Chapter 11
The Interstellar Medium
Star Formation in the Milky Way

11.1 Interstellar Matter

- Gas and Dust
  - The Interstellar Medium is the matter that exists between Stars
    - It is made up of two components
      - Gas – made of atoms or very small molecules
      - Dust – clumps of atoms and molecules like smoke or soot here on Earth
    - A Dust Grain is a typical particle of dust in the interstellar medium
      - Typical size of a dust grain is about the same wavelength as visible light (10^{-7} m)
      - This makes the regions of interstellar space transparent to long-wavelength radio and infrared radiation, but opaque to short-wavelength visible, ultraviolet and x-ray radiation
      - Light from distant stars loses its high-energy radiation as it travels through space
    - Reddening is the effect of radiation from a star losing its blue components of its visible light making them appear to be redder than they really are
      - This is the same effect that causes the bright red sunsets here on Earth as the light from the Sun is reddened as it passes through the dust in the atmosphere
- Density and Composition of the Interstellar Medium
  - On average there are about 1 million atoms per cubic meter in space with about 1 dust particle for every trillion atoms
    - Best vacuums we have made here on Earth are only 1 trillion atoms per cubic meter
    - If and interstellar region the size of Earth were compressed, there would only be enough atoms and dust to create a pair of dice
  - How can something that is basically not even there block so much of the starlight?
    - The distances between stars is so great, the light loses enough to be blocked
  - The matter is distributed very unevenly throughout the universe
    - Some directions have almost none allowing us to look billions of parsecs
    - Some directions have small amounts limiting us to thousands of parsecs
    - Some directions have large amounts making it impossible to see even nearby stars
  - Absorption of starlight tells us about the chemical composition
    - The composition of the gas is 90% H, 9% He, and 1% other elements
    - The composition of the dust is more difficult to determine but infrared evidence indicates silicates, carbon, and iron
      - Assumption that "dirty-ice" (comet-type matter) makes up a lot of it as well

11.2 Star Forming Regions

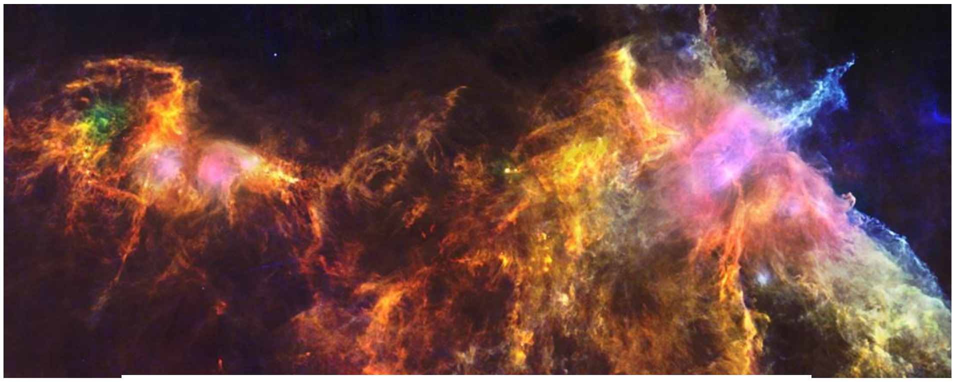
Emission Nebula, Reflection Nebula and Dust Lanes

- Nebula are any "fuzzy" patch (bright or dark) on the sky that are visible with a telescope but not sharply defined like as star or a planet
  - Emission Nebulae are clouds of interstellar gas that emit light
    - Tend to be red as the heat from hot stars within them heat the gas and electrons combine with protons to create hydrogen gas, releasing light in the red region of the visible range
    - Dust Lanes are dark lines that run through an emission nebula that are the interstellar dust that absorbs the emissions coming from the cloud of gas
  - Dark Nebulae are nebulae that appear dark because they block out light from behind it
    - A Reflection Nebulae is a dark region of gas that reflects light from a source
      - Tend to be blue as the blue wavelengths tend to be reflected more than the red wavelengths do so the blue get reflected to us while the red passes through
  - As solar wind and radiation are absorbed by the nebulae, the lower density gas burns off first leaving only regions of the more dense gas which can be amazing images called creation nebula
    - Most nebulae range between temperatures of 7500 and 8500 K

