Lecture 1

Friday, January 6, 2017 1:35 PM

Types of astronomical data

- Astronomy is limited to three types of measurements
- Limitations due to large distances, extreme conditions
- Unlike most other sciences: requires indirect proxy measurements of physical properties

1. Images- pictures of the sky, intensity and colour as a function of position on the sky.
   - Helps to determine positions: astrometry
   - Helps to learn morphology: structure & evolution
2. Time Series: variations in the intensity or other properties of a celestial signal with time
   - Helps to measure motions: dynamics
   - Helps to measure rotations: pulsation
   - Helps to study instabilities: e.g. Sunspots, x-ray bursts
3. Spectra:
   - Intensity of light as a function of colour
   - Energy distribution of light
   - Determines temperature, composition, evolutionary state
     - Determines motion toward and away from us

All types of data revolve around light & photons
We rarely use actual samples of matter
There are also gravitational waves

- Newton was the first person to show that white light is actually a spectrum of colours
- Light is part wave part particle
- Waste nature is categorized by wavelength
- Particle nature is categorized by Energy E
- Shorter wavelength = higher energy
- Light exists on the electromagnetic spectrum
- Light can be called electromagnetic radiation
- Wavelength is the distance from crest to crest on the light waves
- Frequency can also be used to measure wavelength/wave nature
- Frequency(wavelength)=speed of light

Lecture 2

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Light Continued

- light can also be characterized by its frequency (measured in Hz)
- Done through the relationship: frequency * wavelength = speed of light
- Therefore, wavelength = speed of light / frequency

Light Travel Time

- Light travels at 3*10^8 m/s in a vacuum
- Light takes finite time to travel from one place to another
- Light from a source at distance d=10m takes
  T= d/v =d/c =10/(3*10^8) = 3.3*10^-8 =33ns
- Looking at the cosmos=looking back in time

Light Years

- The distance light travels in a year
- 9.4*10^15 metres =1 light year

Astronomical Unit

- Equal to the average distance between the sun and earth
- 150 million km
- 1.5*10^11 m

Astronomical Distances

- Distance to sun = 8.3 light minutes
- Distance to nearest star = 4.3 light years

Matter

- Made of atoms and molecules
- Light originates from matter
- Light interacts with matter
  - Can emit light
  - Can absorb light
  - Can transmit light
  - Can reflect light

Atoms

- Atoms are made of protons, neutrons, and electrons

Spectral Lines

- When electrons jump between energy levels, they emit light of energy equal to the difference between the levels
- Atoms can also absorb light if it has energy exactly equal to the difference between energy levels
- This atom (and molecule) property allows us to determine the composition of astronomical objects

Lecture 3

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Change in electron energy = planck's constant *frequency
Wavelength * frequency = speed of light

Thermal Radiation

- Aka black body radiation
- All objects emit electromagnetic energy because of the motion of their atoms/molecules
- The emission is a continuous spectrum
- This is why heat makes things red/white/blue
- Wavelength max = (2.9 million / temperature) NANOMETRES

Lecture 4

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- 0 latitude = the equator = north/south
- 0 longitude = Greenwich England west/east
- Zenith: point directly overhead
- Meridian: the circle through the zenith connecting the north and south poles
- Sun rises on the east and sets on the west
- Stars also have "lat" and "long"
    - Declination (lat) , right ascension (long)
        - Right Ascension is constantly changing as earth rotates
        - If dec = lat, the star passes directly overhead when right ascension crosses local meridian
- Altitude of Polaris = your latitude
- Circumpolar stars: Stars that never rise or set
- Constellation: apparent group of stars
- Earth orbits sun on an ecliptic plane
- Obliquely: tilt of a planets axis (earths is 23.5 degrees)
- Constellations that lie in the ecliptic are the constellations of the zodiac
- Solstice is when the separation between celestial equator and ecliptic is maximal: occurs twice per year
    - June 21, December 21
    - Longest, shortest days
- Equinox is when the planes intersect
    - March 21, September 21
    - Night & day are both 12 hours
-

Lecture 5

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- The celestial equator is the earths equator with its tilt factored in
- The ecliptic plane is earth equator in reference to the sun (aka flat)
- Tropic of Cancer is above the equator
- Tropic of Capricorn is below the equator
- Sun above equator = long days
- Sun below equator = short days

THE MOON

- Orbits earth every ~29.5 days
- Is visible via reflected light from the sun
- Has phases depends on where it is in cycle
- New moon->waxing crescent->first quarter->waxing gibbous->full->waning gibbous->Third Quarter->waning crescent
- Moons orbit about earth is tilted 5 degrees
- When the earth blocks the sun's light going to the moon, a lunar eclipse occurs
- Sets approx. 50 minutes later each day
- Solar eclipse is when the moon blocks out the sun for certain regions on earth

Lecture 6

Friday, January 20, 2017 1:34 PM

- During a lunar eclipse mars appears reddish because light is refracted by earth's atmosphere
- We can only have eclipses twice a year

TIDES

- Tides arise because of gravitational force due to the moon pulling on one side of the earth greater than the other side
- Important effect in astronomy
- Not hard to calculate for earth/moon since
    - Earth/moon separation is 384,000 km
    - Earth diameter is 12,700 km
- Tidal bulge does not point directly at Moon beaches of Earth's rotation (ocean cant keep up)
    - Actual offset is about 10degrees
- This effect pulls the moon ahead in its orbit, giving it energy, causing it to spiral outwards slowly
- The earth moon distance is increasing by 3.8 cm per year
    - Verified via bouncing radio waves off the moon
    - Energy for this comes from earths rotation
    - This means when earth was first formed, earth was spiralling so fast that days were 5-6 hours

Moon Tide

- The moon also feels a tidal force
- Moon has no ocean
- Tides stress the moon, causing moon-quakes
- In the past the moon was molten, causing large tides

Parallax

- Technique to measure distance
- Also known as triangulation
- 1 degree = 60 arc minutes
    - 1 arc minute = 60 arc seconds
- P=d^-1
- 1 parsec = 3.26 light years

Lecture 7

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Aristotle

- Famous Greek philosopher
- Believed that the universe could be understood on aesthetic grounds
  - Not a scientist
- Earth was stationary
- All celestial bodies orbit earth
- Unknown force keeps spheres revolving

Ptolemy

- Alexandria, Egypt
- Introduced epicycles
  - Planets spin on their orbits

Copernicus

- Polish
- Noted that Ptolemaic predictions for planetary positions off by many degrees
- Realized that orbits would be much more simple if planets orbited the sun
- Church dogma stated earth was at the centre of the universe

Tycho Brahe

- Made the first precision astrometric measurements
- Earth and moon at the centre, all other planets orbit the sun

Kepler

- Worked for Tycho
- Realized that planetary orbits are not circular, they are elliptical

Keplers Laws

- Planets travel in elliptical orbits with Sun at one focus
- Planets travel fastest when they are closer to the sun
  - Equal areas of the orbit are swept out in equal time
- Square of orbital period P is proportional to cube of semi-major axis
- Kepler didn't understand why the laws worked, he just knew that they did

Lecture 8

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Galileo

- Italian
- First to use a telescope
- Discovered…
  - Saw craters and shadows on the moon; the moon is not a perfect sphere
  - Saw sunspots; discovered sun's rotation
  - Discovered the 4 moons of Jupiter; not everything orbits earth
  - Phases of Venus; fit nicely in copernican view
- Was hounded by the church, placed under house arrest for years, forced to recant beliefs

Essential Physics

- Galileo also understood inertia/mass
- As objects fall towards earth, they accelerate in the same way independent of their mass
- Neglecting air friction, two dropped objects will hit the ground at the same time
- Acceleration is rate of change of speed
  - m/s/s=m/s^2
- Earths acceleration due to gravity is 9.8

Newton

- British
- Invented Calculus(with Liebniz)
- Made fundamental contributions to optics
- Three laws of motion
- Universal law of gravitation

Laws of Motion

1. An object stays at rest or at constant speed unless a force acts on it
2. A force results in an acceleration that depends on the object's mass
   F=MA
3. Every force has an equal and opposite reaction force

Newton realized that the moon is constantly falling towards earth

- All planet orbits are actually due to gravity
- G is newtons gravitational constant
- R is the separation of objects
- M is the mass of the object(S)
- A=(GM)/r(^2)

