$\mathcal{L}$: Luminosity $\mathcal{T}$: Temperature $\mathcal{D}$: Density $\mathcal{P}$: Pressure $\mathcal{M}$: Mass

Chapter 1 A Modern View of the Universe

Cosmic Address: *Universe: Filaments and Voids: Local Supercluster: Local group: Milky Way Galaxy: Solar system: Earth: Asia:*
Planet: Rocky, icy, or gaseous object that orbits a star, shining by reflected light. $d_{\text{Earth}} = 0.009 d_{\text{Sun}}$ $d_{\text{Jupitar}} = 0.1 d_{\text{Sun}}$
Satellite: Man-made object that orbits a planet.
Asteroid: Relatively small and *rocky* object that orbits a star, often non-spherical in shape.
Comet: Relatively small and *icy* object that orbits a star. Comets usually have two tails: plasma tail and dust tail.
Solar system: Stars and all the material that orbits it, including its planets and moons.
$1:10^{10}$ scale: $d'_{\text{Sun}} = 0.14\,\text{m}$ (Grapefruit), $d'_{\text{Earth}} = 0.0012\,\text{m}$ (Tip of ballpoint pen) (15 m away), $d'_{\text{Neptune}} = 0.0048\,\text{m}$ (449 m away).
Nebula: Interstellar cloud of gas and/or dust
$1:10^{19}$ scale: distance to nearest star $= 0.004\,\text{m}$.
Currently, $d_{\text{observable universe}} \approx 9.3 \times 10^{10}\,\text{ly}$.
No. of galaxies $\approx 10^{11}$. No. of stars $\approx 10^{11} \times 10^{11} = 10^{22}$. As many stars as grains of sand on Earth's beaches.
Universe is at least 250 times larger than observable universe.
Look-back time (LBT): Time elapsed between when light was emitted and when we detect the light on Earth.
Speed of light $c = 3 \times 10^5\,\text{km}\,\text{s}^{-1}$ Light year: $1\,\text{ly} \approx 9.46 \times 10^{12}\,\text{km} \approx 10^{13}\,\text{km}$
The farther away we look in distance, the further back we look in time.
Cosmic Calendar: A scale on which we compress the history of the Universe into 1 year.
Human civilization: Few seconds. Human lifetime: Very small fraction of a second.
Earth rotates around its axis once every day. Earth orbits the Sun once every year. Average distance $= 1\,\text{AU} \approx 1.5 \times 10^8\,\text{km}$.
Earth's axis tilted by $23.5°$ pointing to Polaris, rotates in same direction it orbits (counterclockwise viewed from above North Pole)
Earth spins at $1650\,\text{km}\,\text{h}^{-1}$ about its axis and orbits at $\sim 107{,}000\,\text{km}\,\text{h}^{-1}$ around the Sun.
We don't feel Earth's motions due to almost constant and smooth motions and low angular speeds (0.04 turns h^{-1}) $F = \frac{mv^2}{R}$.
Sun moves randomly at $> 70{,}000\,\text{km}\,\text{h}^{-1}$ relative to other stars in local solar neighbourhood.
Sun orbits the center of galaxy every 230×10^6 yrs with speed $\approx 800{,}000\,\text{km}\,\text{h}^{-1}$.
All stars appear to be stationary and fixed due to large distance between stars.
All galaxies outside our Local Group are moving away from us. The more distant the galaxy, the faster it is racing away.

