Lecture 01: A Sense of Scale

The Science of Astronomy

- The First Science
- Purpose…To advance our knowledge and understanding of the physical nature of the universe.

The Scientific Method

- Observation and description of the phenomena.
- Formulation of a hypothesis to explain the phenomena (model or formula).
- Use the hypothesis to make predictions.
- Perform of experimental tests of the predictions.
- Experiment must be repeatable.
- Must have several independent experimenters.

Hypotheses that perform well become…

- Theories
- Laws

The Laws of Physics

- Sometimes called the ‘physical laws.’
- A basic principle/assumption → *the laws of physics are the same every where in the Universe.*
- Describe/Explain the interactions of matter and energy in the universe.

Astronomy gives us a Sense of Scale

- The Earth
- Solar System
- The Milky Way Galaxy
- Local Group of Galaxies
- Super Cluster of Galaxies
- Visible Universe

Angular Measurements

- Developed by the Babylonians (~3000 BC)
- Subdivide one degree into 60 **arc minutes**
  - minutes of arc
  - abbreviated as 60 arcing or 60´
- Subdivide one arc minute into 60 **arc seconds**
  - seconds of arc
  - abbreviated as 60 arced or 60”
    - 1° = 60 arcing = 60´
    - 1´ = 60 arced = 60”

The Small Angle Formula

- Astronomers can use the angular measurement of an astronomical object to determine a rough estimate of the object's diameter.

$$D = \frac{\alpha d}{206265}$$

D = linear size of object
a = angular size of object (in arced)
d = distance to the object

Small Angle Formula Examples

(1) On July 26, 2003, Jupiter was 943 million kilometers from Earth and had an angular diameter of 31.2". Using the small-angle formula, determine Jupiter's actual diameter.

(2) On February 3, 2007, Venus will be 226,380,000 kilometers from Earth. If the diameter of Venus is 12,104 kilometers, what will be the angular size of Venus that evening?

The Basic Yardsticks

THE ASTRONOMICAL UNIT
- Astronomical Unit - average distance from the Earth to the Sun
  - 1 AU = 1.5 x 10^8 km = 9.3 x 10^7 miles

THE LIGHT YEAR
- One light year is the distance a beam of light travels during a one year trip across the void of space (Speed of Light = 186,000 miles/second = 3 x 10^8 meters/second).
  - 1 ly = 63,240 AU= 9.46x10^{12} km $\underset{\sim}{\ }$ 6 trillion miles

THE PARSEC
- This distance at which 1 AU subtends an angle of 1 arc second (1/3600 degree).
  - 1 pc = 3.09 x 10^{13} km = 3.26 ly
  - 1 kpc = 10^3 pc
  - 1 Mpc = 10^6 pc

Measuring a Star's Distance

- Parallax - the apparent change in the position of a star due to the motion of the Earth; nearby objects exhibit more parallax that remote ones.
  - Distance (parsecs) = 1/(parallax angle)
  - Stellar Parallax for all known stars: p < 1.0"

Lecture 02: Light
Astronomy Today - Chapter 3

What is the speed of light?
- c = $3x10^8$ m/s = 186,000 miles/sec ($1.86x10^5$ miles/sec)

What is light?
- 1670: Isaac Newton - light is made of tiny particles (corpuscles).
- 1678: Christian Huygens - light is made of tiny waves.
- 1801: Thomas Young confirmed the wave nature of light in double slit experiment.
- 1860: James Clerk Maxwell - light is an electromagnetic wave
- 1905: Albert Einstein - light is composed of tiny bundles of waves called photons.
- Today: Light has a wave-particle duality.

Light is an Electromagnetic Wave - Electromagnetic Waves are energy-carrying waves emitted by vibrating electrons. EM waves consist of vibrating electric and magnetic fields which are perpendicular to each other.

EM Wave Properties: Frequency, Wavelength, & Wave Speed

Wavelength...
- Distance between two successive peaks (or valleys) in a wave.
- Measured in meters, nanometers (10^{-9} m), or Angstroms (10^{-10} m).

Frequency
- Number of vibrations for a source of waves per unit time.
- Measured in Hertz (cycles per second).

Wave Speed
- The speed with which waves pass by a particular point.
- Wave Speed = Frequency × Wavelength

Examples
- What would be the speed of a wave with a wavelength of 521 meters and a frequency of 12 Hz?

- Calculate the wavelength of a wave with a speed of 1200 m/s and a frequency of 30 Hz.

- Calculate the frequency of a wave with a speed of 65 m/s and a wavelength of 3 m.

Electromagnetic Wave Speed - EM wave speed is the same as the speed of light. This speed is a constant for all forms of EM waves, radiation, or light.

EM wave speed equation: $c = f\lambda$

Electromagnetic Wave Speed Examples

- Calculate the wavelength of a radio wave emitted from a radio station with a frequency of 1230 kHz.

- Calculate the frequency of an electromagnetic wave with a wavelength of 2.37×10^{-12} m.

The Electromagnetic Spectrum

- ***<u>Radio Waves</u> – (> 10 cm)***
- ***<u>Microwaves</u> – (1 mm – 10 cm)***
- ***<u>Infrared</u> – (1 μm – 1 mm)***
- ***<u>Visible Light</u> – (400 nm – 700 nm)***
- ***<u>Ultraviolet</u> – (10 nm – 400 nm)***
- ***<u>X-rays</u> – (0.01 nm – 10 nm)***
- ***<u>Gamma Rays</u> – (<0.01 nm)***

Energy Carried by Light

- "Short wavelength radiation carries more energy than long wavelength radiation".

$$E = hf = \frac{hc}{\lambda}$$ where *Planck's Constant:* $h = 6.6 \times 10^{-34}\ J{\cdot}s$

Examples

- What is the energy of a photon with a frequency of 5.14×10^{14} Hz?