Lecture 9

Friday, January 27, 2017 1:39 PM

Optical Telescopes

- Traditional astronomy
- Uses glass lenses to magnify and focus light
- First telescopes were refractors
- Refractors have disadvantages
    - Lens can get very large
    - Telescope structure bends
    - Chromatic aberration
- Modern telescopes are reflectors
    - Use a curved mirror to collect and focus light
        - No chromatic aberration
        - Lighter, can be supported from behind
        - Very large mirrors can be constructed
- The diffraction limit of a telescope is the minimum angle it can resolve
    - Theta= **2.5*10^5 *(wavelength / diameter of the telescope)**
- Hubble telescope diameter = 2.4m
- Hubble is excellent for imaging
- Ground telescopes are better for spectroscopy

Telescope sensitivity

- Amount of light collected is proportional to the are of the telescope
- S is inversely proportional to **pi(D/2)^2**

Optical telescope detectors

- Used to be the eye
    - Unreliable
- Film
    - Better
- Charge coupled devices
    - Convert photons to electrons, produces electrical current
    - Very light sensitive

Lecture 10

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Radio Telescopes

- Collect radio waves from stars, nebulae, galaxies
- Like large satellite dishes
- Doses focus radio waves to antenna
    - This is the detector of the radio telescope
    - Converts signal to electric current
    - Easily recorded, quantified, etc…
- Neat trick is possible
    - Can simulate a really big telescope aperture with several telescopes that are far apart
    - Aperture synthesis
    - Total collecting area = sum of telescope collecting areas of all telescopes
    - Resolution equal to having aperture equal to largest distance between telescopes

X-ray Telescopes

- Must be in space as atmosphere absorbs X-rays
- X-ray telescopes are unlike conventional telescopes as X-rays go through most materials
- Use grazing incidence mirrors to focus X-rays

Lecture 11

Wednesday, February 1, 2017 1:35 PM

The Sun

- Ultimate source of energy in the solar system
- Is a G2V star
- Makes its own light
- Has a powerful source of energy
- Facts:
    - Mass= 2*10^30kg
    - Radius= 700,000km
    - Rotates every 29 days
    - ~5 billion years old
    - Luminosity= 2*10^33 erg/s
        - 2*10^26 watts
- Produces energy/light through nuclear fusion
- Surface=photosphere
- Nuclear reactions happen at the centre of stars

Conservation of Mass

- Mass cannot be created or destroyed
- Mass is conserved in any chemical reaction

Nuclear Reaction

- Reactions
    - Nuclear Fission
    - Nuclear Fusion
    - Nuclear decay
- In neither case is mass conserved
- Fission
    - Unstable parent nucleus splits into more stable daughter nuclei
    - Starting mass = daughter mass + daughter mass + energy
- Fusion is the inverse of fission

Mass-Energy Conversion

- Albert Einstein realized that E=mc^2
- C is the speed of light
- Get a lot of energy out of a small amount of mass

Iron is the only stable nucleus

Has lowest binding energy

Nuclear Fusion

- Efficient clean way to produce energy
- No radioactive byproducts
- Very hard to start
    - Light nuclei don't know they prefer to be fused
    - Like charges repel
    - Need to push them together very close before they will fuse
    - Needs lots of energy to fuse: but then more is released

Back to the Sun

- Sun overcomes Nuclear Fusion problems easily
    - Pressure, density at core of sun so large that nuclear fusion happens easily
    - Hydrogen fused to helium

Lecture 12

Friday, February 3, 2017 1:41 PM

PP chain

- Start with two unbound hydrogen nuclei (2 protons)
- Step 1: fuse to produce deuterium: bound p+n
  - Produce neutrino, positron in the process
- Step 2: deuterium hits another proton, forms helium 3 (p+p+n)
- Step 3: two helium 3 collide, form helium 4 (p+p+n+n) and two extra protons
- In a p-p reaction, 0.007 of rest mass of initial 4 protons is released
  - Energy released = 0.007 (4mpc)c^2

Sun

- Every second, Sun converts 4 million tons of hydrogen to energy + helium
- 4 billion years of fuel
- Fusion takes place in solar core only
  - Inner 1/4 of solar radius
  - 15 million degrees K
  - Energy and radiation propagate outward

Standard Solar Model

- Fusion is the only known means of producing enough energy
- Composition shows that the sun is 76% hydrogen and 22% helium
- Helioseismology = study of oscillations of the sun
- Solar Neutrino Solution
  - Problem is that neutrinos oscillate between difference flavours
  - Homes take experiment was sensitive to election neutrinos only

Suns External Structure

- Deepest visibility region : photosphere
- Below photosphere, gas is opaque
  - Photosphere is where opacity is low enough to let light pass through
- Photosphere just above convection zone
  - Can see convective cells
- Just above Photosphere is Chromosphere
  - Coloured layer: glowing hydrogen
- Above chromosphere is the Corona
- Temperature decreases from core to photosphere
  - Temp high in core due to gravitational compression
  - Temp high in Corona due to magnetic field
- Sunspots are dark spots on the sun
  - Appear in groups
  - Very large (10ks km)
  - Regions where plasma magnetic field is relatively strong

Lecture 13

Monday, February 6, 2017 1:36 PM

Stars
- Sun is an example of a star
- A factory of nuclear fusion, creates heavy elements, produces heat and light
- Many different kinds of stars
- Well defined evolutionary path
  - Born, live, die
- Time scales are much longer than humans: billions of years
- Very far away
- Closest star is 260000 times the distance to the sun (Proxima Centauri)(4.3 ly)
- Distance to the sun is 1 au (1.5 *10^11)
- 1 parsec = 3*10^16 m
- 1 light year = 9.5*10^15

Apparent Brightness
- Stars that are far away explain why the sun is so bright
- Define luminosity: amount of energy star radiates per second
  - Equivalent to power
- Apparent brightness decreases with distance
- Inverse square law = (d)^-2
- Some stars are intrinsically brighter than others
- To compare stars, you must compare their intrinsic luminosity
- Parallax is best method we have
- Apparent brightness = (L/(4pi(D^2))) ONLY FOR ISOTROPIC RADIATOR
- Intrinsic luminosity = J/s

Stars Cont…
- Intrinsic luminosity of star determined mainly by its temperature
- Red stars cooler than blue stars
- To quantify, measure star's spectrum
- Look at continuous emission, use Wien's law
- Spectra have lines too
- Clear patterns in line features of spectra
- Intrinsic luminosity of star determined by temp & radius
- **Stefan-Boltzmann Law:**
  - Luminosity=4pi(radius)^2 * (5.67*10^-8) * Temp^4
- If you can measure a star's spectrum and distance then
  - From peak in continuous spectrum measure T, from total luminosity, measure R
- Measuring luminosity is difficult
- Detectors generally sensitive to narrow range of wavelengths
- Photometry: measurement of brightness in a specified wavelength range; or colour
- Combine measured colours to get total luminosity over all wavelengths: bolometric luminosity
- The calibration is very tricky; need excellent weather conditions for all measurements

Stellar Spectroscopy
- Spectra have lines too
- Clear patterns in line features of spectra
- Wavelengths of lines easy to measure
- Stellar temperature determined spectroscopically, using lines
- Astronomers in early 1900's studied spectra from millions of stars
- Major puzzle to understand this
- Patterns of lines occur because which electron transitions occur depends on temperature

Lecture 14

Wednesday, February 8, 2017 1:35 PM

Basic Stellar Properties

- Luminosty (L) = energy output (J/s = W)
- Temperature T (K)
- Radius R (m, Rsun)
- Mass M (Kg,Msun)

How to measure stellar properties

- Apparent brightness (b) using a telescope
- Measure colours or use Wien's law to determine black body temperature (T)
- Measure distance D to the star using the parallax technique
- With b & D determine the intrinsic luminosity (L)
- From T and L, use the Stefan-Boltzmann law to determine the stellar radius R

Wien's Law

- Lambda max in metres = 0.0029/T

Stefan Boltzmann law

- L=4piR^2sigmaT^4

Classifying stars

- Understanding stellar spectra took painstaking work over years
- Annie Jump Cannon, Cecelia Payne Gaposhkin pioneers in early 1900's
- O B A F G K M