Chapter 2 Discovering the Universe for Yourself

Constellations: Regions of the sky. Total 88. Star appears to go around once per day.
Celestial Sphere (c.s.): A model which helps us visualize positions of objects in the sky. Imaginary sphere with Earth as center.
Sphere appears to rotate about celestial pole axis once a day due to Earth's rotation.
Sun, moon and planets appear to move from one place to another on the sphere.
Zenith: Point on c.s. directly overhead *Nadir*: Point on c.s. directly underneath *Horizon*: Plane with zenith as normal
Celestial equator: projection of Earth's equator onto the c.s.
North (South) celestial pole: projection of Earth's north (south) pole onto the c.s.
Milky Way in c.s.: A band of light that makes a circle around c.s..
Milky Way is flat spiral galaxy. Solar system is half way between center and edge.
Meridian: Half circle from N horizon through zenith to S horizon
Axial tilting effects: Longer day in summer and shorter in winter, Sun's altitude changes with seasons
Cause of Analemma (figure-8 shape): Earth's $23.5°$ axial tilt and eliptical orbit
More spread light: Lower $\mathcal{T}$ (Distance doesn't matter as variation of distance is small (3%))
At equinoxes: both hemisphere's receive same amount of sunlight
At summer/winter solstice: axis tilt at largest angle with northern/southern hemisphere towards the sun (Tropic of Cancer/Capricorn)
4 seasons only at temperate latitudes (TLs) (Between tropics and polar regions $23.5 - 66.5°$)
Tropics: Region surrounding the Equator
Gravity of moon, sun, other planets causes Earth's axis to precess (over about $26{,}000$ yrs) Polaris won't always be North ($22.1 - 24.5°$)
Phases of Moon (Light from empty, appear start in right): Rise: 6 a.m., Highest: noon, Set: 6 p.m., adding 3 h
New Moon, Waxing Crescent, First Quarter, Waxing Gibbous, Full Moon, Waning Gibbous, Third Quarter, Waning Crescent
Sidereal month $= 27.3$ days Synodic month (Full cycle) $= 29.5$ days
Umbra: Region of total darkness *Penumbra*: Region of partial darkness
Lunar eclipses: full moon
Total eclipses: Red moon (violet scattered away, red is refracted), completely immersed in umbra Partial Penumbral
Solar eclipses (new moon): Total (totality reached, sees corona), annular (moon smaller than sun), partial
Moon's orbit tilted $5°$ with Earth's orbit. Line of nodes: Moon on Earth's orbit plane (Possible eclipse when point towards Sun)
Apparent retrograde motion: Planets move westward instead of eastward

Chapter 3 Ancient Science of Astronomy

Modern science trace roots to Greeks: Developed models of nature and emphasized predictions of models agree with observations
Ptolemaic model had each planet move on small circle whose cener moves around Earth on larger circle
Kepler's First Law: Orbit of each plenet around Sun is ellipse with Sun at one focus
Perihelion: Point nearest to Sun *Aphelion*: Point farthest to Sun
Kepler's Second Law: Line joining planet and sun sweeps out equal area in equal time (Planets travel faster when closer to sun)
Kepler's Third Law: $p^2 = a^3$ (p: Orbital period in yrs, a: Semi-major axis in AU)
Copernicus: Sun-centered model. Tycho provides data to improve the model. Kepler found a model that fit Tycho's data.
Galileo: Reject: Nature of motion, heavenly perfection, parallax

