Consider the enormity of volumes in space

- If we have a volume of 1 cubic parsec, and a density of 1 H atom per cubic cm, it will contain 1/40 the mass of the sun.
- Or, 1 solar mass in a cube 3.4 parsec on a side.
- Or, if the density is 40 per cubic cm, one cubic parsec will have one solar mass.

- This is one reason why the seemingly “empty” space between the stars can be so important.

How does fluorescence work?

- Consider hydrogen atom
- Hydrogen is most abundant element in ISM
- Near hot stars are many ultraviolet (UV) photons which ionize hydrogen (remove the electron)
- When electron encounters a proton, it recombines and emits a photon, which is usually visible
- UV light of stars is converted to visible

Nomenclature

- Photoionization is the technical term astronomers use
- HII indicates ionized hydrogen, thus emission nebulae are HII regions
- Fluorescence in ISM refers to photoionization plus recombination
Interstellar Gas

- Remarkably transparent in general
- Detect by
  - emission (fluorescence)
  - absorption (in spectrum of background star)
  - radio emission

Types of nebulae

- HII regions
  - HII means hydrogen is ionized. Near hot stars. Shine by fluorescence.
    Gas temperatures around 10,000 deg abs.
- HI regions (neutral hydrogen clouds)
  - Away from hot stars
  - Detect by absorption lines or radio emission
  - Gas temp. around 100 to few thousand deg

Interstellar absorption lines

- Discovered in 1904 - stationary lines in a spectroscopic binary
- Interstellar gas is often cold, so
  - lines are narrow
  - low ionization
- Optical spectra show lines of
  - sodium and calcium
  - also molecules like CN, CH, CH+

- From ultraviolet space observatories, see lines of hydrogen, carbon, oxygen

Radio observations

- Consider the cold interstellar gas
- Hydrogen (H) atoms are neutral (not ionized) and in ground state
  - H nucleus (proton) and electron each have spin
  - If spins line up, atom has slightly more energy
  - If spins opposed, atom has lower energy
• If electron flips from high to low state
  it emits radio radiation (very low energy)
  – at wavelength of 21 cm
  – or 1421 MHz frequency
  – 21 cm radiation is observed by radio telescopes,
    used to map the cold interstellar gas

What causes atom to flip from the low state to
the high state?
• Collisions with other atoms
  – may occur only once in 400 years (density is so low)
  – then it takes 10 million years to flip back spontaneously and emit radio
    wave
• But there is so much hydrogen in space,
  the radiation is detectable

H I clouds
• Temperatures about 100 deg K (absolute)
• Densities about 10 - 1000 atoms / cubic cm
• Sizes of a few parsecs

Summary so far
• ISM has 5 - 10% of the mass found in stars in the Milky Way
  galaxy
• Gas is main component of ISM
  – 99% of mass, mostly hydrogen and helium
  – can be seen in HI and HII regions
• Dust grains also important part of ISM
  – only 1% of mass
  – will discuss later
Continue tour of ISM

• Warm gas regions (mix of neutral, ionized gas)
• Hot interstellar gas (million degree temp, highly ionized)
• Can we fit all these components into a model?

Warm Gas

• Discovered after emission nebulae, cold HI regions
• Temp about 8000 deg
• Densities about 0.3 atoms / cubic cm
• Fill about 20% of space in galaxy near sun
• Mix of neutral and ionized gas

Hot Interstellar gas

• Observations from space observatories showed gas with
  – temperatures of million degrees
  – very highly ionized
  – low density
  – produced by supernova explosions (explosions of dying stars)

Model of interstellar gas

• How can we fit the different observations together?
• Two main clues:
  – Gas in ISM is clumpy, patchy, not uniform, with space between clouds
  – The very hot gas seems to fill the space between the clouds

Gas law

• Need to apply some physics
• For a gas,
  – pressure is proportional to density x temperature, i.e.,
  – Pressure = constant x density x temp
  – Think about how pressure, density, temp are related by this law
Pressure equilibrium

– should hold for many gas clouds in space
– otherwise, clouds will expand or contract

• For clouds in equilibrium, gas law says
  – density is inversely proportional to temp
  – high temp implies low density
  – low temp implies high density
  – hot, low density gas can balance pressure of clouds of cold, high density gas

What happens at boundary between hot and cold gas?

• Hot gas begins to heat outer parts of cold cloud
• Thus, get the warm clouds

Region around sun

• We live in region of hot (million deg) gas of low density (5 x 10^{-3} atoms / cubic cm)
• Practically no clouds of gas near sun
  (maybe one warm cloud nearby)
• Perhaps a supernova exploded in last million years and cleared out the gas

Evolution of Clouds

– Hot stars, supernova eject gas into space
– Supernova triggers formation of small clouds (100 solar masses)
– Small clouds collide, merge
– Build up to 100,000 solar masses, maybe 60 pc in diameter
– Star formation begins anew in large clouds
– The ultimate in recycling!
• Note that the previous discussion is a sketch.
• There is much more to learn about the details of what happens in the ISM

Astronomy 162, Week 3
Cosmic Dust and Molecules
Patrick S. Osmer
Spring, 2006

Cosmic Dust

• What is it?
• What effect does it have on radiation?
• Why is it important?