11.3 Dark Dust Clouds


Horsehead Nebula in the Orion Constellation

- More than 99% of space is devoid of emission nebula and contains no stars at all
  - Dark Dust Clouds are dark cool regions of space with relatively high densities (one trillion atoms per cubic meter) which is much more dense than the nebulae, but still barely more than the vacuums her on Earth
- Obscuration of Visible Light
  - Most dark dust clouds are bigger than our solar system and contain mostly gas but have enough dust within them to completely absorb all of the starlight it receives
  - The Horsehead Nebula in the Orion Constellation is a good example of a dark dust cloud blocking the light from an emission nebula behind it
- 21-Centimater Radiation
  - Astronomers have learned of a specific type of radiation that is able to penetrate the interstellar clouds allowing them to see beyond the dark clouds that are blocking our vision
    - Hydrogen atoms have two possible configurations of the spin of the electron attached to the nucleus and the one where they both spin the same direction has a very slightly higher energy associated with it.
      - This energy corresponds to an energy with a wavelength of 21 centimeters and this wavelength can probe any region in space containing hydrogen
      - The 21-Centimeter Line is the spectral emission line that results from the hydrogen-spin-flip of the electron within a hydrogen atom
- Molecular Gas
  - Molecular Clouds are regions of interstellar space that are neutral and cold (10-20 K) and contain densities of up to 10^{12} particles per cubic meter.
    - Only long-wavelength radio radiation can escape from these dense, dusty parts of space
    - Molecular hydrogen (H_2) is by far the most common gas
      - It cannot emit or absorb radio radiation so it cannot be used to probe structure
      - The 21 cm radiation only works with atomic hydrogen, not molecular hydrogen
    - Heavy molecules like carbon dioxide and formaldehyde are used to probe these clouds
      - These molecules absorb and emit in the radio region so they can be used to determine structure of the cloud
        - They are only about one part per billion of a cloud, but they indicate which regions contain high densities of molecular hydrogen as well as dust and other important components
  - Studying these molecular clouds reveals that molecular clouds do not exist by themselves and that star forming regions are actually just parts of amazingly larger molecular clouds
    - Molecular Cloud Complexes are the giant interconnected clouds of gas with enough gas to make millions of stars like our Sun that can be up to 50 parsecs across


Interstellar Molecular Cloud Complex

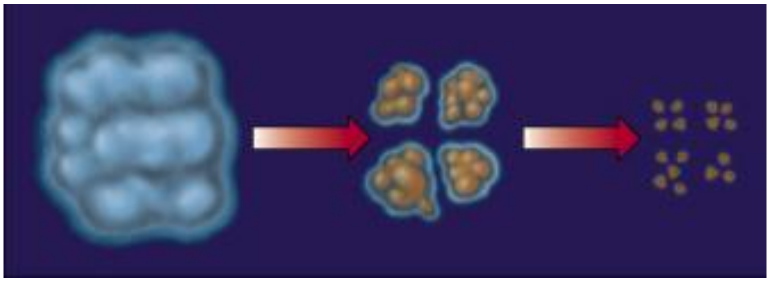
- Why are molecules found only in the densest and darkest of interstellar clouds?
  - Dust particles could shield the molecules from high frequency radiation that would ionize them and split them apart by absorbing it, explaining why we cannot see into these clouds
  - Dust particles could also act as a catalyst that helps form the molecules by providing a place where the atoms can stick and react as well as dissipate any heat associated with the production of new molecules that could destroy the newly formed molecules
  - Astronomers think that it is most likely both roles, but it is still being debated

11.4 The Formation of Stars Like the Sun

- Gravity and Heat
  - These are the two factors that determine everything about a star
  - Most matter will disperse before ever having enough gravity to clump together
    - Need about 10^{57} atoms for gravity to prevent it from dispersing back to space
    - This many atoms will not automatically come together and must be triggered
  - Three ideas of how it comes together and compresses
    - Gas loses so much heat it doesn't have enough energy to fight gravity
    - Emission of a type -O or type-B stars
    - Shock-wave from a Supernova explosion