Midterm Review

Tuesday, February 7, 2017 5:01 PM

- Equatorial coordinates
  - Celestial equator versus ecliptic
    - where's Polaris?
- Arc minutes/arcseconds
- Parallax angle to distance
  - P(arcsec)=1/d(parsec)
    - 1parsec = 3.26 light years
- Keplers laws
  a. Planets orbit in ellipses with the Sun at one focus
  b. Planets sweep out equal areas in equal time
  c. The square of the orbital period is proportional to the cube of the orbital semi-major axis (P^2[years] = a^3[AU])
- Classical dynamics formulae
  - F=ma
  - Fg= (GMm)/r^2
  - Ag = (GM)/r^2 = 9.8m/s/s on earth
  - G=6.67*10^-11 (m^3/s^2kg)
- Formula for light
  - C=3*10^8 m/s
  - F(lambda)=c
  - H=6.62*10^-34
  - S=4.14*10^-15
  - Ei-Ef+E=hf=hc/lambda
- Blackbody Radiation
  - Lambda max = 2,900,000nm/T in kelvin
  - L = 4piR^2(sigma)T^4
  - Sigma=5.67 *10^-8 W/K^4m^2
  - B=L/(4pid^2)
  - Brightness is inversely proportional to (R^2T^4)/d^2
- Key formulae for telescopes
  - S is inversely proportional to PiR^2
  - Thetamin[arcsec] ~= 2.5*10^5*(lambda/D)
- Properties of the sun
  - Msun = 2*10^30kg
  - Rsun = 700000 km
  - Sun = 3.8*10^26
  - Tsun ~=5700K
  - E=Mc^2

Lecture 15

February 15, 2017 1:35 PM

Measuring Intrinsic Parameters

- Astronomers first measure apparent brightness and then factor in distance to find intrinsic luminosity
    - Also find intrinsic temp, mass

Stars in the Sky

- Do a careful study of distribution of stars on sky, see many are very close to other stars
- Too many to be random: suggests clustering
- 1804 William Herschel found Castor has a fainter star orbiting it
- **Binary Star:** two stars orbiting each other
- **Multiple System:** several stars orbiting each other
- 2/3 of all stars are in binary/multiple systems

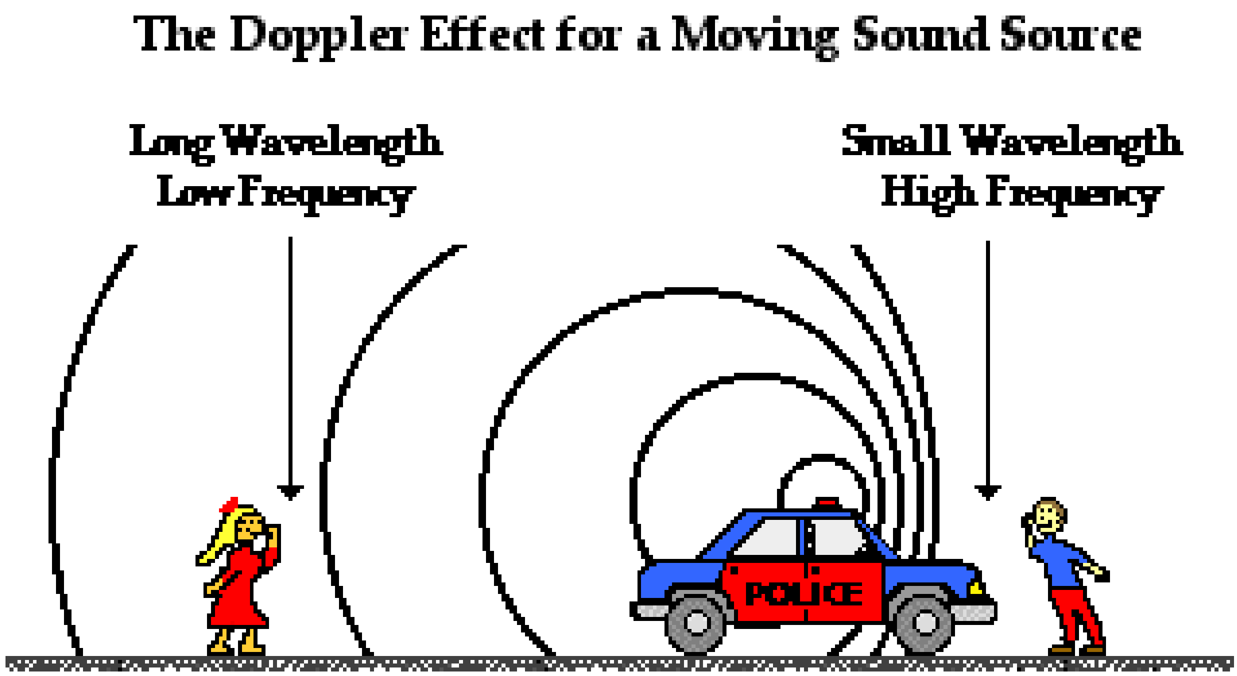
Types of Binary Stars

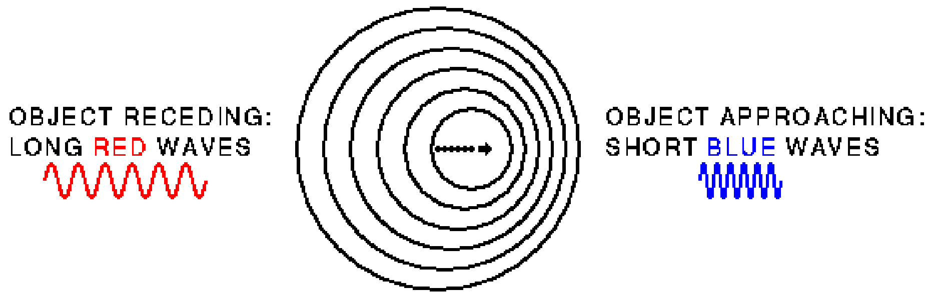
- Visual Binaries: we observe both stars directly
- Astrometric Binary: see "wobble" of a star but cant see 2nd star
- Composite Spectrum Binaries: observe one star but it has spectral lines from 2 different spectral types
- Eclipsing Binaries: light gets periodically dimmer and brighter
- Spectroscopic Binaries: Spectral lines of a star oscillate periodically about their average wavelength

Delta wavelength / wavelength = radial velocity/ light speed

Lecture 16

February 17, 2017 1:40 PM





Spectroscopic Binaries

- From double-line binary, can deduce **mass ratio** of stars
- From single-line binary, can only deduce combination of masses and unknown **orbital inclination angle**
  - Because you are detecting only radial motion, don't have all the information
  - Gives a *minimum* companion mass
- A binary which is visual or eclipsing and double-line spectroscopic binary gives all information about orbit, including both masses

Lecture 17

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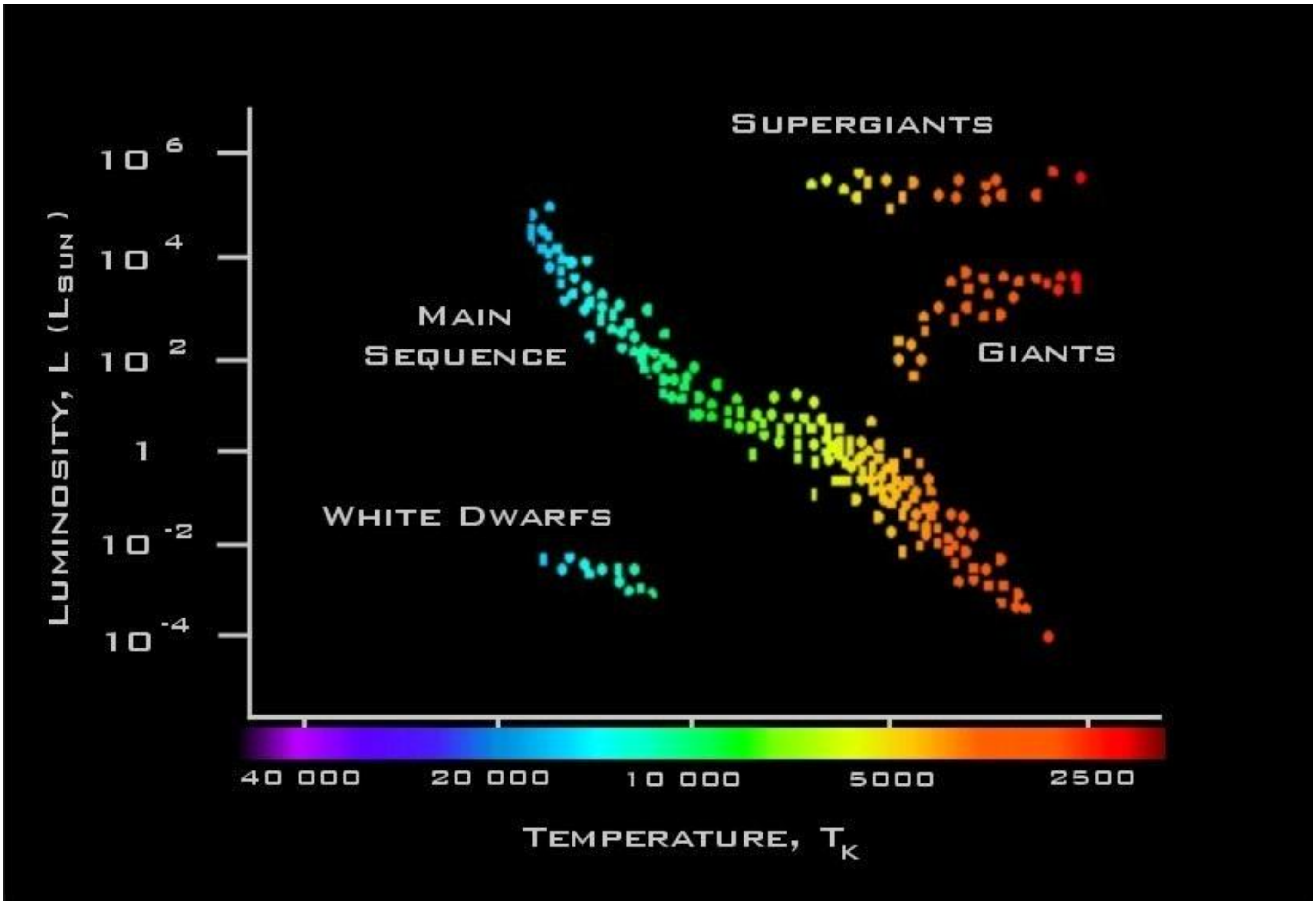


