Trapezium.

Orange and red, infrared. The red is 8 microns, and traces emission from Polycyclic Aromatic Hydrocarbons, also excited by the Trapezium.

To the upper right about 1 arcminute is the BNKL region, where new stars are currently forming out of the gas and dust of the Orion Molecular Cloud



NGC 1333 in Perseus at infrared wavelengths.

Many stars have recently formed, and are currently forming, in this nearby molecular cloud (about 300 pc distant).

Green (4.5 microns) shows supersonic outflows from the youngest, still forming stars.

Red (8 microns) again shows emission from Polycyclic Aromatic Hydrocarbons, a ubiquitous component of the Interstellar Medium and the ultimate source of much of the organic material in our solar system.

Complexity of star formation

It is crucial to know how and why stars form. In broad terms, we know collapse can occur if gravity overcomes pressure (i.e. virial disequilibrium). But the details are complex, and important. There is gas, dust, radiation, magnetic fields, angular momentum, and cosmic rays. The structures are complex (look at a picture of typical molecular clouds). There are many questions: What is the efficiency (speed) of star formation? What different masses form? How do these depend on the environment (Giant molecular cloud Orion, vs. modest molecular cloud Ophiucus)? Are planets commonly formed with stars? Of all masses? Like our planets?

Interstellar medium

- The raw ingredients of star formation come from the ISM
  - Average density near sun 1 H-atom/cm^3
  - Submicron dust grains ~ 1% gas by mass
    - Most refractory elements in dust grains
      - Fe, Si, Mg, etc.
      - The stuff of earth!
    - Grains ~ 0.1 μm radius cause visible extinction
      - “visibility” 0.5 kpc
      - Most of our galaxy hidden at visible wavelengths

Dust

- Dust is important
  - Couples to radiation
    - Opacity dominated by dust
  - Hides the galaxy
    - 30 mag visual extinction to galactic center
  - Protects molecular H from photo-dissociation
    - Cloud with > 1 mag visual extinction
  - Cools clouds
    - Enabling collapse
  - Crucial for planet formation

Extinction and reddening

- Extinction given by $\tau = n\sigma L$
  - For grains of radius a $2\pi a > \lambda$, $\sigma = \pi a^2$
    - i.e. like baseballs blocking light geometrically
  - For smaller grains
    - $\sigma = Q\pi a^2$, and $Q < 1$, and Q decreases with λ
      - Reddening of starlight
      - Same reason sunsets red, sky blue
  - ISM grains causing extinction and reddening
    - Radii 0.01 to 0.25 μm
      - Graphite (i.e. Carbon) – 2200 Angstrom feature
      - Silicates – rocky material – 10 and 20 μm features

Ultra-small organic grains

- Classical dust grains come to equilibrium in the radiation field
  - T ~ 10 – 100 K
  - Peak emission at 30 – 300 μm
    - Far IR
- Excess emission at 3.3 – 12 μm
  - T ~ 300 to 1000 K
    - Can't be equilibrium
      - Dust grain emits $L = Q_{emission} 4\pi a^2 \sigma T^4$
      - And absorbs $4\pi \langle I \rangle Q_{abs} \pi a^2$

Non-equilibrium emission
Kristin Selgren and others

- Dust grain < 10 Angstrom size
    - i.e. very large molecule
  - < 1000 atoms
  - Heat capacity correspondingly small
  - One UV photon raises T to **1000 K**
    - Note: 2 photons, 2000 K, grain evaporates
- Features in spectrum ➔ composition
  - Resonances at 3.3, 6.2, 7.7, 8.6, 11.3 μm
    - C-H stretch 3.3, C-H bend 11.3
- Probably ***P***olycyclic ***A***romatic ***H***ydrocarbons
  - Based on Benzene – rings of 6 C with H's attached
- Represent 20-30% IR emission from ISM
  - ~ 20% of C tied up in ***PAH***'s

Gas: atomic and molecular

- Diffuse clouds $A_V < 1$ mag
  - Mostly atomic, dominated by H
    - UV absorption (Lyman lines and cont.)
    - Hyperfine spin-flip, 21 cm wavelength
      - 1420 MHz frequency
      - Tiny energy difference ➔ long wavelength
      - Very weak (forbidden) transition
        - Lifetime excited state 3 My!
      - Intensity ~ column density
      - Intensity ~ optical depth
      - Intensity ~ Temperature – see next slide

Intensity of H 21 cm line

$$\nu = 1420 \cdot MHz \qquad A = \left(3 \cdot 10^{6} \cdot yr\right)^{-1}$$

emissivity: $$j = \frac{A \cdot h \cdot \nu}{m_H \cdot 4 \cdot \pi} \qquad dI = j \cdot \rho \cdot ds = \frac{1}{4 \cdot \pi} \cdot n_{upper} \cdot A \cdot h \cdot \nu \cdot ds$$

$$I = \frac{A \cdot h \cdot \nu}{4 \cdot \pi} \cdot \int n_u \, ds = \frac{A \cdot h \cdot \nu}{4 \cdot \pi} \cdot N_u \qquad N_u = n_u \cdot L = column\_density$$

$$I_\nu = I \cdot \phi_\nu \qquad \int_0^\infty \phi_\nu \, d\nu = 1$$

Spectrum

$$I_\nu = \left(1 - e^{-\tau_\nu}\right) \cdot B_\nu(T)$$

Temp. dependence of optical depth