- What is the energy of a photon with a wavelength of 550 nm?

The Visible Spectrum: A range of light waves extending in wavelength from about 400 to 700 nanometers.

Temperature Scales: Fahrenheit, Celsius, & Kelvin

Wien's Law - The wavelength of the peak of the blackbody curve is inversely proportional to the temperature.

$$\lambda_{\max} = \frac{2.9 \times 10^{-3}\,Km}{T}$$

Wien's Law Examples

- What is the peak wavelength of light emitted by a star with a surface temperature of 10,000 K?

- What is the surface temperature of a star whose peak wavelength of emitted light equals 780 nm?

Star Colors
◆Red← coolest star
◆Orange
◆Yellow
◆White
◆Blue← hottest star

Stefan – Boltzmann Law - The intensity (relative amount of energy) an object emits is determined by the object's temperature.

- Called Energy Flux (F) in W/m^2
- Stefan-Boltzmann Constant = $\sigma = 5.67 \times 10^{-8}\ W/m^2 \cdot K^4$

$$F = \sigma T^4$$

Doppler Effect - The change in wavelength of light due to motion of the source of light (also occurs in water waves and sound waves).

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Doppler Shift Example
The wavelength of the H_β line in hydrogen is measured to be 486.133 nm in the lab. In the spectra of star HGX0034, the H_β line is measured at 485.981 nm. Is this star moving away from us or coming toward us?

Lecture 03: Spectroscopy
Astronomy Today – Chapter 4

The Kirchhoff-Bunsen Experiment

- Burning chemicals over an open flame resulted in a spectrum with bright lines.
- Each chemical element produced its own characteristic pattern of bright spectral lines.

Kirchhoff's First Law
Hot, dense gases or solids produce a continuous spectrum.

Kirchhoff's Second Law
Hot, rarefied (low density) gas produces an emission line spectrum.

Kirchhoff's Third Law
Cool gas in front of a continuous source of light produces an absorption line spectrum.

A Brief History of Atomic Theory

- Democritus (~400 BC): matter was made of atoms (Greek for *"uncuttable")*
- John Dalton (early 1800s): revived the idea of atoms, atoms were *'indivisable'*
- JJ Thompson (1897): discovered electron, proposed a 'plum pudding' model of atom
- Ernst Rutherford (1910): discovered atomic nucleus, later found *proton*.
- James Chadwick (1932): discovered *neutron*

Bohr's Hypotheses

- Electrons can transfer between orbits so long as the electron ends up with the energy of the new level.
    - The electron must gain energy to move up to the next energy level.
    - The electron must loss energy to move down to the next energy level.

The Origin of Spectra

- Absorption occurs when a photon causes an electron to jump from a low energy level to a high energy level.
- Emission occurs when a photon is emitted after an electron jumps from a high energy level to a low energy level.

Stellar Spectra

- A star's spectrum tells us what types of chemical elements are present in the star.
- A star's spectra can also reveal something about its motion through space.
    - A moving star's spectra will exhibit a Doppler shift.

Lecture 04: Telescopes
Astronomy Today - Chapter 5

Why use a telescope?
- Brighten
- Magnify
- Resolve

<u>Focal Point</u> - the place where light rays converge to a point
<u>Focal Length</u> - the distance from a curved mirror or lens to its focus

Reflection...
- …is the rebounding of light rays off a smooth surface (diffuse or specular).
- <u>Convex</u> and <u>concave</u> <u>***mirrors***</u> reflect light.

Refraction...
- …is the bending of light rays upon passing from one transparent medium to another.
- <u>Convex</u> and <u>concave</u> <u>***lenses***</u> refract light.

REFRACTORS - Use only lenses (objective lens, assorted eyepieces)
Problems with the Simple Refractors
- Chromatic aberration
- Spherical aberration

Problems with Large Refractors
- can't support heavy lenses
- small lenses permit limited absorption of starlight
- larger lenses are prone to imperfections

REFLECTORS - Use mirrors and lenses

<u>Newtonian Reflector</u>
- a concave primary mirror
- flat secondary mirror (diagonal)
- eyepieces

<u>Cassegrain Reflector</u>
- concave primary mirror
- convex secondary mirror
- eyepieces

Problems of Reflectors
- Early mirrors were metal
- Tarnished easily
- Not very reflective
- Some light must be blocked
- Usually a second mirror is inserted to divert light

Advantages of Reflectors
- No chromatic aberration
- No spherical aberration
- Mirrors don't have support problems
- No problems with imperfections in the mirror or absorption in the mirror

Telescope Mounts

- Equatorial - RA and DEC
- Altazimuth - Altitude and azimuth
    - example: Dobsonian

Telescopes Brighten

- Light-Gathering Power *of a telescope depends upon the cross sectional area of the telescope tube*
    - Aperture - diameter of the telescope tube's opening where light enters
    - F/RATIO - The f/ratio is often called the speed of the telescope.
        - F/ratio = aperture/focal length

Telescopes Magnify

Magnification - the number of times larger an object appears through a telescope than as seen by the naked eye

$$M = \frac{\text{Focal Length of the Objective Lens or Mirror}}{\text{Focal Length of the Eyepiece}}$$

Telescopes Resolve

- Angular Resolution - measure of the clarity of images
    - Telescope with larger diameters are able to resolve smaller objects.
- Adaptive Optics – a way to mechanically and electronically compensate for atmospheric distortion

Observing Problems

- Atmospheric dispersion is the spreading out of light into a spectrum by Earth's atmosphere.
- Scintillation is the twinkling of stars caused by turbulence in the Earth's atmosphere.
- Light Pollution makes it difficult to see stars in the city.