Main Sequence Stars

- Most stars lie on the main sequence
- Main sequence not equally populated: many more cool stars than hot stars
- But cool stars hard to observe
- Most prominent stars in night sky are luminous ones
- All stars on main sequence have as their primary energy source, nuclear fusion of hydrogen
    - Also called hydrogen "burning"
- Stars off the main sequence have a different primary energy source
- What determines where a star lies on the main sequence
    - Mass
        - Low mass stars are cool, faint, red
        - High mass stars are hot, bright, blue
        - Stellar size is determined by principle of hydrostatic equilibrium
            - Gravity pushes inwards
            - Gas and radiation push outwards
                - Hydro: gas acts like a fluid
                - Static: star neither expands nor contracts
                - Equilibrium: star reaches a balance between inward crushing gravity, outward pushing radiation
                - More mass stars have greater gravity pressure, but they heat up their cores more so more nuclear reactions occur, more pressure is pushed outwards by the gas, and a higher temperature is achieved.
- Main sequence represents region of stable configuration of stars burning hydrogen
- When stars run out of hydrogen to burn, they leave the main sequence
- The time for this to happen depends on stellar mass
- Hot stars live for a short time
- Cool stars live for a long time

Stellar Lifetimes
- Massive stars use fuel fast
- Lighter stars use fuel slowly
- Age of a star = 10^10(M/L)yr (Solar Masses/Solar Luminosity)

Leaving the Main Sequence
- Stars move to red giant branch of HR diagram
- Primary energy source is still nuclear fusion but internal structure changes

Star Clusters
- Most stars are in stellar clusters
    - **Globular Clusters**
        - Dense, gravitationally bound cluster of 10^5 - 10^6 stars
        - In the halo of the Milky Way
        - Old stars
    - **Open Clusters**
        - Loose collection of stars, barely gravitationally bound together
        - In the disk of the Milky Way
        - Young stars
            - If very small called "associations"

Globular Clusters
- Central regions have high stellar density
- Stars interact with each other, unlike in the Galactic disk where distances between stars are enormous
- Debated what is at centre
- No young stars
- Very old systems
- Can determine age using HR diagram

Open Clusters and Associations
- Open clusters: groups of 100-1000 stars
- Most have prominent young stars
- Stars in open clusters formed at same time
- Most stars were born in clusters
- Gravitation binding so weak eventually stars disperse
- Open clusters are short lived
- Associations: groups of ~dozen stars
- Looser structure, less bound, also short lived

Lecture 18

March 12, 2017 2:47 PM

Stellar Evolution

- We divide typical stellar life into 4 phases:
  - Formation and pre-main sequence
  - Main sequence
  - Post main sequence
  - "death"

Star Formation

- Stars from gas in **molecular clouds**
- Cold: 10-30K
- Lots of dust in these clouds
- Obscures most light
- Only infrared light emerges
- Star formation regions appear dark and reddish
- Density perturbations form "core" for star formation
- These cores collapse gravitationally
- Material near the core collapses first
- Rapid rotation
- When core material very dense, nuclear reactions begin
- Supports from further collapse
  - Leaves pre-main sequence star
  - Dusty cocoon
  - Jets produced along stellar poles

Pre-Main Sequence

- Protostar: undergoing unimpeded gravitational collapse, little inside pressure
- Pre-main-sequence star: interior pressure slows collapse, but no nuclear reactions yet
- Relatively short phase
- Massive stars reach main sequence fastest
- Pre-main-sequence phase very bright
- Energy from gravitational energy
- Not all protostars get to MS
- Need M>0.8 solar masses to have enough gravity for nuclear reactions to begin
- Boundary between stars and planets
- Brown dwarf: object that just didn't make it to star status
- Also, protostars with M>100 solar masses are unstable and just explode

Main Sequence

- Hydrogen burning phase
- Star's chemical composition, structure constantly changing
- Main seqeuence is a thick badn on HR diagram not a thin line
  - Stars start on line
  - As stars age, line gets thicker

Lecture 19

March 12, 2017 2:47 PM

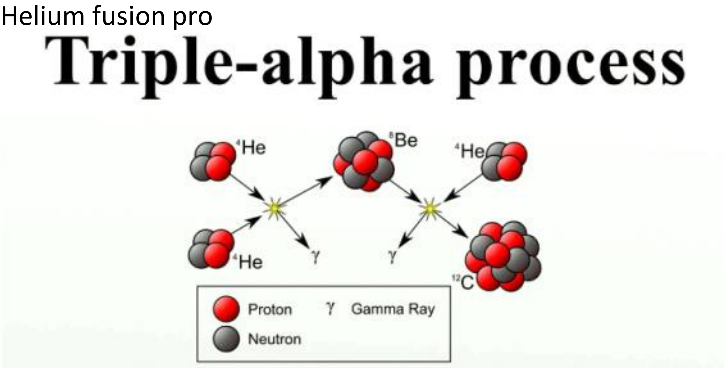
Three Possible Deaths

- Depends on mass
- M<2 sm = white dwarves
- 2<M<8 sm = red giants, other stuff, planetary nebulae, white dwarves
- M>8 sm = supernova

Low, intermediate-mass stars

- Main sequence:
  core hydrogen 'burning' ie fusion: pp chain
- Hydrostatic equilibrium maintained
- Modest evolution upward in HR digram
- Spends ~90% of lifetime on MS
- Eventually hydrogen depleted, core mainly helium
- Stellar core begins to shrink as gravity pulls inward, with less and less outward pressure

Red Giant Phase

- Helium core inert (no fusion)
- But unfused hydrogen shell surrounding core contracts too, fusion can begin
- Hydrogen shell burning phase
- Once shell burning star(t)s, very efficient burning
- More energy released than core burning
- Increases star's luminosity
- Puffs out outer layers
- Outer regions cool as they puff out
- Hydrogen shell burning creates more helium
- Inert helium core grows: subgiant phase
- Core continues to contract inward due to gravity
- Temperature rises in core
- At ~100 million K, helium starts to fuse
- Helium fusion pro
- 

Helium Core Fusion

- Theoretical computer models show that He fusion commences explosively
- "Helium flash"
- Takes seconds to minutes
- Huge energy release, doesn't escape star
- Thought to cause mass loss
- Physical origin related to electron **degeneracy** in the core
- No strong observational support but theory predicts it
- Following He flash, steady He core fusion begins, lasts ~100 Million years
- Analogous to main sequence but with core He burning and shell H burning
- Inert Carbon core forms
- Transitions to double-shell burning
  - Inert carbon core
  - He burning shell surrounds core

- H burning shell surrounds He burning shell

Death of a Low-Mass Star

- Eventually He depleted in the core
- Carbon core shrinks due to gravity
    - Again, nothing to sustain it as no fusion occurring
    - Double-shell burning efficient and outer layers expand again
    - Star becomes larger and more luminous than ever
    - Fuse carbon? Need temps greater than 600 million K
    - Solar-type stars never reach that
    - Electron degeneracy halts the core collapse

Planetary Nebulae

- Final end to solar-type stars in outer layers ejected
- Forms beautiful nebulae with hot carbon core visible
- NOTHING TO DO WITH PLANETS
- Ejected gas disperses into interstellar medium in ~100,000 yr
- Leaves behind hot inert carbon core: white dwarf