Chapter 4 Understanding Motion, Energy and Gravity
Gravitational constant $G = 6.67 \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$ $a = \frac{v^2}{r} = \frac{G\mathcal{M}}{r^2}$
Newton's version of Kepler's Third Law: $p^2 = \frac{4\pi^2}{G(\mathcal{M}_1+\mathcal{M}_2)}r^3$ Assume $\mathcal{M}_1 = 0$ when $\mathcal{M}_1 << \mathcal{M}_2$
Period of orbit: $p = \frac{2\pi r}{v}$ Angular momentum: $L = \mathcal{M}r \times v$ Torque: $\tau = rF\sin\theta$
Gravitational Potential Energy: $\mathrm{PE} = \mathcal{M}gh = -\frac{G\mathcal{M}_1\mathcal{M}_2}{r}$ Mass Potential Energy: $E = \mathcal{M}c^2$
Change orbit: Object lose or gain orbital energy Change by: Atmospheric drag, gain orbital energy, gravitational encounter
Escape velocity: $v_{\mathrm{escape}} = \sqrt{\frac{2G\mathcal{M}}{r}}$
Tides: Periodic variation in height of Earth's ocean (Mainly due to tidal force of moon, sun slightly)
Tidal force (differential force): Non-uniform gravity Vertical: Stretching force Horizontal: Compressing force
Tidal force on Earth is hardly noticeable. That on stellar black hole is very large (Spaghettification)
High tide near and far side (Moon pulls Earth away from water on far side) Sun do only $\frac{1}{3}$
Tidal Friction: Earth's self-rotation drag tidal bulges around with it (Slowing Earth's rotation)
Gravity of bulges pulls Moon ahead: increasing orbital distance (0.0378 m per yr)
Tidal locking: Tidal friction slow Earth's down trying to have rotation be equal to orbital motion of Moon
Increase Earth-day from $5-6$ h to 24 h, kocking of Moon is faster due to less massive
Chapter 5 Light, The Cosmic Messenger
Light is electromagnetic wave Light speed: $c = 3 \times 10^8\,\mathrm{m\,s^{-1}} = f\lambda$ Low f: Radio wave High f: Gamma rays
Photons: particles of EM radiation Photon energy $E = hf$ ($h = 6.626 \times 10^{-34}\,\mathrm{J\,s}$) Photon momentum $p = \frac{E}{c} = \frac{h}{\lambda}$
Atom: $d_{\mathrm{H\ nucleus}} = 1.75 \times 10^{-15}\,\mathrm{m}$, $d_{\mathrm{U\ nucleus}} = 15 \times 10^{-15}\,\mathrm{m}$
Atomic no.: No. of protons in nucleus Atomic Mass No.: No. of protons and neutrons
Isotopes: Sane no. og protons but different no. of neutrons Molecules: Consist of ≥ 2 atoms
Matter emit. absorb, transmit, reflect and scatter light
Three basic types of spectra:
Continuous spectrum: Spectrum span all visible λ
Emission Line Spectrum: Excited thin or low $\mathcal{D}$ cloud emit lights at specific λ (Bright emission lines)
Absorption Line Spectrum: Cold, thim or low $\mathcal{D}$ cloud absorb lights at specific λ (Dark absorption lines)
Specific atom has unique set of energy level: Downward transitions: Produce emission lines Upward: Produce absorption lines
Use spectral fingerprints to determine chemical compositions
Thermal radiation: all thing above absolute zero ($-273°$C) emit thermal radiation
Stefan-Boltzmann's Law: Flux $F = \sigma\mathcal{T}^4$ ($\sigma = 5.7 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$) Wien's Law: $\lambda_{\max} = \frac{2.9\times10^6}{\mathcal{T}}$ nm
Luminosity: Total amount of light energy given out by star per second
Doppler Effect: λ of wave received by observer is changed when source is moving with respect to observer
$\frac{\Delta\lambda}{\lambda_{\mathrm{rest}}} = \frac{v_r}{c}$ v_r: radial velocity of source relative to observer
Blueshift: Object moving towards us Redshift: Object moving away from us
Chapter 6 Telescopes: Portals of Discovery
Telescope collect more light than eyes: Larger light-collecting area
Telescope see more detail than eyes: Higher angular resolution
Some telescopes detect light that is invisible in eyes: Broader spectral coverage
Bigger telescope: Higher light gathering power (no. of photons collected, proportional to square of diameter), higher resolving power
Angular resolution: Minimum angular separation to distinguish
Resolving power $\alpha = \frac{1.22\lambda}{D}$ D: Aperture (Diameter of lens)
Refracting telescope: Chromatic aberration (Lens will not focus different color in same place since index of refraction varies with λ)
Reflecting telescope: E.g. Keck I/II
Radio telescope: Big dish due to weak radio signal from space and long λ (Low resolving power)
Telescope in space: No light pollution, no air movement blurs (Turbulence cause twinkling), no atmosphere absorb EM spectrum (X-ray, gamma ray, far-UV)
Adaptive optics: Rapid change in mirror shape to compensate for atmospheric turbulence (Use bright star as reference)
Interferometry: Combine signals detected from no. of radio telescopes. D becomes distance between telescopes
Chapter 7 Our Star
$r_{\mathrm{Sun}} = 6.9 \times 10^8\,\mathrm{m}$ $\mathcal{M}_\odot = \mathcal{M}_{\mathrm{Sun}} = 2 \times 10^{30}\,\mathrm{kg}$ $\mathcal{L}_\odot = 3.8 \times 10^{26}\,\mathrm{W}$ Source of energy: Nuclear energy (Nuclear fusion) $E = \mathcal{M}c^2$
Nuclear fusion: Need $> 10 \times 10^6$ K, high $\mathcal{D}$, high $\mathcal{P} > 10^{10}$ atm to overcome electric repulsion
Gravitational contraction: Provide energy for fusion
Stellar Balance: Hydrostatic equilibrium (Gravity inward and internal pressure outward)
Pressure-temperature thermostat: Rely on strong $\mathcal{T}$ dependence of fusion rate
Core contracts and gets hotter, fuse H faster, more radiation and pressure, core expands, core gets cooler, reaction decrease
Structure of Sun: Solar wind: Flow of charged particles from surface Corona: Outermost layer of solar atmosphere (1×10^6 K)
Chromosphere: Middle layer of solar atmosphere ($10^4 - 10^5$ K) Photosphere: Visible surface of Sun (5800 K)
Convection zone: Energy transport upward by rising hot gas (Bottom 1.5×10^6 K)
Radiation zone: Energy transported upward by photons $7 - 1.5 \times 10^6$ K Core: Energy generated by nuclear fusion (15×10^6 K)
Heat transfer: Radiation, convection depends on $\mathcal{T}$, thermal and density gradients, and $\mathcal{P}$
Scattering: Radiation zone: less-absorptive Convective zone: more absorptive (Takes photon 1×10^6 yrs to go out)
$< 0.4\mathcal{M}_\odot$: Star conductive $\approx 1\mathcal{M}_\odot$: Core, radiative, convective $>> 1\mathcal{M}_\odot$: Convective core, radiative shell
Solar neutrino: electron neutrino (v_e), muon neutrino (v_μ), tau neutrino (v_τ)
Sunspots (4500 K): Cooler part of surface (Strong magnetic fields) Zeeman effect: Split spectral line into 3 lines
Strong magnetic activity causes solar prominences, magnetic storm causes solar flares
Coronal mass ejection (huge, balloon-shaped plasma bursts): Send bursts of energetic charged particles out through solar system