Radio Telescopes

- Radio telescopes are similar to reflecting telescopes.
- Several radio telescopes can be used together to improve the resolution of images.
    - This is called interfermometry.

The Hubble Space Telescope...

◆…is the largest telescope in space.
◆...is 30 times more sensitive than ground based telescope.
◆…gives high resolution images because it does not suffer from the effects of atmospheric turbulence.

Lecture 05: The Sun
Astronomy Today – Chapter 16

The Sun's Exterior

- Photosphere - "sphere of light", the visible surface of the Sun (~400 km (250 miles) thick)
- Chromosphere - "sphere of color", visible during solar eclipses (~2000 km (1250 miles) thick)
- Corona - the Sun's outermost atmosphere.
    - The outflow of gas in this region is called the solar wind, which are particles that have escaped the Sun's gravity.
    - 99.9% H, He ions; also Si, S, Ca, Cr, Ni, Ne, Ar

Surface Features of the Sun's Photosphere

- Granulation - convection features about 1000 kilometers (625 miles) in diameter seen constantly in the solar photosphere.
- Sunspot - a temporary cool region that appears darker than surrounding photosphere
    - Occur in pairs
    - Sunspot Cycle Indicators
    - Caused by local variations in the Sun's Magnetic Field
        - Zeeman Effect - the splitting of some of the spectral lines of hydrogen gas into two or more components.

Solar Cycle

- The rotation rate varies from once every 25 days (equator) to once every 35 days (poles).
- This differential rotation twists the magnetic field lines.
    - This causes the number of sunspots to vary over an 11 year period.

Typical Explosive Solar Phenomena

- Flare -eruptive event that sends out vast quantities of high energy particles, X-Rays, and UV radiation.
- Prominence - a flame-like protrusion seen near the limb of the Sun and extending into the solar corona. Associated with sunspots and follow magnetic field lines.
- Coronal Mass Ejections - explosions from the photosphere that expel approximately 2 trillion tons of matter at 400 km/s that last up to a few hours. Can temporarily alter the shape of the Sun's magnetic field.

The Sun's Interior

- Thermonuclear core - the central region of Sun where fusion takes place due to high temperatures and pressures.
- Radiative zone - a region inside a star where energy is transported outward by the movement of photons ("random walk pattern" - 1 million years).
- Convective zone - a layer inside a star where energy is transported outward by means of heat flow through the gasses of the star (convection).

The Sun's Temperature - Surface: 5800K, Core: $1.5x10^7$K.

Hydrostatic Equilibrium - The outward pressure force balances the inward gravitational force everywhere inside the Sun.

Luminosity – the amount of energy emitted each second from a star.

- Sun's luminosity = 3.9 x 10^{26} Watts (joules per second), or
- 1 Solar Luminosity

What makes the Sun shine? - Thermonuclear fusion at the Sun's core is the source of the Sun's energy.

Fundamental Forces

✦Gravity
✦Electromagnetic Force
✦Weak Nuclear
✦Strong Nuclear

Hydrogen Fusion

✦Net result: 4H --> He + e^+ + ν + energy

Energy – Mass Equivalence: $E = mc^2$

Lecture 06: The Properties of Stars
Astronomy Today – Chapter 17

Stellar Distances

- Light-year - the distance that light travels in one year (1 light year = 6 trillion miles)
- Parsec - the distance from our Sun at which the angle between the Earth and the Sun subtends an angle of one arc second (1 parsec = 3.26 light years = 19 trillion miles)

Measuring a Star's Distance

- Parallax - the apparent change in the position of a star due to the motion of the Earth; nearby objects exhibit more parallax that remote ones.
- Distance (parsecs) = 1/(parallax angle)
- Limit of accurate parallax measured by ground based telescopes is 0.005" which is a limit of 200 pcs.
- IMPORTANT - Stars (galaxies, etc…) farther than ~300 pcs require different distance measurement techniques that build on the accuracy of measuring stellar parallax.

Stellar Brightness

- Stellar brightness is affected by ….
    - Distance
    - Size
    - Temperature
    - Luminosity

Apparent Magnitude *(or apparent brightness)*

- The APPARENT MAGNITUDE SCALE is the brightness scale for stars as they appear in the sky to the naked eye (e.g. the size of the dots on star charts).
- The Apparent Magnitude scale was first proposed by the Greek astronomer Hipparchus (150 BC)
- Pogson (19th century) established a logarithmic scale for stellar magnitudes; said that 1st magnitude stars are 100 times brighter than 6th magnitude stars.

Measuring A Star's Brightness

•Inverse-Square Law - the apparent brightness of a star decreases with increasing distance from Earth

Luminosity

- Surface temperature and surface area determine the luminosity of a star.
- Luminosity: the rate at which a star radiates energy.
- Luminosity is proportional to the product of a star's surface temperature and surface area.

$$L = 4\pi R^2 \sigma T^4$$

Stefan-Boltzmann Law - a star of temperature T radiates an amount of energy each second equal to σT^4 per square meter

Absolute Magnitude (M_v)

- The magnitude that a star would have if it were 10 parsecs away from Earth.
- Absolute magnitude is a measure of a star's actual luminosity.
- To calculate M_v, you must determine the star's apparent magnitude and distance (using the parallax method).

How useful is Absolute Magnitude?

- A star's luminosity is affected by…
    - Size
    - Temperature
  - These things determine the luminosity and hence the absolute magnitude (M).
- By comparison, a star's M can easily be determined by examining in its temperature and apparent magnitude (m).
- Once we have 'm' and 'M', we can determine the distance to that star without using parallax.
  - Distance Modulus = $m_v - M_v$
  - $m_v - M_v = 5 \log d - 5$ (d is the distance to the star in parsecs)

Stellar Temperatures - A star's surface temperature can be determined from its color using Wien's Law.