Lecture 20

March 6, 2017 1:35 PM

- High mass stars explode (supernova)

Guiding Physics in Stellar Evolution

- Throughout the star's life, **Constant battle** between the inward crushing pull of gravity and outward pressure of gas and radiation
- Starr constantly readjusting to changing structure as fusion proceeds
- Main sequence: longest period of equilibrium in star's life
- Other stages: equilibrium lost, adjustment to new equilibrium

Evolution of High-Mass Stars

- In a solar-type star, the inert carbon core never ignites
- Star insufficiently massive for core to contract and reach high enough temperatures
    - Core shrinkage halted by electron degeneracy pressure
- In more massive stars, carbon can be fused
    - Forms O/Ne/Mg core…
- Slowly develops 'onion' structure: layers of different elements

Post Main Sequence Evolution

- Continued evolution follows pattern…
    - When core fusion eases, hydrostatic equilibrium disrupted
    - Core contracts; outer layers expand
    - Next heaviest element starts fusion
    - Hydrostatic equilibrium restored
- Burbidge * 2, Fowler & Hoyle 1957:
    - Worked out which nuclear reaction happen
- Onion-Layer Structure is in core
    - Stellar radius ~1000Ro
    - Stellar core ~0.01R0
- When iron forms, fusion reaches ultimate obstacle
- Fusion of iron with anything requires energy, does not produce it
- Once iron forms, no more fusion can proceed
- Note that only for very massive stars does this happen
- Need sufficient gravity to get heavier elements to fuse

SuperNovae

- Fe core collapse occurs with enormous explosion: supernova
- Huge release of gravitational potential energy when collapse occurs
- Occurs every ~50-100 years in the milky way
- Crab Nebula
    - Result of a supernova from 1054 AD
    - Brighter than full moon for a month
- During explosion, nuclear fusion of heavy elements occurs
- **Explosive nucleosynthesis**
- Explains(in part) why we have elements heavier than iron

Lecture 21

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Quantum State of Matter

- At extreme densities, mater behaves strangely
- When compressing sub-atomic very closely, quantum mechanics matters
- Pauli Exclusion Principle: subatomic particles cannot have identical properties
  i.e. cannot be degenerate
- Creates real pressure when moving 2 identical particles together: can't have same position
- Called **degeneracy pressure**
- Matters after nuclear reactions cease

White Dwarves

- In stars having less mass than ~8 solar masses, when they run out of nuclear fuel
- Core collapses, outer layers expelled
- Core: matter squeezed together so densely that electron degeneracy pressure supports star from further collapse
    - Electrons keep the star from collapsing even further
- Mass < 1.4 solar masses
- Very dense: one teaspoonful = 5 tons
- Interior consists mainly of crystalline carbon (remains of core) plus 'sea' of degenerate electrons
    - There exists He WDs, O/Ne/Mg Wds but rare
- Star is very faint
- Once collapsed, just cools forever

Chandrasekhar Mass

- Electron degeneracy pressure supports Wds
- But if mass too large, either as core mass to high, or if matter dumper onto WD, electron degeneracy pressure fails
- Maximum white dwarf mass: 1.4 solar masses
- Also called Chandrasekhar limit
- Above the Chandrasekhar limit, electron degeneracy pressure fails and star collapse

Neutron Stars

- Support by neutron degeneracy pressure
    - Analogy of electron degeneracy pressure but from neutrons
    - Radius ~10km
    - Highest known density in universe (except for black holes)

Lecture 22

March 10, 2017 1:34 PM

Neutron Stars

- Supported by neutron degeneracy pressure
    - Analogy of electron degeneracy pressure but from neutrons
- Mass ~1.4 solar masses
    - Observed range = 1.25-2 solar masses
- Radius ~10km
- Highest known density in Universe (except for black holes)
- Likely have complex structure
- Density increases inward
- Normal matter in crust, atmosphere
- Central density exceeds that in atomic nuclei by a factor of ~10 at least
- Nature of matter at these densities unknown
- *Active area of research*

Radio Pulsars

- Rapidly rotating, highly magnetized neutron stars
- Rotation axis misaligned with magnetic axis
- Light beams emerge from magnetic poles
- Copious radio waves produced but emission across EM spectrum

Basic Neutron Star Facts

- Neutron star mass ~1.4 solar masses
    - About a half-million earths
- Typical radius = ~10km
- Birth surface temperature ~2-3million K
- Typical neutron star magnetic field: 10^12G=10^12 * earth's field
- Fastest known pulsar rotates 716 times per second

Lecture 23

March 13, 2017 1:35 PM

Doppler Shift in Binary Star

- In regular stars, detect binary orbital motion from Doppler shift of wavelengths of absorption lines

Doppler Shift

- You can determine the velocity of a stare from the change of wavelength
- Change of wavelength/wavelength = radial velocity/speed of light
- If pulsars are in a binary system then longer period between beeps = red shift, shorter period between beeps = blue shift

Doppler Shift in Pulsar

- Determines the velocity of the pulsar from change of period
- Change of period/true period = radial velocity/speed of light

Binary Stars: Review+

- Recall previously identified 4 types
  - Visual binaries
  - Astrometric binaries
  - Composite spectrum binaries
  - Eclipsing binaries
  - Spectroscopic binaries
- Binaries can fall in more than one class
- Also: Close Binaries
  - Binaries where stars are so close, one (or both) are gravitationally distorted by the other
  - When star's are close to each other, one star's gravitational pull distorts the other into a "tear-drop" shape: Roche Lobe
  - Star with Roche shape loses mass to other star through accretion stream to accretion disk
  - Mass falls onto other star from accretion disk because the falling matter has angular momentum: cannot fall straight in
  - Roche Lobes
    - Contours of constant gravitational potential energy
    - Near star, circular
    - Closer to other star, distorted
    - Red contour: Roche Lobe
    - If star large enough to "fill" its Roche Lobe, transfers matter through L1: "inner Lagrange Point"

More on Binaries

- Dethatched Binaries (normal)
- Semi-detached Binaries:
  - One star fills its Roche Lobe
  - Transfers matter onto second star
- Contact Binaries:
  - Stars are so close they share a common envelope (atmosphere)
  - Still have 2 separate cores

White Dwarf Novae

- Martial (hydrogen) falling onto WD surface becomes hot enough for nuclear fusion to occur in thin shell
- Bright burst of optical/X-ray emission
- Lasts a few weeks
- Can repeat sometimes every few decades

White Dwarf Supernovae

- A white dwarf in a close binary can accrete enough mass to put it over the Chandrasekhar limit: 1.4 solar masses
- Collapses and (if made of carbon) carbon begins to fuse but explosively: destroys the WD
- Like a core-collapse(aka massive star) supernova, can be extremely bright: 10^10 solar

luminosities
- But light curves are different so we can distinguish

Neutron Stars in Close Binaries

- Similar to WDs in close binaries: companion fills its Roche Lobe, matter flows via accretion stream into accretion disk and eventually onto NS surface
- Material hitting NS surface produces X-rays" "X-ray Binaries"
- Can have explosive nuclear burning on surface of NS: "X-ray Bursts"

Lecture 24

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Black Holes

- For high enough mass stars, neutron degeneracy pressure fails to stop gravitational collapse
  - True for stellar masses of >~20 masses or cores of >~3 solar masses
- No physical mechanism can halt gravity
- Former core of star collapses completely
  - Same can happen if dump a lot of matter onto a neutron star
- All the mass is crushed to a single point of infinite density… gravitational forces get very large

General Relativity

- Gravitational force interpreted geometrically
- GR describes distortion of space-time due to mass
- How objects, including light, travel through the distorted space-time
- Einstein realized from Equivalence Principle that mass distorts space-time
- The presence of mass causes a distortion of the space and time around it
- What we feel in a gravitational field is really just that distortion
- Takes gravitational force and makes it a geometric phenomenon so that Equivalence Principle is naturally followed, with acceleration that is independent of mass
- Particles (and light) move on trajectories determined by the distorted space-time, independent of their mass

Principle of General Relativity: Equivalence of Inertial and Gravitational Mass

- F = ma
- F = GMm/R^2

Principle of Equivalence

- Starting point for general relativity
  - A uniform gravitational in some direction is indistinguishable from a uniform acceleration in the opposite direction

Equivalence of inertial and gravitational masses

- Central issue is that **'mass' felt by the gravitational force is identical to 'inertial' mass felt by any other force F**
- Didn't have to be that way
  - Why should 'mass' involved in pushing an object sideways with some force F be the same as that involved in gravity?
- All objects fall with same acceleration in a gravitational field, independent of mass
  - Rock & feather fall with same velocity in vacuum
- Principle of equivalence verified to 1 part in 10^12

Mass Distorts Space-Time

- Think of space time as a flat rubber sheet. A mass distorts it, making it curved, far from the mass, space time is still flat. A particle must follow a geodesic line, which is curved in the presence of mass, since space itself is curved by mass. Motion is independent of mass, since determined by geometry, consistent with equivalence principle.

