Astronomy 162
Week 3, Part 1

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Spring, 2006

The Interstellar Medium, continued

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 (5×10^{-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

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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_2, CO, CH, C_2, CN
- Complex - ethyl alcohol (9 atoms), $HC_{11}N$ (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_2 is most common molecule, but hard to observe
- CO is readily observable w. radio telescopes
- CO is good tracer of where H_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

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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