Measuring a Star's Composition

- Each atom absorbs a unique combination of wavelengths of light -- from this we can determine the composition of a star.
- Spectroscopy reveals what chemical substances are present in the star.
- Star's are composed of mostly hydrogen.

Temperature vs. H lines

- Hot Stars (T >> 10,000K) have weak lines - H is ionized by very high energy photons.
- Cool Stars have weak lines also - Photons don't have enough energy to excited H electrons.
- H lines appear better in stars with surface temperatures around 10,000K - Photons in these stars have the right amount of energy to excite H electrons to produce the lines.

Stellar Spectroscopy (began in 1817) is the study of the properties of stars by measuring absorption line strengths (line spectra).

Stellar Classification System:

- O B A F G K M
- Due to recent discoveries of 'brown dwarf' sub-stars, astronomers have added two new classification labels.
  - O B A F G K M L T

CLASS	COLOR	SURFACE TEMP (K)
O	BLUE-VIOLET	30,000 – 50,000
B	BLUE-WHITE	11,000 – 30,000
A	WHITE	7,500 – 11,000
F	YELLOW-WHITE	5,900 – 7,500
G	YELLOW	5,200 – 5,900
K	ORANGE	3,900 – 5,200
M	RED-ORANGE	2,500 – 3,900
L	RED	1,300 – 2,500
T	RED	BELOW 1,300

Hertzsprung-Russell Diagram

- Plots of luminosity versus temperature for known stars
- Most stars on the H-R diagram lie along a diagonal curve called the main sequence.
- Main sequences stars are still 'burning' Hydrogen through the process of fusion.

Luminosity Classes

Luminosity Class	Star Type
I	Super Giant
II	Bright Giant
III	Giant
IV	Sub-Giant
V	Dwarf

Stellar Motion

Two Methods

- Astrometry – the precise measurement and observation of a star's <u>proper motion.</u>
    - This is the only direct method of measuring a star's motion.
- Spectroscopy – Doppler shift in stellar spectra can reveal a star's motion.
    - This is an indirect method of detecting a star's motion.

Multiple Star Systems and Stellar Mass

•More than half of what appear as single stars are in fact multiple star systems.

•*Optical doubles* are two stars that have small angular separation as seen from Earth but are not gravitationally linked.

•*Binary star system* is a system of two stars that are gravitationally linked so that they orbit one another.

Stellar Mass

- Speed and Direction of motion.
- If the star is part of a multiple star system…
    - Orbital motion
    - <u>Using Kepler's 3rd Law, we can determine the mass of each star in the system (this is the only way to do this!!!).</u>

Mass-Luminosity Relationship

- <u>It gives astronomers another method to determine the mass of star.</u>
- Especially if that star isn't part of a multiple star system!

Binary Stars

- <u>Spectroscopic Binary</u> - two stars that are found to orbit one another through observations of the Doppler effect in their spectral lines
- <u>Eclipsing Binary</u> - two stars that regularly eclipse one another causing a periodic variation in brightness

Variable Stars

- Stars that have a change in brightness over time are called <u>variable stars</u>.
    - Examples:
        - eclipsing binary stars
        - Cepheid variables
        - Mira variables
- <u>Light Curve</u> - a plot of a variable star's apparent magnitude versus time

Lecture 07: Stellar Evolution
Astronomy Today – Chapters 18, 19, & 20

Gas and Dust

- The combination of gas and dust in the galaxy is called the interstellar medium.
    - 90% H, 9% He, 1% Other
- Evidence for Gas and Dust
    - Various types of interstellar dust clouds.
    - Extra lines in the spectra of binary star systems.
    - Dimming and reddening of distant stars.
- Interstellar gas clouds are called NEBULAE.
- There are three types of nebulae.
    - Emission
    - Dark
    - Reflection

Evolution of Low-Mass Stars

1. The Sun began its life like all stars as an <u>interstellar cloud</u> that collapsed.
    - possible causes include
        - Spiral density waves
        - Shockwaves from Supernovas *
        - Galactic Collisions

2. This cloud collapses due to gravity into a <u>dense core</u>. As the cloud collapses, it spins faster (conservation of angular momentum). Rate of collapse is greater nearer the center ($F \sim 1/d^2$).

3. (a) Over the next few million years a <u>protostar</u> forms that is heated by gas compression (ideal gas law: PV=nRT).
    - Radius = ~50 R_{sun}
    - Core Temp = 150,000 K
    - Surface Temp = 3500 K
    - Energy Source = Gravity

   (b) Approaching the 10 million year mark, pressures and temperatures in the core of the protostar are ripe for nuclear fusion (proton-proton chain). The protostar becomes a <u>pre-main sequence star</u>.

    - Radius: ~1.33 R_{sun}
    - Core Temp: ~10,000,000 K
    - Surface Temp: 4500 K
    - Energy Source: H fusion begins

4. ZERO AGE MAIN SEQUENCE STAR - temperature reaches a steady 15,000,000 K (~27 million degrees F) and the pressure reaches 1 billion ATM in the core, fusion is sustained in the core and we now have a main-sequence star.

    - Radius: ~ R_{sun}
    - Core Temp: ~15,000,000 K
    - Surface Temp: 6000 K
    - Energy Source: H fusion is sustained

5. Low mass stars like the Sun remain on the main-sequence for about 10 billion years. They are in a state of hydrostatic equilibrium. Note: Massive stars stay on the main-sequence for about 1 billion years.