Tests of General Relativity: Gravitational Redshift

- Recall light's wavelength changes depending on its motion:
  redshifted if moving away
- GR: light's wavelength changes when passing through gravitational field: gravitational redshift
- Gravitational field does 'work' on light, changes its energy
- Z = gravitational redshift, Z = delta wavelength/wavelength = GM/rc^2
  delta wavelength = waelength2 - wavelength1

Black Holes & Schwarzschild Radius

- For any sphere of mass M, if $R<R_s$ it is a black hole
- Gravity so strong that nothing, not even light can escape
  - Equivalent to having an infinite gravitational redshift
- Also known as the event horizon
- R_s is critical radius for an object of mass M to be a black hole, a singularity in space time
- Note can have a black hole for any mass, a long as radius within R_s

- R_s = (3.0km)(M/MΘ) for a 1 solar mass object
- R_s = 2GM/c^2

Lecture 25

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Types of Black Holes: Stellar Mass

- Stellar mass black holes
  - Born in gravitational collapse of massive star
  - Observed through motion in binary system, accretion luminosity
  - Black hole mass inferred from velocity curve of companion
  - Often associated with jets observed at radio wavelengths

Currently Known Galactic Black Hole Binaries

- Roughly between two dozen stellar mass black holes or black hole candidates known
- All in binaries with mass transfer occurring
- Observe as bright X-ray sources
  - X-rays emitted from accretion disk
- Can measure doppler shifts of companion star's lines, determined mass of the black hole
- Typically 4-12 solar masses
- Varying degrees of certainty:
  - some extremely certain
  - Others less so

Gravitational Waves

- Key prediction of General Relativity is that moving masses produce **gravitational waves**, moving ripples in space-time
- Effect is weak; need large masses moving fast!
- Observable is a stretching of space-time: **"strain" h**, fractional change in length
- Typical strains h~10^-21

3 Classic Tests of GR

- Deflection of starlight (verified 1919 by Eddington Expedition)
- Gravitational Redshift
  - Verified in 1959 at Harvard U. by Pound & Rebka verified the frequency of a gamma-ray emitted from the roof of a tower was blue-shifted at the bottom of tower

Classical Tests of General Relativity: Precession of Mercury's Orbit

- In Newtonian mechanics, after one orbit, a mass returns to same place
- In General Relativity, eccentric orbits <u>**precess**</u>:
  - After each orbit, mass does not return to same place
- Mercury's precession had been noticed long before Einstein
- Einstein's theory explained it

Modern GR Test: Binary Pulsar

- Some radio pulsars in binaries
- Some pulsar binaries have few-hour eccentric orbital fields
- Stars 'feel' distorted space-time from one another
- Need General Relativity to correctly describe orbit
  - Huge precession! Degrees/yr
  - Can use the system to test GR
  - Gravitational waves emitted -> **orb should decay**

First Binary Pulsar Discovered in 1974

- Joe Taylor & PhD student Russel Hulse
- Pulsar 59 ms,
  companion 2nd unseen neutron star
- Orbital period 8 hrs, highly eccentric
- Orbital precession like mercury but 4 degrees/year
- Predicted emission of gravitational waves not detected but **expect orbit to decay**

Advanced LIGO

- Laser Interferometric Gravitational Wave Observatory:
  - Livingston Louisiana; Hanford, Washington each have 4-km interferometer

- Searching for gravitational wave signals from merging black holes, merging neutron stars, BH/NS systems
- Uses powerful lasers to measure distances with extreme accuracy

LIGO: Interferometer

- Laster beam split in two directions
- Bounce off mirrors
- Return to interfere: add or subtract depending on path length difference

Lecture 26

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Milky Way Galaxy

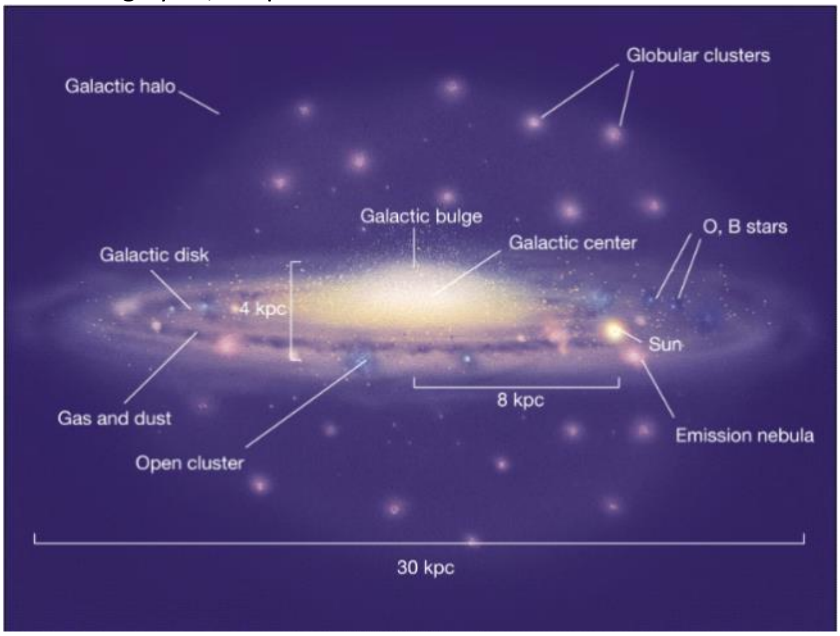
- We live in a spiral galaxy called the milky way
- We are right in it, so we cannot observe its form
- Likely looks a lot like nearby andromeda galaxy
- The different parts differ not only in where the stars are located, but in the shapes of the star orbits
- Also differ in age and chemical composition
- Halo stars, globular clusters: old, low metal abundances
- Disk stars, open clusters: young, high metal abundance
- Bulge stars: intermediate, mixture
- These are clues, like a fossil record, of how the Milky Way formed
- Roughly 10 billion years old
- Yet we find O and B stars with ages of 10^7 years
    - Galaxy continually forming stars
    - Star formation in giant gas clouds that collapse gravitationally
- Stars just one component: Galaxy contains lots of gas & dust
- Interstellar Medium: region between the stars
    - Not a vacuum!
    - Dust, cold & hot gas

Interstellar Extinction

- Dust permeates the interstellar medium (ISM)
    - Microscopic solids, complex molecules
        - Silicates, water ice, ammonia ice, polycyclic aromatic hydrocarbons, solid at CO, etc
- Can detect it at infrared wavelengths
- But dust blocks starlight: extinction of starlight

Structure of Milky Way

- Roughly 30,000 parsecs across



Milky Way Structure

- Milky Way is a disk galaxy with spiral arm structure
- Stellar content can be classified into 2 main groups
    - Population 1 stars: Young, in disk and arms, bluer, high metallicity
    - Population 2 stars: Old, in halo, redder, low metallicity

- Metallicity = elements heavier than He

Motion in the Galactic Disk

- Stars rotate around the Galactic Centre
- Stars in the disk rotate differentially
    - Stars at different distances from the centre rotate at different rates
    - Sun orbits once every 230 million years
- Halo stars move on elliptical orbits well outside of the disk

Motion of Stars

- Stars move on the sky because of:
    - Overall rotation about galactic centre
    - Local effects (e.g. motion in a cluster or binary)
- Proper motion: motion of stars on sky
    - Detect only motion that is tangential to our line of sight
- Can get 3-D (i.e. tangential + radial) information via doppler shifts
    - e.g. hydrogen has 21-cm radio transition
    - Used to map entire Galaxies, etc…

Interstellar Gas

- ISM includes molecular gas clouds: CN, Ch, Co
- Molecular gas clouds are cold (if not, molecules would dissociate), T~100K
- Observed via absorption lines in stellar spectra
- Gas cloud absorption lines are much narrower than are stellar absorption lines
- Gas at higher T produces broader lines due to Doppler broadening
- **Doppler Broadening**
    - Gas particles at rest, ie at low T, absorb at the rest wavelengths of their atomic transitions
    - Moving gas particles, ie at high T, absorb wider ranges of wavelength, due to Doppler shifting o particles some moving towards the observes, some moving away