How do we detect cosmic dust?
• The dark lanes in the Milky Way and the dark clouds in/near nebulae are clear signs
• Dust blocks visible light
• Dust also emits infrared light
  – Recall Wien’s radiation law - matter at cool temp emits at longer wavelengths
  – Room temp. emits at 10 microns
  – 100 deg abs. emits at 30 microns

Reflection Nebulae

• Dust can also reflect some light
• Need to understand concepts of absorption and scattering
  – Absorption - light absorbed by matter, its energy converted to heat, matter re-radiates at other wavelengths (solar heating on earth)
  – Scattering - light bounces around, is not absorbed, wavelength doesn’t change
• Back scattering acts like reflection
• It produces reflection nebulae
  – Trifid Nebula
  – Pleiades (surrounding some of the stars)
  – See also Fig. 20-2, 20-4
• Note also that reflection nebulae are blue
  – Happens because blue light is scattered more than red light

Reddening
• Astronomers observed 70 yrs ago
  – some B-type (hot) stars had colors like G-type stars (cool)
  – realized interstellar dust was also producing a reddening effect

  Why is sky blue, sunsets red?
• Same kind of effect
  – Earth’s atmosphere scatters blue light more than red light
  – (See Box 5-4)

Dimming and reddening
• If starlight passes through dust cloud, it is
  – reddened and
  – dimmed (see Fig. 20-5)
  – it appears fainter and redder than it really is
  – need to correct, otherwise will overestimate distance

Dust and Distance
  – Recognizing and correcting for dust effects crucial for getting distances
  – Historical picture of Milky Way seriously in error until dust effects were discovered and corrected
  – Dust clouds very concentrated to plane of our galaxy
  – Dust clouds completely block our view of center of our galaxy in optical light
Nature of Dust Grains

- Why are they important?
- Smallest structures I know of in outer space
- Absorb some light, so must be solid particles
- Can learn about their structure by the way they absorb and scatter light

- Elements like iron, magnesium, silicon are less abundant in interstellar gas than expected - have condensed onto dust grains
- Some grains have a rocky core of such elements, with mantle of ices like water, methane, ammonia
- Others may be nearly pure carbon in form of graphite

- Grains may have a million to a billion atoms but sizes of only 0.01 to 0.1 microns (visible light is 0.5 microns)
- Prof. Sellgren of our department is a world expert on dust grains

Origin of grains

- Grain cores may have formed from carbon and silicon material ejected by red giant stars.
- In ISM, cores get coated with water and other ices, also pick up heavier atoms like iron
- Grains are examples of how solids can form in space

Interstellar Molecules

- Only 3 (simple) molecules known in pre-radio astronomy days
- Emission from OH molecule was then found at 1612 Mhz frequency
- Now have sensitive receivers and telescopes that can observe at mm wavelengths (100s of Ghz)
- Have found evidence for almost 100 different types of molecules
What kind of molecules are out there?

- Simple - H\textsubscript{2}, CO, CH, C\textsubscript{2}, CN
- Complex - ethyl alcohol (9 atoms), HC\textsubscript{11}N (13 atoms)
- Very complex (60 or more atoms), perhaps even amino acids
- This is a very active field of research
  – OSU Profs. DeLucia and Herbst very well known for their work in this area

- Show viewgraph here

Importance of molecules

- How did such complex molecules form in space? Are they clues about the origin of life itself?
- Next, we’ll see they trace out the largest structures in the Milky Way Galaxy

Giant Molecular Clouds

- H\textsubscript{2} is most common molecule, but hard to observe
- CO is readily observable w. radio telescopes
- CO is good tracer of where H\textsubscript{2} is.

GMC, cont.

- CO observations led to discovery of
  – Giant Molecular Clouds
  – Can be 100 parsec in diameter, have 200,000 solar masses
  – Occur in dusty regions of Milky Way
GMCs are complicated regions
• They have very cold, dusty regions where stars are forming today
• Once new, hot stars form, they heat and ionize the gas, produce emission nebulae
• When hot stars die and blow up, they disrupt the cloud

The ultimate recycling (reprise)
• Start with a GMC
• Form new stars from material in cloud
• Stars ionize part of cloud
• Supernova (SN) explosions disrupt clouds
• But SN return material to ISM
• and SN shock waves can trigger formation of new stars

Astronomy 162, Week 3, Part 3
Star Formation
Patrick S. Osmer
Spring, 2006

Quiz 2 – Friday, Apr. 21
• Review Session: Wednesday, Apr. 19, 5PM, Planetarium, 5033 Smith Lab
• Review sheet will be available on the web by Wed., Apr. 19

Star Formation
• How did the sun & solar system form?
• How do stars form?
  – These are now very active scientific questions
• Start with observations
  – Where do we see “protostars”, stars that are forming now?
Star Formation

• Recall the Giant Molecular Clouds (GMCs)
  – Stars observed to be forming in dark, cold, dusty regions within GMCs
  – Regions may be 0.1 pc in size, have about 1 solar mass

What kinds of forming stars do we see?