6. When hydrogen fusion begins in a shell around the core, the star expands into a Red Giant.

7. After most of the hydrogen is fused into helium the core begins to collapse. Core pressure increases temperature to 200,000,000 K (~360 million degrees F). Helium fusion begins in an event called the Helium Flash.

8. Stars can then become unstable and turn into pulsating stars like RR Lyrae Variables or Cepheid Variables: Cepheid Variables-High Mass (periods=several hundred days), RR Lyrae-Low Mass (periods < day)

9. As a star burns helium into carbon (*helium-shell flashes*) the radiation pressure pushes the star's outer atmosphere away from the core creating a Planetary Nebula.

10. This leaves an exposed core called a White Dwarf. These have about the same diameter as the Earth.

Evolution of High-Mass Stars

1 to 5. Same as before…

- interstellar cloud
- dense core
- protostar
- pre-main sequence star
- main-sequence star

6. When a high-mass star exhausts the hydrogen fuel in its core the star leaves the main sequence and begins to burn helium. At this stage the star becomes a Cepheid Variable.

7. The star becomes a Red Supergiant after millions of years of helium fusion.

8. When helium is depleted, fusion of heavier elements begins. This process is called nucleosynthesis:

H -> He -> C -> O -> Si -> Fe

H burning (main sequence) = ~10 million years
He burning (triple alpha) = ~1 million years
C burning = ~300 years
O burning = ~2/3 year
Si burning = ~2 days

9. A star with an iron core is out of fuel. Reason: Iron atoms cannot fuse *and* release energy.

10. The core collapses due to reduced pressure converting the iron core into mostly neutrons. Core temperature is on the rise which begins the following sequence of events. Some nuclei convert back into He which then breaks down…

$He \rightarrow p^+ + n$

$p^+ + e^- \rightarrow n + \nu$

11. The core pressure then surges and lifts the outer layers from the star in a titanic explosion - a supernova!

Russel-Vogt Theorem

- M*<0.01 Solar Masses = Planet
  - Jupiter mass = 0.001 Solar Mass
  - Heated Internally (PV=nRT)

- 0.01 Solar Masses < M*<0.085 Solar Masses = Brown Dwarfs
  - Never become hot enough for H fusion.
  - Heated internally (PV=nRT).
  - Core Temp = 3 million K
  - Surface Temp < 2000K (seen in IR)

- 0.085 Solar Masses <M*<0.4 Solar Masses = Red Dwarfs
  - H fusion happens.
  - Never get hot enough for helium fusion later.
  - Very long lived stars.

- 0.4 Solar Masses < M* < 1.2 Solar Masses – Sun Like
  - Typical sun-like star.
  - Burns H to He via P-P chain.
  - Burns He to C via the Triple-alpha process.
  - Core fusion ends at electron degeneracy.

- M*> 1.2 Solar Masses
  - Core temps can get high enough to burn H via the CNO cycle.

- M*>8 Solar Masses
  - Can have a large number of fusion processes at work in the core.
  - Cores are larger than 1.4 solar masses.
  - End lives as *supernovae.*

Lecture 08: Stellar Remnants
Astronomy Today – Chapters 21 & 22

White Dwarfs...

- ...are stellar remnants for low-mass stars (less than 8 $M_\odot$)
- ...are found in the centers of planetary nebula.
- ...have diameters about the same as the Earth's.
- ...have masses less than the Chandrasekhar mass (1.4 Solar Masses).
- …cores are held up by electron degeneracy.
- …a teaspoon full of WD material would weigh 5 tons.
- …nuclear fusion isn't happening in its core.
- …have temperatures ~30,000 K (~54,000^{o}F)
- …take billions of years to cool off.

Remnants of High Mass Stars

- …have masses higher than 8 solar masses.
- …can create the temperatures and pressures inside their cores to fuse elements heavier than carbon and oxygen (nucleosynthesis).
- …eventually explode as supernovae.
- …seed the universe with heavy elements through this process.
- …leave behind an expanding nebula of material.
- …also leave behind a neutron star or a black hole (depending upon core mass).

Supernova - a stellar explosion that marks the end of a star's evolution

Type Ia Supernovae
- Occur in binary systems in which one is a WD.
- Produced by runaway C fusion in WD core.
- No H or He lines; strong ionized Silicon II lines

Type Ib and Ic Supernovae
- Mark the end of a high mass star when the core collapses.
- No H or He lines because most of it was lost when star 'puffed' off its outer layers long before the explosion.

Type II Supernovas
- Occur when a massive star's iron core collapses.
- Envelope intact at time of explosion, therefore H and He lines are prominent in spectra.

Large Mass Star - Core Remnants

- Too massive for electron degeneracy to halt collapse (> 1.4 $M_\odot$)
    - Electromagnetic force
- Neutron Degeneracy can halt collapse
    - $M < 3\ M_\odot$
    - Strong nuclear force
    - Neutron Star
- Quark Stars
    - Held up by 'quark pressure'
    - Smaller than Neutron Stars

Strange Properties of Neutron Stars

■Tenuous Atmosphere

- Soft X-rays
- Plasma state

■Brittle Crust

■Superfluid Neutrons (no friction)

■Superconducting Protons (make magnetic field)

Pulsars

■Pulsars are rotating, magnetized neutron stars.

- Interior is composed of superfluid neutrons.
- Flow without friction.

■Light House Model

- Beams of radiation emanate from the magnetic poles.
- As the neutron star rotates, the beams sweep around the sky.
- If the Earth happens to lie in the path of the beams, we see a pulsar.

Rotation Rates of Pulsars - The neutron stars that appear to us as pulsars rotate about once every second. Before a star collapses to a neutron star it probably rotates about once every 25 days.