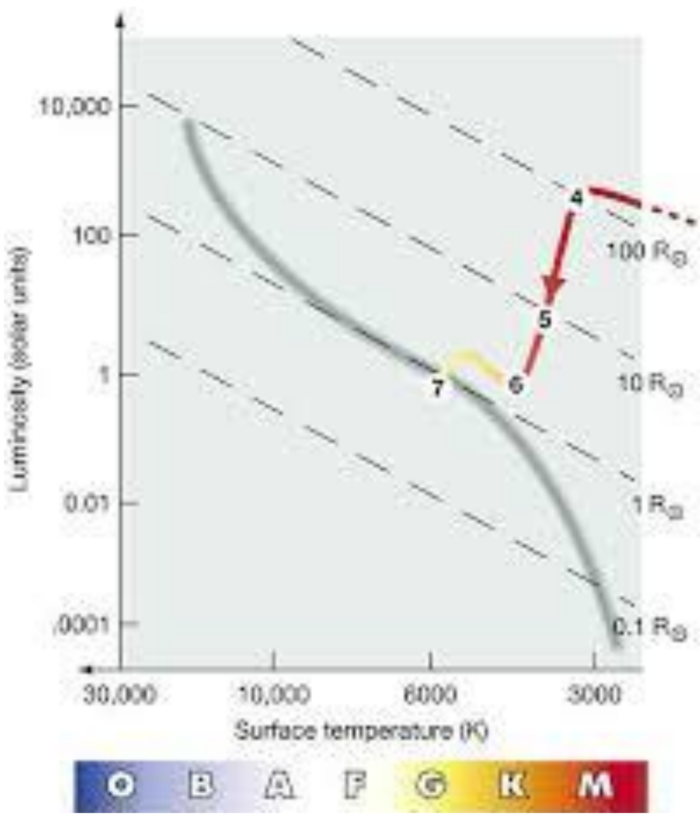
STAGES OF STELLAR EVOLUTION						
Stage	Time	Temp (C)	Temp (S)	Density	Diameter	Object
1	$2x10^6$ yr.	10 K	10 K	10^9 part/m^3	10^{14} km	Interstellar Cloud
2	$3x10^4$ yr.	100 K	10 K	10^{12} part/m^3	10^{14} km	Cloud Fragment
3	10^5 yr.	10,000 K	100 K	10^{18} part/m^3	10^{14} km	Fragment/Protostar
4	10^6 yr.	1 mil K	3,000 K	10^{24} part/m^3	10^{14} km	Protostar
5	10^7 yr.	5 mil K	4,000 K	10^{28} part/m^3	10^{14} km	Protostar
6	$3x10^7$ yr.	10 mil K	4,500 K	10^{31} part/m^3	10^{14} km	Star
7	10^{10} yr.	15 mil K	6,000 K	10^{32} part/m^3	10^{14} km	Main Sequence Star

- Stage 1 – An Interstellar Cloud
  - As a molecular cloud complex about 1 parsec across starts to collapse, it will begin to fragment, or clump into separate yet distinct smaller clouds with more density, but the same temperature

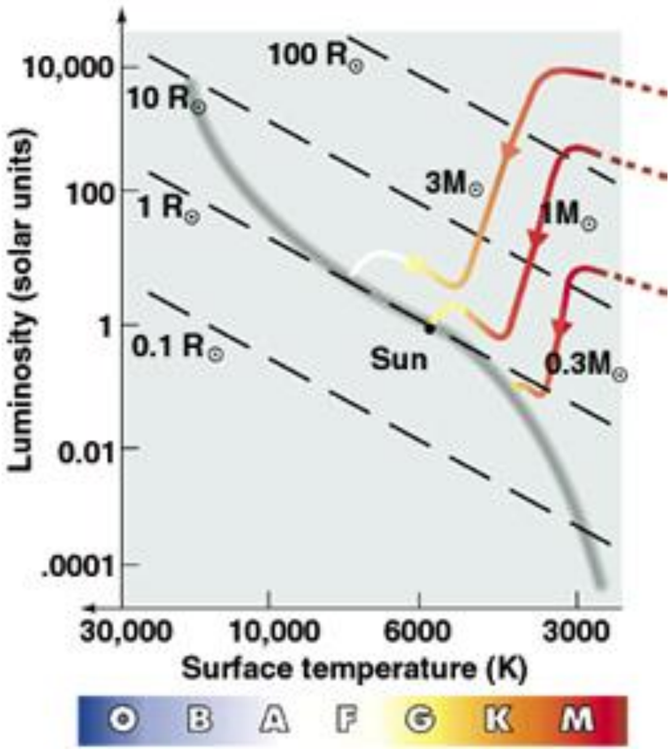


- Stage 2 and 3 – A Contracting Cloud Fragment
  - Stage 2
    - The fragments will contain between 1 and two solar masses of materials and are only a few hundredths of a parsec across.
      - As it compresses, friction goes up producing some heat warms the cloud to about 100 K
      - By this time the gas is still hundreds of times larger than our solar system
      - After tens of thousands of years it will shrink to the size of our solar system
  - Stage 3
    - By the time it has compressed to the size of our solar system, the friction within the cloud has gone up quite a bit
      - Temperature in the center is about 10,000 K and is now officially a protostar
      - The hot dense center continues to increase mass by pulling colder gas in from outside the center adding to the friction and gravity of the cloud
      - Surface temperature is only about 100 K
      - After continuing to contract for about 100,000 years it moves to stage 4