• In visible light
  – T Tauri Stars
    very young
    occur in associations (not bound together)
  – Pre-main sequence stars
    young stars that have not arrived on main sequence of HR diagram

• Herbig-Haro Objects
  – related to star formation
  – fuzzy, variable nebulae often found in pairs
  – result from material flowing out of protostars
  – shock waves occur when material hits other clouds of gas

• Eagle Nebula
  – HST image shows the dark, dusty “pillars” illuminated by nearby hot stars
  – The hot stars are evaporating and blowing away the dust, permit us to see newly formed stars

• Radio, infrared observations provide key information
• Dust blocks visible light
• Molecules like ammonia emit radio waves from dense regions
  – Radio waves penetrate dust and show evidence for disk of material around protostar
  – material flowing out from polar regions
What is happening?
• Recall inverse relation of temperature and density
• In cold (10 deg), dense ($10^4$ particles/cm$^3$)
• clouds can fall together under own gravity
  – which doesn’t happen in hotter regions
  – gas pressure too high

Contest of Pressure and Gravity
• First round
• Gravity overcomes gas pressure
  – pulls matter towards center
  – build up rapid concentration at center
  – outer material falls in more slowly

Accretion Disk
• Material around protostar flattens into a disk shape as it contracts
• Material in disk orbits protostar
  – controlled by gravity of protostar
  – continues to spiral inward, builds up mass of protostar
  – think of rings of Saturn as analogy

Bipolar Outflow
• Meanwhile, some matter is ejected from system at both poles of protostar
• Ejection is called the bipolar outflow
• Thus, protostars have both
  – inflow from accretion disk
  – outflow along poles of star
Summary so far

• Now have a first concept for origin of
  – solar system
  – rings of Saturn
  – T Tauri stars and Herbig Haro objects
• Later we’ll see similarity to formation of
  – disk galaxies
  – quasars

Star Formation, continued

• Have discussed so far
  – effect of gravity pulling material in
  – gas pressure pushing material out
• What triggers star formation?
  – Unlikely it just happens

Potential causes

• Shock wave from supernova
• Ionization from nearby hot stars
• Collisions of molecular clouds
• Spiral waves from Milky Way galaxy (will discuss later)
• Main point - need an impulse to initiate contraction of cloud

Additional concepts in star formation

• Conservation of angular momentum
  – related to disk structure
• Gravitational contraction as source of heat
  – an energy source for the protostar
First stage

• Shock wave helps gravity overcome resistance of gas pressure and magnetic fields
  – later, only gas pressure offers resistance
• Core collapses first
  – Cannot see protostar in visible light at this stage because of surrounding dust

Conservation of angular momentum

• As disk and core contract, they rotate faster
  – think of a spinning skater. Pulls in arms, spins faster
  – conservation of ang. momentum means objects will rotate faster as they contract
  – Core spins up until it loses energy via magnetic braking and ejection of matter

Gravitational contraction

• Contraction also converts gravitational energy into heat
• Density and gas pressure increase, balance gravitational pull, slow contraction
• But heat is radiated away
• Star continues to contract slowly

Effects of heat

• Heat in outer part of core produces radiation, clears away inner shell of dust
• Heat in center of core keeps raising temperature, and eventually leads to nuclear reactions
When can we see the protostar?

- Surrounding dust shell blocks visible light
- Protostar is first seen in infrared
- Later, bipolar outflow and radiation from star break through the dust shell
  - then see protostar in visible light
  - e.g., as a T Tauri star

What happens next?

- Star continues contracting
- But outer temperature stays same
- Consider location in HR diagram
  - Stars are above and to right of main sequence
  - Stars move almost straight down in H-R diagram as they shrink in size
  - Core continues to get hotter

What stops contraction?

- Note Fig. 20-9
- 1 solar mass star moves down, then to left in H-R diagram
- Arrives at main sequence and stabilizes
- When core gets hot enough, nuclear fusion of hydrogen atoms starts, provides enough energy to stop contraction, balance gravity

Young star clusters

- Review Figs. 20-16, 20-17, 20-18
What about massive stars?
– Contraction process goes much faster
– Outer part is hot enough to destroy dust, molecules, and ionize gas
– has enough energy to produce expanding bubble in birth cloud
– The most massive stars are about 120 solar masses
– It seems stars cannot stay together at higher masses - pressure beats gravity!

What are brown dwarfs?
– Stars forming with less than 0.08 solar masses
– Do not get hot enough in center to sustain nuclear reactions
– They shine, dimly, from energy of gravitational contraction
– Eventually just fade away
– Important because much of “dark” mass of galaxy could be in brown dwarfs

Summary
• We have covered the main concepts involved in understanding how stars form
  – Start with dusty, dense, cold clouds
  – Give them a push to trigger contraction
  – Understand and follow the (complicated) processes that take place
  – Eventually the newly formed star can be seen in visible light