End Points of Stellar Evolution

■Low Mass Stars

–$M^* < 8\ M_\odot$

–Become White Dwarf ($M_{core} < 1.4\ M_\odot$)

■Electron Degeneracy Pressure

■Density = 1 ton/cc

■Medium Mass Stars

–$8\ M_\odot < M^* < 25\ M_\odot$

–Become Neutron Stars ($3\ M_\odot < M < 1.4\ M_\odot$)

■Neutron Degeneracy Pressure

■Also possible, Quark Degeneracy Pressure

■Density = 200 million ton/cc

■High Mass Stars

–$M^* > 25\ M_\odot$

–Hypernovae (subclass of Type II Supernovae)

–Become Black Holes ($M > 3M_\odot$)

■Density = Infinite

Black Holes

■...are stellar remnants for high-mass stars.

■…have a gravitational attraction that is so strong that light cannot escape from it.

■…are found in some binary star systems and there are super-massive black holes in the centers of some galaxies.

Black Holes and Einstein

■The existence for black holes was predicted as a result of the Einstein's work in understanding the behavior of light.
■Special Theory of Relativity (1905)
–Speed of light is always constant.
–Consequences of Traveling Near the Speed of Light
»Time Dilation
»Length Contraction
»Mass Inflation
■General Theory of Relativity (1915)
–Gravity is a result of a distortion in the fabric of "space-time".
–Gravity can bend (and slow) light.
»Gravitational red shift.

Black Hole Properties

■Singularity – at the center
–infinitesimally small
–infinite density
■Energy radiates in the form of gravitational waves.
–Explains the loss of magnetic field.
■Only retains 3 former properties.
–Mass
–Angular Momentum
–Electrical Charge
–"No Hair Theorem"
■Two basic types:
–Non-rotating black holes (Schwarzchild)
–Rotating black holes (Kerr)
»Ring-shaped singularity
»Spins thousands of times per second.

Schwarzschild Black Hole Radius: R = 3M

Lecture 09: Galaxies
Astronomy Today – Chapters 23, 24, & 25

■How many stars are in the Milky Way?
- ◆~200 billion

■How big is the Milky Way Galaxy?
- ◆~163,000 light years in diameter

■How old is the Milky Way Galaxy?
- ◆According to the levels of Beryllium produced in globular clusters it is 13.7 billion years old (Aug. 2004)
- ◆It should continue producing stars for another 10 billion years.
- ◆Recall: The Sun is 4.5 billion years old.

Where are we inside the Milky Way Galaxy?

- William Herschel made an attempt to map the Milky Way Galaxy in the 1780s.
- He thought that he could see equal numbers of stars in all directions along the plane of the Milky Way.
- This led him to incorrectly place our solar system at the center of the galaxy.
- Another Problem! He didn't know about gas and dust in the MW and how it affects star light. Interstellar dust obscures our view at visible wavelengths along lines of sight that lie in the plane of the galactic disk

Where in the Milky Way is our solar system located?

- The solar system is located in a spiral arm about <u>26,000 light years</u> from the center of the Milky Way.
- In 1917 Harlow Shapley discovered that the <u>globular clusters</u> form a huge spherical system that is <u>not</u> centered on the Earth. He observed RR Lyrae variables in the globular clusters in order to determine their distances. Combined with their direction, the globular clusters gave us the Sun's location

Mapping the Milky Way Galaxy

- Visual light is absorbed by gas and dust. This limits our viewing out to 4000-5000 pcs.
- Astronomers use radio telescopes to map the Milky Way Galaxy.
- They 'listen' to the faint hiss from cold hydrogen in the 21 cm wavelength.
- 21 cm wavelength from cold H
- In addition to mass and charge, protons and electrons also have angular momentum called SPIN.
- When an electron's spin orientation changes it gives off a little energy in the form of photon with a wavelength of 21 centimeters.

The Center of the Milky Way

- Harlow Shapley discovered that the globular clusters orbit about the center of the Milky Way Galaxy.
- He deduced that the center of the galaxy would be in the direction of Sagittarius.
- This was later proven in the 1930s (Jansky, Bell Telephone Laboratory) when an intense source of radio waves (synchrotron radiation) was detected in the direction of Sagittarius. It was labeled Sgr A*.

The Black Hole at the center of the Milky Way Galaxy!

- Astronomers long suspected a black hole at the center of the galaxy, but couldn't detect the x-rays that it would emit.
- The Chandra X-ray observatory was placed into orbit for the sole purpose of observing in x-rays.
- Chandra even detected the characteristic 'jets' associated with black holes observed at the center of other galaxies.
- Sgr A^* is at the focus of the orbits of several stars. Using Kepler's 3rd law, these stars seem to be orbiting a black hole with a mass of 2.5×10^6 solar masses and a volume about the size of our solar system.
- In 2001, an X-ray burst from SgrA* indicated a black hole with a diameter of 1 AU.

The Galactic Halo

- Globular Clusters
- Halo Field Stars
- Sagittarius Dwarf Galaxy is trapped in the halo and is being slowly devoured by the Milky Way.
- Dark Matter

Globular Clusters

- Found mostly in the galactic halo.
- 10,000 – 1,000,000 stars
- Spherical Shape
- Radius ranges from 40 to 160 light years.
- There are an estimated 150-200 globular clusters in the galactic halo.

How do Spiral Arms form?

- Density-Wave Theory (best so far)
    - Spiral arms are created by density waves (caused by gravity) that sweep around the Galaxy
    - Similar to ripples in a pond (Lindblad, Lin, Shu).
    - This action compresses interstellar clouds and triggers the formation of the OB associations and H II regions that illuminate the spiral arms.
- Density wave theory explains 'Grand-Design' galaxies pretty well but doesn't work for 'Flocculent' galaxies.