Chapter 8 Surveying the Stars
Luminosity: Total amount of power a star radiates Apparent brightness: Amount of starlight that reaches Earth
Brightness $B = \frac{\mathcal{L}}{4\pi d^2}$ (Inverse Square Law)
Parallax: Apparent shift in location of object with respect to ones further away due to change in observation point
Stellar parallax θ: Half of total shift in angle of that star using Earth's orbital diameter (Works for nearby stars)
$1\,\text{pc} = 206265\,\text{AU} = 3.26\,\text{ly}$ $1\,\text{rad} = 1\,\text{arcsec}$ $d = \frac{1}{\theta}$ θ : in arcsec d : in pc
Stars luminosity: $10^{-4} - 10^6 L_{\text{Sun}}$ Dim stars are far more common
Apparent magnitude m: Magnitude 1 stars (first class): brightest Magnitude 6 stars (sixth class): faintest
Ratio: $\frac{B_A}{B_B} = (100^{\frac{1}{5}})^{m_B - m_A}$
Absolute magnitude M: $\mathcal{L}$ of stars $\frac{\mathcal{L}_A}{\mathcal{L}_B} = 2.512^{M_B - M_A}$ Distance modulus $= m - M$ Distance in pc $d = 10^{0.2(m-M+5)}$
Measure surface $\mathcal{T}$: $\mathcal{L}$, level of ionization (absorption line) Surface: (50000 K) O B A F G K M (3000 K)
If $\mathcal{T}$ is too high, most or all H atoms have electrons staring out at level 2.
If $\mathcal{T}$ is too low, most of H atoms have electrons on ground state.
Optimized $\mathcal{T}$ (10000 K A star) at which absorption line strength hits maximum
Stellar mass: Need 2 of 3 observables: orbital period (p), orbital separation (a or r), orbital velocity (v) $v = \frac{2\pi r}{p}$
Types of Binary star systems: Visual Binary: Pair of stars that we see distinctly
Eclipsing Binary: Cchange in apparent rightness Spectroscopic Binary: Measuring blueshift (Approach) and redshift (Recede)
Eclipsing binary offers orbital period. Spectroscopic binary offer orbital velocity and period, thus the $\mathcal{M}$ of heavier star.
Most massive star: $226\mathcal{M}_\odot$ Least massive star: $0.08\mathcal{M}_\odot$
Hertzsprung-Russell (HR) diagram: Plot $\mathcal{L}$ and surface $\mathcal{T}$ of stars on a graph
Radii of stars: Cannot be measured directly due to too small angular diameter, use $\mathcal{L} = 4\pi\sigma\mathcal{T}^4 R^2$ Size of stars: $0.01 r_{\text{sun}} - 2000 r_{\text{sun}}$
Stars with low $\mathcal{T}$ and high $\mathcal{L}$: Giants and supergiants
Stars with high $\mathcal{T}$ and low $\mathcal{L}$: White dwarfs
Collisional broadening: Broadening of spectral lines increases with frequency of collisions which increases $\mathcal{D}$ of atmosphere of stars
Uncertainty principle: $\Delta x \Delta p \geq \frac{\hbar}{2}$
Supergiants: Larger in size → Lower $\mathcal{D}$ in atmosphere → Sharper spectral lines
Same surface $\mathcal{T}$: Sharp to broader lines, high to low $\mathcal{L}$: supergiants, giants, main sequence, white dwarf
Star's full classification includes spectral type and $\mathcal{L}$ class E.g. Sun (G2 V)
Main-Sequence (MS) Line: Luminous stars are hot (blue), less luminous ones are cooler (red) Most stars fall on lower ends
Core $\mathcal{P}$ and $\mathcal{T}$ of more massive MS star is higher to balance gravity → Greater $\mathcal{L}$, higher surface $\mathcal{T}$, larger radius
$\mathcal{M}$ and $\mathcal{L}$ of MS stars: $\mathcal{L} = \mathcal{M}^{3.5}$ L: In terms of $\mathcal{L}_\odot$ $\mathcal{M}$: In terms of $\mathcal{M}_\odot$
Life expectancies of stars: $t = \frac{\mathcal{M}}{\mathcal{L}} = \mathcal{M}^{-2.5}$ Cool stars live longer
MS Star after fusion has ceased: $> 0.25\mathcal{M}_\odot$: Giant and supergiant $< 0.25\mathcal{M}_\odot$: Blue dwarf → white dwarf → black dwarf
Star clusters: Group of stars born around the sane time at about same distance to Earth (Determine age and distance)
Two types of star clusters: Globular clusters (round, very dense and old) and open clusters (Random, not dense, younger)
Massive stars move out of MS sooner than lower $\mathcal{M}$ star More massive stars begin leaving MS in cluster over time
Turn-off point: All MS stars above the point have moved away Age of cluster $t = \mathcal{M}_{\text{turn-off}}^{-2.5}$
Distance: Using standard HR diagram for absolute magnitude (M) and using HR diagram for apparent magnitude (m)