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The Centre of the Galaxy

- Traditionally hard to study
- Dust extinction at visual wavelengths enormous
    - Total obscuration in visible light
- Studied mainly at radio, near-infrared, X-ray energies
- Star-like object called "Sagittarius A*" close to geometric position of galactic centre
- Thought to be the actual black hole

Stellar Orbits Near Sgr A*

- Group at UCLA working at near-IR wavelengths found several bright stars orbiting Sgr A*
- By watching motions of the stars for many yeas, orbits were deduced
- Orbital periods determined enclosed mass via kepler's laws
- Deduced unseen Sqr A* has 4 mil solar masses
- From sizes of orbits, known the mass must be very concentrated -> has to be a black hole

Measuring Mass in the Milky Way

- M_r = (r*v^2)/G
    - M_r= Galaxy's mass interior to orbit of radius r

Rotation Curve

- Is the orbital velocity as a function of radius
- In the solar system, as you move away from the Sun, velocity of planets drops as predicted by Newton's law of Universal Gravitation
- Expect this because Sun's gravitational pull dominates Solar System dynamics: less pull further away

Dark Matter in Galaxies

- Only plausible explanation for behaviour of rotation curves AND
    - Motions of galaxies in galaxy clusters
    - Shape of gravitational lenses
    - Evolution of structure in the universe since the big bang
- Is the existence of vast amounts of matter that we cannot see (produces no light) but which exerts gravitational pull = 'dark matter'

What is Dark Matter

- We don’t know
- Cant be faint stars or dead neutron stars or black holes
    - Ruled out by looking at magellanic cloud stars, see nothing passing in front of t
    - Hem "gravitational microlensing"
    - WE believe it's n exotic form of matter yet unseen in laboratories "WIMPs"
    - Many Dark Matter detection experiments underway

Lecture 29

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Earth/Moon System
- Central to origin and evolution is age
- First estimates based on religion, not science, suggested a few thousand years old
- Slowly over years science has demonstrated Earth/Moon is several billion years old
- Radioactivity dating offers for estimating ages:
    - Some atoms are unstable and generally "prefer" to decay to a different type of atom
    - Every type of atom has a (lab measured) half-life or time for half to decay
    - Decay produces heat
- Earth rocks are 4-5 billion years old

Earth Internal Structure
- Ongoing radioactive decays in centre of Earth produce lots of heat
- Drives geological activity, including volcanism, earthquakes
- Use seismic waves produce by this activity to study interior
- Structure largely determined by gravity: slowly pulls denser objects inward
- Earth Structure:
    - Dense solid metal core at centre
    - Surrounded by dense liquid metal core
    - Surrounded by mantle of dense rock
    - Surrounded by crust of less dense rock
- From ocean floor to highest mountain peak is 0.1% of Earth's radius

Lunar Internal Structure
- Seismometers left by astronauts on Moon allow similar studies
- They found that the moon has/is:
    - Many fewer earthquakes
    - Much smaller core
    - Surrounded by a liquid mantle
    - Surround by a solid mantle
    - Then crust
- Easy to estimate Moon less dense than Earth; consistent with seismic data

Earth's Geology: Active
- Heat of radioactivity deep within earth drives evolution of geological features
- Heat propagates outward via convection
- Crust stressed
    - Buckling, folding can create mountains
    - Stretching produces faults
    - Crackling produces earthquakes
    - Volcanism when molten rock (lava) comes to surface
- Plate tectonics
- Main point: surface features typically only few hundred million years old… young compared to age of earth

Moon's Geology: Dead
- Moon's surface very different:
    - Craters: large and small, impacts of rocks
    - Highlands: remains of molten surface
    - Mare: lava plains-dark patches
    - Rilles: collapsed underground river beds
- Moon cooled 3.5 billion years ago, no interior heat eft
- No "engine" to drive geological activity as on Earth
- Craters more prominent because impacts left unchanged as no active geology

Origin of Earth/Moon System
- Best hypothesis: Moon formed from ejecta after huge asteroid impact on Earth over 4.5 billion

years ago:

- Collision-ejection theory
    - Lunar surface highly cratered; increased cratering rate early in solar system history
    - Moon geochemistry similar to Earth Mantle
    - Absence of massive iron core in Moon
    - Absence of water on moon
    - Could have tipped Earth's axis
- No direct evidence for such an impact on earth
- Capture hypothesis can't explain Moon's much smaller iron core compared to Earth, nor the similarities in their mantles; hard for Earth to capture large moon
- Cocreation theory can't explain differences in Earth, Moon geochemistry

Mercury: Dead Geology

- One-third size of Earth
- Closest planet to Sun; very hot
- Hard to study; most learned from US mariner space probe in mid 1970's
- Heavily cratered, like moon
- No evidence for plate tectonics: dead
- Plains from lava flows as on Moon
- Scarps: long cliffs, probably from formation
    - Magnetic field ~1% of Earth's
    - No Moons

Mercury's Orbit and Rotation

- Mercury orbits the Sun every 87.97 days
- Mercury turns on its axis every 58.65 days
- Rotation measured using Doppler radar using Arecibo radio telescope
- Notice that (2/3)(87.97)=58.65
- Planet is not a perfect sphere, has a bulge
- If orbit were circular, would be rotating synchronously, as Moon does
- But large eccentricity (e=0.2) of Mercury's orbit means that the gravitational twisting force is less as aphelion than at perihelion
- Mercury rotates 1.5 times on its axis per revolution around the Sun
- Thus it rotates 3 times during 2 orbits
- Mercury's long axis only points at the Sun at perihelion
- Time from noon to noon is 176 days
- Large day/night temperature difference
    - Day=430 degrees C
        - Lead & Zinc boil
    - Night: -170 degrees C
        - Carbon dioxide, methane freeze
- Axis of rotation not tilted so no "seasons"
- Craters at N, S poles may contain ice as never see Sun; same is true of moon

Terrestrial Planets

- Mercury, Venus, Earth, Mars
- Observability from Earth depends on their elongation

Venus

- Similar in radius,, mass to earth
- Striking difference in atmosphere
- Clouds are made of sulfuric acid; they reflect most of the sunlight that hits them
- Average surface temperature 460 degrees Celsius
- High temperature due to greenhouse effect
- Clouds are made of sulfuric acid
- Avg surface temp is 460 celsius
    - Due to greenhouse effect

Lecture 30

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Greenhouse Effect

- Sunlight penetrates atmosphere, clouds and heats the surface
- Surface reradiates hear at infrared wavelengths
- Carbon dioxide atmosphere opaque to infrared radiation, so heat is trapped, surface gets hotter
- Some infrared does leak to space
- Equilibrium when heat lost via infrared equals that brought in via sunlight

Greenhouse Effect on Earth

- We have greenhouse effect on Earth: mostly good
- But, rise in carbon dioxide production by humans may be causing temperature rise
  - Carbon dioxide rise of 20% since 1700's
  - Suggests causes global warming
  - Temperature since 1850 rising
  - Could cause polar caps to melt, oceans to rise, New York to submerge
- Doomsday scenarios suggested; may be wrong but better safe than sorry
- Venus is proof-of-principle

Venus Continued

- Doppler radar can study Venus' rotation: its clouds are transparent to radio waves
- Rotation period slow: 243 days
- Orbital period 225 days
- Rotation is retrograde
  - Rotation in opposite direct to orbital motion
  - Sun rises in west, sets in east
- Origin not well understood
- Giant impact… no evidence
- Rotation axis within 3 degrees of alignment
- Venus has an active geology like Earth; surface is 500-800 million years old
- Essentially all surface at same age: complete resurfacing (many times) in past
- Has ~1600 volcanoes
- Venus shows no evidence for plate tectonics
- Very weak magnetic field though likely similar core to Earth's… related to slow rotation?