- Stage 4 – A Protostar
    - The cloud continues to contract down to about the size of Mercury's orbit
        - Temperature in the center is now over 1 million K and electrons are stripped from the protons and fly around and hundreds of kilometers per second
            - They still do not have enough temperature to ignite the fusion of Hydrogen into Helium (10,000,000 K)
        - Temperature of surface is about 3000 K
        - Knowing the radius and surface temperature, the luminosity can be calculated and it is 1000 times the luminosity of the Sun
            - All the luminosity is coming from massive gravitational energy being released
        - The gas outside of the protostar is now called a solar nebula
    - The protostar will now appear on the H-R Diagram in the Red Giant Region
        - The Evolutionary Track of a star is its motion around the H-R Diagram as its luminosity and temperature change over the course of its lifetime
- Stage 5 – Protostellar Evolution
    - The protostar is still not in equilibrium at this point
        - The temperature is now high enough that the outward pressure is slowing the force of gravity but it is not able to perfectly counterbalance it so the star contracts slowly
            - The smaller it gets, the less energy it can radiate, making it less luminous
                - This causes the star to move down on the H-R Diagram
                - The temperature also goes up as it contracts due to friction making it move slightly to the left on the H-R Diagram as well
            - The core is now approximately 5 million K and has completely ionized the gas
                - Still not hot enough to start nuclear fusion
    - Protostars will exhibit violent surface activity during this phase resulting in very strong protostellar winds that are much stronger than our Sun's solar wind
        - A T-Tauri Phase star is one that is in stage 5 of its evolutionary track
            - Often times there is a bipolar flow or two jets of matter ejecting perpendicular to the protostellar disk
    - As the protostar gets closer and closer to the main sequence, things slow down as the two forces within it get closer and closer to equilibrium
- Stages 6 and 7 – A Newborn Star
    - Stage 6
        - The cloud has now shrunk to a radius of about 1 million km and the internal temperature has now reached 10 million K, allowing it to officially be a star as nuclear fusion ignites
        - It will continue to slightly shrink and its temperature will continue to slowly go up for more than 30 million years before settling into the main sequence at stage 7
    - Stage 7
        - The star has now reached hydrostatic equilibrium with an internal temperature of 15 million K and a surface temperature of 6000 K
        - It will remain in the main sequence for 10 billion years!



11.5 Stars of Other Mass



- The Zero-Age Main Sequence
  - The formation of stars more massive and less massive than our Sun follow the same type of path to their spot on the main sequence either above or below the Sun based on their mass
    - Each of them travel along the same shaped path from their interstellar cloud of gas toward stage 7 in the main sequence
  - Zero-Age Main Sequence is the band of paths that lead to the main sequence for stars of all masses
    - Low mass stars will end up on the bottom and high mass stars end up at the top
    - Once a star arrives at the main sequence it will stay there for a vast majority of its life
      - If it enters as an A-class star it will stay there until it leaves staring its death
- "Failed" Stars
  - Some fragments are too small to ever become stars
  - The pressure and gravity come into equilibrium before reaching the temperature required to ignite the nuclear fusion reaction in the core
    - A Brown Dwarf is a failed star and is an object that is small, faint, and cool
      - They are very difficult to find as they are not luminous, cool, and dark
      - Jupiter would be a brown dwarf if it did not orbit the Sun

11.6 Star Clusters

- Clusters and Associations
  - Star Clusters are groups of stars that formed from the same interstellar cloud and the cloud fragmented allowing the various stars to form in separate regions of space.
    - Open Clusters are loose, irregular clusters
      - Found in the plane of the Milky Way
      - Usually contain hundreds or thousands of stars
      - Spread out over a few parsecs
    - Associations are less massive, but more extended clusters where the stars are further apart and there is much less mass either in number of stars or size of stars.
      - Most stars are very young
    - Globular Clusters are spherical, dense clusters
      - Contain millions of stars
      - Spread out over up to 50 parsecs
      - Tend to have no upper main sequence stars
      - Contain the oldest know stars in the galaxy
- Clusters and Nebulae
  - Nebulae will eventually become star clusters
    - Low mass stars are more common than high mass stars
      - High mass stars die faster
        - More mass means less lifetime
      - High mass stars harder to form
        - Need to fragment very large amount of gas
  - Star clusters will eventually just dissolve into individual stars as the stellar gas gets pulled into more protostars and stars over millions of years