Chapter 9 Life of Stars
Interstellar Medium: Nebulae (visible/invisible parts of molecular clouds) between stars
See nebulae in 3 ways:
Emission nebulae: Stars are embedded in/near nebula, emitting ultraviolet that excite H to give emission spectra (Pink-red in general)
Reflection nebulae: Scattering of blue starlight by dust (Blue)
Dark nebulae: Dense clouds of gas and dust blocking light of distant stars
Interstellar reddening: Stars visible near the edges of dark nebula are reddened (Red slightly reduced, blue greatly reduced)
Formation of stars: Start at molecular cloud ($\mathcal{T} \approx 30\,\text{K}$, $n \approx 300\,\text{cm}^{-3}$) contain at least few hundred $\mathcal{M}_\odot$ for gravity to overcome $\mathcal{P}$
Prevent $\mathcal{P}$ buildup via emitting infrared, microwave, radio photons generated from gravitational contraction → further contraction
Stars begin to form: Dust grains that absorb visible light emit infrared
Conservation of energy: Cloud heats up when it contracts. Continue contraction if part of thermal energy is radiated away
Conservation of angular momentum: Cloud becomes smaller cause it to spin faster
Flattening: Gas settles into spinning disk as spin hampers collapse perpendicular to spin axis and collision between particles
Formation of jets: Rotation causes bipolar jets of matter to shoot out (Due to dynamic interactions in accretion disc)
Accretion discs (Thought) generate tangled/twisted magnetic fields that collimate jets
Protostar: Fragment collapses under self-gravity. Very high $\mathcal{L}$ due to gravity, $\mathcal{T}$ too low for nuclear reaction
MS Star: Protostar contracts and heats until $\mathcal{T}$ is enough for H fusion Contraction ends at hydrostatic equilibrium
$\mathcal{L}$ drops and shell shrinks, surface $\mathcal{T}$ increases and size drops
Upper limit: $150\mathcal{M}_\odot$: So luminous that collective pressure of photons drives matter into space
Lower limit: $< 0.08\mathcal{M}_\odot$ (Brown dwarf): Fusion cannot begin as $T < 10^7\,\text{K}$
Degenerate electron gas: Pauli exclusion principle: No 2 electrons occupy same state Degeneracy pressure: Do not depend on $\mathcal{T}$
Brown dwarf: Electron degeneracy pressure halts contraction → no fusion (Emit infrared due to heat left from contraction)
Loss $\mathcal{L}$ over time to become black dwarf Infrared observation can reveal recently formed brown dwarfs
Born star: begins at zero-age main sequence (ZAMS) line in HR diagram Older star: More $\mathcal{L}$ and cooler surface $\mathcal{T}$
Life of star: 4H → 1He Use up H and core contracts → more luminous and surface expands → cooler surface $\mathcal{T}$
Medium star: H shell heats up and do H fusion (hydrogen shell burning) → more He, He core contracts, becomes red giant
Red giant: Higher $\mathcal{L}$ and lower surface $\mathcal{T}$ H burning shell deposits He ash into He core
He core increases in $\mathcal{M}$ and contracts until electrons become degenerate for red giants with $0.25\mathcal{M}_\odot < \mathcal{M} < 2.25\mathcal{M}_\odot$
Core $\mathcal{T}$ goes up with no change in $\mathcal{P}$, degenerate $\mathcal{P}$ increase with $\mathcal{D}$ as more He ash drops into core