Mars

- Rmars=3390KM
  Mmars=6.4*10^23 kg
  Rotates every 24hrs 39min
- Orbital period 687 days
- Planet has long captured our imagination; best studied
- Historically because of claims of "canals": since disproved
- Has CO2 ice polar caps that change in morphology over time
- Canals
  - Giovanni Schiaparelli 1877: saw "canals" : straight lines on surface
    - No photography
  - Percival Lowell late 1800's: claims Mars inhabited by intelligent life
    - Canals seemed to change over years
    - Built canals to get water from polar caps
    - Agriculture: seeing vegetation grow seasonally
  - Later realized optical illusions
    - Many point-like features in low-resolution telescopes joined up to form 'lines'
    - Winds -> dust storms
  - Not seen by modern telescopes or flybys
  - Today we know there are no canals
- Surface
  - Mars has volcanoes, though probably dormant

    - Most are in northern hemisphere
        - Fewer craters in north than south
    - Largest is Olympus Mons
    - One of several volcanoes in the Tharsis rise region, just north of Mar's equator
    - Valles Marineris: giant canyon spanning both hemispheres: 4000km long
        - Rift valley: crust broke
        - Unlike grand canyon which was caused by water erosion
    - No evidence for plate tectonics
    - Average surface temp is 218K
    - Very thin CO2 atmosphere: average pressure 0.007atm
        - Water cannot exist on surface today as a liquid
        - Today, surface is an arid desert

- Water
    - A lot of evidence water once flowed on mars
        - Dried up lakes and rivers, especially in old southern highlands
        - Evidence for floods
        - Evidence for water erosion of crater rims
- Climate Change
    - Today the thin atmosphere is 95% water
    - Previous volcanism produced more atmosphere
    - Rain eventually washed out carbon dioxide
    - Or carbon dioxide escaped due to abatement of magnetic field which enabled solar wind to strip off atmosphere
    - Volcanism stopped to no replenished
    - Planet froze

Jupiter

- Most massive planet in the solar system
- 317 earth systems
- 70% of total mass of all planets
- Large (11 earth radii)
- Orbital period: 11.8 years @ 5.2 AU
- Low density compared to terrestrial planets
    - 1.3 g/cm^3 versus 5.6g/cm^3 for Earth
- Mainly hydrogen, some helium
    - More similar to a star! But no fusion "failed star"
- Rotates fast: period 9.6 hrs
- Does not have a surface:
    - Descending downward, gas gets denser, eventually liquifying
- Colours, Patterns, Features are atmospheric effects
- In constant motion
- Energy source: gravitational contraction
- Colours due to sulfur, phosphorous, organic molecules
- Belts: dark regions, falling gas
- Zones: light regions, rising gas
- Great Red Spot
    - Storm system
    - Like a hurricane
    - Clouds rotate every 6 days
    - Has existed for >300years
        - Reported by Cassini in 1665
    - 3 times the size of earth
- Gas atmosphere>Liquid Hydrogen>Liquid metallic hydrogen>core of heavy elements

Lecture 31

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Saturn

- Similar to Jupiter in many ways:
  - Massive (95 earth masses)
  - Large (9.5 earth radii)
  - Low density compared to terrestrial planets
  - Similar inferred interior structure
  - Rotates fast (10.2 hrs) compared to orbital period (29 yr @ 9-10 AU)
  - Substantial magnetic field
  - Zones and belts seen
    - Less obvious on Saturn due mainly to its lower mass hence less compressed atmosphere than Jupiter's
  - Mainly hydrogen atmosphere
- Rings
  - Not solid, made up of millions of highly reflective ice-covered rocks, few cm to few m
  - In Saturn's equatorial plane
  - Saturn's rotation axis at 27 degrees to ecliptic
  - We see rings from different perspectives
    - Cant really see them when exactly on edge as rings very thin (2km in thickness)

Jovian Planet Moons

- Jupiter: 67 known moons
  - 4 Galilean moons: Io, Europa, Ganymede, Callisto
- Saturn: 62 known moons
- Uranus: 27 known moons
- Neptune: 14 known moons

Active Io Volcanoes

- Tidal deformations stretch and strain Io, cause "tidal heating" due to friction

Europa

- Next further out; roughly same size as Io, but half mass
- Suffers tidal heating as well
- Surface covered by water ice
- Many cracks, folds seen in ice due to tidal stresses
- Suggestive of liquid ocean of water below ice layer that is a few km thick
- Could like exist there?

Asteroids

- Rocky, metallic objects with little ice
- Travel in circular orbits around the sun
- Found mainly in asteroid belt between Mars and Jupiter
- Range in size up to 1000km (Ceres)
- Over 200000 catalogued
- Generally irregularly shaped
- None detectable with the naked eye

Comets

- Occasional visitors to inner solar system
- Composed of head or (coma) and tail
- Centre of head is solid nucleus: dirty ice
  - Water, methane, ammonia, carbon dioxide
- Rest is gas and dust
- Nucleus typically 1-20km
- Two tails present near Sun only:
  - Ion tail: always points exactly away from sun
    - Charged particles forced away by solar magnetic field
  - Dust tail: curves away a bit from ion tail

        - Dust released from comet, continues to orbit, but feels radiation pressure from Sun -> curves
    - Can stretch as long as 1 AU
- Trail
    - Remains of comets create occasional showers of meteors
    - Also known as shooting stars
    - Quick streak of light across night sky

Collapse Model

- Collapse model for solar system explains
    - Most mass in sun
    - Rotation of sun
    - Near circular orbits of planets
    - Planetary orbits lie in disk
    - Sun's equator in same disk
    - Planets orbit in same direction as solar radiation
    - Planets (mostly) rotate in same direction

Formation of Planetesimals

- Eventually gas pressure at center so large that collapse is halted: protosun has been formed, surrounded by the **solar nebula**
- Disk began to cool, as no more energy from gravitational collapse available
- Different materials condensed
- Different materials condense at different temperatures
- Compositional structure of solar system determined by condensation sequence

Structure of Solar System

- Terrestrial Planets:
    - First condensates: metals
    - Tiny "dust" over-densities slowly grow, accrete more
    - Inner solar nebula swept up into a few large planets
    - Remaining gas, dust blown away by solar radiation pressure
- Giant Planets:
    - Formed like Terrestrials but farther out where ices available; grew larger
    - So large that accreted lots of gas
- Asteroids:
- Planetesimals that never reached planet status
- Asteroid belt: disturbed by Jupiter

Lecture 32

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Extrasolar Planets

- Revolution in astronomy in past decade
- Planets outside solar system found
- Found orbiting other stars
- Properties of new-found solar systems that are very different from our own
- Discovered through direct and indirect detection
  - Direct
    - See planet directly via imaging
    - Stars are typically 1-10 billion times brighter than planets
      - Jupiter only reflects 0.3 billionths of the Sun's light
    - I.e. contrast ratios of 10^9-10^10 at separations of 0.01"-1"
    - Contrast ratios better at infrared wavelengths but still challenging
    - Atmospheric blurring distorts images so impossible to see such small separations
    - Adaptive Optics
      - Telescope uses "laser guide star" to determine effect of atmospheric turbulence in real time
      - Corrects stellar images using guide star corrections
      - Demands fast local computing
      - Provides near diffraction-limited imagines from the ground
        - Can have more sensitivity as ground-based telescope larger than space-based
    - Adaptive Optics solves the atmospheric blurring problem
      - Allows near diffraction-limited imaging i.e. superb angular resolution
    - But doesn't solve the contrast ratio problem
    - Solution: a coronagraph
      - Device that blocks light from the star
      - An artificial eclipse
    - Blocks bright star so faint planets become visible
    - Detection Biases
      - Will find planets far from the star
      - Will find large planets that reflect a lot of light i.e. lower contrast ratios

  - Indirect
    - Observe starlight affected by planet but not the planet itself
    - Transit Detections of Exoplanets
      - Planet passes in front of star, star light dims briefly
      - Orbit must be correctly aligned
      - Brightness changes related to projected area of planet i.e. size
      - Typically few percent
      - Similar to eclipsing binary star system but much smaller effect
      - NASA's Kepler mission has found >2000 exoplanets using the transit method
        - Stared at fixed region of sky for long time, record brightnesses of millions of stars vs time
      - In some systems it is possible to detect 'phases' of the exoplanet and its eclipse
      - Also in a few systems can do 'transit spectroscopy': compare spectrum of starlight before and during transit
        - Can determine planetary atmospheric composition
        - Very few systems now
    - Stellar Wobble
      - AKA Radial Velocity Method

- Exoplanet orbits star but star moves too!
    - Both orbit common centre of mass which for high mass ratio, is very near (or inside!) star
- Happens in our solar system
    - Main effect on Sun is due to Jupiter
    - Centre of mass of solar system near solar photosphere
- Can in principle measure the wobble directly but need microarcsecond angular resolution
    - GAIA mission, now operating, can do this
- Thus far wobble measured spectroscopically from the stellar spectrum
- Measure stellar radial velocity from motion of spectral lines -> infer information about planetary mass
    - Not mass itself since only radial component of velocity!
    - Measure mass up to a factor of sin(i), where I = inclination angle
- Nearly 1000 exoplanets discovered this way
- Typical radial velocities for exoplanets: tens of m/s
    - Recall for binary stars: tens of km/s