The Milky Way Galaxy Rotates

- Exhibits differential rotation. It doesn't rotate like a solid disk.
- The galactic orbital speed of the Sun is 790,000 km per hour (~0.5 million mph).
- The Sun orbits the galactic center once every 220 million years.
- According to Kepler's 3rd law, stars farther from the galactic center must orbit slower than the Sun. Observation shows the opposite is true. Orbital speeds increase beyond the disk of the galaxy. For this to occur, there must be more matter beyond the orbit of our Sun to create the gravity necessary for this effect.

The Mass of the Milky Way Galaxy

- The mass of the MW galaxy has been calculated to be 10^{12} solar masses (using Newton's form of Kepler's 3rd Law). However, astronomers can only account for about 10% of this total (only 10% is stars). There is an additional 90% of mass yet to be found in our galaxy.
- Most of the mass must be in the form of DARK MATTER.

DARK MATTER

- Dark matter doesn't emit much radiation and can only be detected by its gravitational influence on its surroundings.
- Dark matter is distributed in a halo surrounding our galaxy.
- What is dark matter really?
    - MACHOS – Massive Astrophysical Compact Halo Objects
        - Dim objects less than 1 solar mass.
        - Could include Brown Dwarfs, White Dwarfs, or Black Holes?
        - Detected through Microlensing.
        - Neutrinos with a small amount of mass.
    - WIMPS – Weakly Interacting Massive Particles
        - Predicted by Theory.
        - Masses as much as 10,000 times that of protons and neutrons.
    - Mystery Stuff

The Galactic Disk

- The disk consists of…
    - Stars (bulge-old red stars, disk-young blue stars)
    - Clusters
    - Nebulae
        - Most of these objects are cataloged…
            - Messier Objects
            - New Galactic Catalog (NGC)
            - Smithsonian Astrophysical Observatory (SAO)
            - Etc…

Open Star Clusters
- Consist of only a few hundred stars.
- Radius: 7-20 light years
- Form out of nebulae.
- Found throughout the galactic disk in the spiral arms.
- Estimated to be about 20,000 in total.

Messier Catalogue
- Charles Messier made the first catalog of non-stellar "fuzzy" objects during the 1770's. He made a list of 109 such objects that he did not want to mistake for comets.
- These objects turned out to be the following:
    - galaxies
    - star clusters
    - nebulae

Spiral Nebula or Island Universes?
- William Parsons the 3rd Earl of Rosse in Ireland built this large telescope in 1845.
    - Observed "spiral nebulae"

The Great Debate – April 26, 1920
- Heber D. Curtis & Harlow Shapley
- Debate concerned the true nature of "spiral nebulae"

Henrietta Leavitt – Cepheid Variables
- Leavitt discovered Cepheids in the Small Magellanic Cloud.
    - Developed the period-luminosity relationship for Cepheids.
    - Faint Cepheids pulsate with short periods.
    - Bright Cepheids pulsate with long periods.
- Cepheid Period is measure by watching the change in brightness.
    - Once the period is determined, we know the luminosity of the Cepheid.

Edwin Hubble
- In 1923, Hubble photographed the Andromeda Galaxy at Mt. Wilson Observatory.
    - He discovered Cepheid variables in the Andromeda Galaxy.
- He calculated the distance to the Andromeda Galaxy to be ~2.2 million light years. This proved that 'spiral nebulae' were 'island universes' or galaxies.
    - Hubble also developed a classification system for galaxies.

Spiral Galaxies
- Spiral shape with long arching arms which are rich star formation regions.
- Spiral arms are therefore home to young stars (blue & metal rich).
- The halo and nucleus are home to older stars (red & metal poor).
- Large amounts of gas and dust.
- Classified as follows…
    - Sa – tightly wound arms; fat nuclear bulge
    - Sb – moderately wound arms; moderate nuclear bulge
    - Sc – loosely wound arms; tiny nuclear bulge

Barred Spiral Galaxies

- Same properties as normal spiral galaxies with a bar of stars running through the nuclear bulge.
- Bar might form as a result of not having as much dark matter as other spiral galaxies.
- Classified as follows…
    - SBa – large central bulge; tightly wound arms
    - SBb – moderate bulge; moderately wound arms
    - SBc – tiny bulge; loosely wound arms

Elliptical Galaxies

- These galaxies have an elliptical shape.
- Absolutely no spiral arms.
- Very little interstellar matter (gas and dust).
- Mostly old (metal poor) stars.
- Classified on a scale from 0-7.
    - E0 – roundest elliptical galaxies
    - E7 – the most elongated elliptical galaxies
- Range in size tremendously…
    - Giant Elliptical Galaxies - 2 million ly diameter
        - Contain 10 trillion solar masses
    - Dwarf Elliptical Galaxies
        - Only a few million stars.

Irregular Galaxies

- No obvious structure.
- Smaller than most galaxies.
- Lots of gas and dust.
- Mixture of old and young stars.
- Could be formed as a result of …
    - Galactic Collisions
    - Galactic Cannibalism
- There are two irregular galaxies orbiting the Milky Way Galaxy.
    - The Large Magellanic Cloud
    - The Small Magellanic Cloud

Clusters of Galaxies

- Groups of galaxies are held together by their mutual gravitational attraction.
- Local Group – contains the MW galaxy, Andromeda (M31), and several dozen smaller galaxies in a space 3 million light years across.
- Super clusters – very large collections of galaxies; MW belongs to the Virgo Super cluster.

Active Galaxies

- Galactic centers emit abnormally large amounts of electromagnetic energy.
- 10% of all galaxies are considered to be active galaxies.
- Examples: radio galaxies, Seyfert galaxies, blazars, and quasars.

Lecture 10: Cosmology
Astronomy Today – Chapters 26, & 27

Edwin Hubble's Galaxy Observations

- During the 1920's Edwin Hubble and Milton Humason photographed the spectra of many galaxies with the 100 inch telescope at Mount Wilson.
- They found that most of the spectra contained absorption lines with a large <u>redshift</u>.
- Using the <u>Doppler effect</u>, Hubble calculated the <u>velocity</u> at which each galaxy is receding from us.
- Using the period and brightness of <u>Cepheid</u> variables in distant galaxies, Hubble estimated the <u>distances</u> to each of the galaxies.
- Hubble noticed that there was a linear relationship between the <u>recessional velocity</u> and the <u>distance</u> to the galaxies.
- This relationship is know as Hubble's Law:

$$V = H\ D$$

recessional velocity = Hubble's Constant × Distance

H is known as the Hubble constant and is about 72 $\pm$ 8 km/s/Mpc.

Hubble's Constant

- This number has been refined by using a variety of distance measurement techniques.
- These techniques are known as "standard candles".

Standard Candles

- Standard Candles provide measurements of the absolute magnitude.
    - o Remember! If you know the absolute magnitude (M) and the apparent magnitude (m) for a star, you can find the distance to that star.
- Inside the Milky Way Galaxy – Methods that are "direct".
    - o Parallax: 0 - 150 pcs
    - o Spectroscopic Parallax: 40 pcs - 10 kpcs

- Outside of the Milky Way Galaxy – Methods that are 'indirect' and yield an approximate value for absolute magnitude.
    - o RR Lyrae Variables: 5 kpcs - 100 kpcs
    - o Cepheid Variables: 1 kpcs – 30 Mpcs
    - o Tully-Fisher Relation: 700 kpcs – 150 Mpcs
        - *Broad 21-cm H line means bright galaxy*.
    - o Type Ia Supernovae: 1Mpc – 1000+Mpcs

The Age of the Universe - Hubble's constant can tell us the age of the universe.

- Age of the Universe = 1/H
- Today, the age of the universe is considered to be 13.7 $\pm$ 0.2 billion years.

The Big Bang Theory

- The cosmological red-shift of the galaxies tells us that the universe is expanding.
- The expanding universe probably originated in an event called the Big Bang.
- Evidence…
    - Red-shift of receding galaxies.
    - 3K (actually 2.7K) cosmic background radiation
        - Leftover radiation (microwave) from the formation of the universe.

3K Cosmic Background Radiation

- Discovered by Penzias and Wilson while testing a microwave horn antenna designed to relay telephone calls to satellites (1965). They accidentally detected the theoretically predicted 3K cosmic background radiation. This radiation seems to come from all directions in the universe.
- Detailed observations were made by COBE (Cosmic Background Explorer) from 1989-1994.
- The WMAP Mission (2001 – now)
    - Wilkensen Microwave Anistropy Probe (WMAP).
    - Shows small fluctuations in the cosmic background radiation.
    - Results from WMAP set the age of the universe at 13.7 billion years.
    - Results have shed light on the overall composition of the universe (more later).
    - WMAP showing small variations in the cosmic background radiation. Temperature differences in this image are no more than 200μK.

Brief History of the Unviverse

- In the beginning, all energy, time, and space was confined to an infinitesimally small space. Inside this 'ylem', the four forces of nature were combined into one.
    - This was a universe dominated by radiation. Abundance of photons.
- The expansion began (why? how?).
- As the universe cooled, each of the forces of nature 'froze' out of the mix making possible the formation of matter along the way.
    - Gravity
    - Strong Nuclear Force (holds protons and neutrons together in the atom's nucleus)
    - Weak Nuclear Force (governs radioactive decay; the changes in quarks)
    - Electromagnetic Force
- For the first 380,000 years, photons were so energetic that they prevented neutral atoms of Hydrogen to form.
- The universe was filled with a shimmering expanse of high energy photons – this state is called a *plasma* and is opaque to all wavelengths. This era is often referred to as the 'primordial fireball'.
- After about 380,000 years, the universe had expanded to a point that red-shifts were causing photons to lose energy. The event is called decoupling. Neutral atoms of hydrogen could now form.
- Over the next 100,000 years, the universe stopped being hazy and became transparent. This period is call the 'era of recombination'. Telescopes can't see beyond this point.
    - IOK-1 Farthest known galaxy – 12.88 billion light years.

- The universe was making the transition from being dominated by radiation to being dominated by matter. Gravity slowly became the key force controlling the fate of the universe.
    - For most of this transition time, the universe was dark.
- Over the next few billion years, galaxies began to form out of huge clouds of hydrogen gas. Light once again was seen in the universe.

Future of the Universe

- For much of the 20th century, two theories dominated…
    - Universe will expand forever (Big Chill)
    - Gravity will halt the expansion (Big Crunch)
- In order for the Big Crunch to occur, we needed to find more matter in the universe.
    - The search was on for Dark Matter!

Future of the Universe

- Astronomers now know that only about 22% of the mass of the universe is Dark Matter. This isn't enough to halt the expansion.
- Recently, astronomers have determined that the expansion of the universe is actually accelerating due to a repulsive force called "dark energy". It appears that the expansion will go on forever.
- Two ideas for Dark Energy
    - Vacuum energy predicted by Einstein's Cosmological Constant
        - Particles spring in/out of existence in the vacuum of space creating repulsive energy.
    - Quintessence
        - Energy in the vacuum of space that has been accumulating since the expansion and eventually over powers gravity.
- The discovery of 'dark energy' proves that the universe is 'flat'.

Composition of the Universe

4 % Ordinary Matter (called baryonic matter)
22 % Dark Matter
74 % Dark Energy