For medium-mass star, core $\mathcal{T}$ is high enough for He fusion   Triple-α process: 3 ^{4}He $\rightarrow$ 1 ^{12}C
At higher core $\mathcal{T}$ (2×10^8 K), ^{12}C+ ^{4}He $\rightarrow$ ^{16}O
Helium flash: He fusion starts in degenerate core with broken thermostat, fusion rate skyrocket until enough $\mathcal{T}$ to eliminate degeneracy
Core expands, electron gas $\mathcal{D}$ drops and stop degenerate
Helium core fusion: Burn He in core and H in shell $\rightarrow$ Core expands, absorb energy from envelope $\rightarrow$ Contracts, hotter and smaller
C and O produced from He fusion is left behind around the center
Double shell-burning: He runs out at core, C and O core contracts and heats up $\rightarrow$ He shell fusion + H shell fusion $\rightarrow$ Red giant
Hydrostatic equilibrium is impossible, outer layers expelled by high radiation and thermal pressure $\rightarrow$ Planetary nebula
Core left behind is white dwarf
CNO cycle: High mass MS star fuse H to He using C, N, O as catalysts   Greater core $\mathcal{T}$ enables H to overcome greater repulsion
Life of high-mass star: High core $\mathcal{T}$ allow He to fuse with heavier elements   Core $\mathcal{T}$ in star $> \mathcal{M}_\odot$ allow fusion of elements to Fe.
Fe is dead end because Fe has lowest mass per nuclear particle   Builds up in core until degeneracy pressure cannot resist gravity
Supernova explosion: Core collapses due to electrons combine with protons, making neutrons and neutrino
$1.4 - 3\mathcal{M}_\odot$: Neutron star $> 3\mathcal{M}_\odot$: Black hole

Chapter 10 Bizarre Stellar Graveyard

White dwarf: Remaining cores of dead medium and low mass star   Electron degeneracy pressure supports against gravity
Ideal gas law: $\mathcal{P}V = nR\mathcal{T}$ when particles have much room to move
For degenerate matter, gravitational contraction can be balanced by degeneracy pressure
White dwarfs mainly made of C and O from medium mass star, mainly made of He from low mass star   Size similar to Earth
Chandrasekhar Limit: $M < 1.4M_\odot$ takes into account of relativity $> 1.4M_\odot$ allows gravitational collapse
Size of white dwarf decreases with its $\mathcal{M}$ Size goes to 0 when $\mathcal{M} = 1.4\mathcal{M}_\odot$
By $\Delta p \Delta x \geq \frac{\hbar}{2}$, as white dwarf's $\mathcal{M} \rightarrow 1.4\mathcal{M}_\odot$, electrons move nearly speed of light
Stars near white dwarf: Matter orbits white dwarf in accretion disk due to angular momentum
Friction between rings of matter heat up the disk and glow   surface of white dwarf hot enough for H fusion
Fusion begins suddenly and explosively, causing nova   Nova system temporarily appear much brighter, drives accreted matter out
White-dwarf supernova (Type Ia): C and O fusion begins as white dwarf reaches Chandrasekhar limit, causing complete explosion
Release energy larger than gravitational binding energy $\rightarrow$ nothing in center
Massive-star supernova (Type II): Iron core reaches white dwarf limit and becomes neutron star or black hole
In light curves, type II has plateau in luminosity while type Ia doesn't   Type Ia is much more $\mathcal{L}$
Type Ia do not have H absorption lines due to H being consumed by nova and become He
Type Ia show strong ionized silicon emission line at 615 nm
Neutron star: Ball of neutrons from massive-star supernova   Supported by degeneracy pressure
Pulsar: Neutron star that beams radiation along magnetic axis that is not aligned with rotation axis   Emits in form of 2 beams
Source: Non-thermal synchrotron radiation: Emitted from particles accelerated rapidly along magnetic field
Thermal radiation: Particles colliding with neutron star surface at magnetic poles
Contain x-rays, optical and radio radiation since protons smash at extremely high velocities
Why Pulsars are neutron stars: Spin rate of fast pulsars = 1000 cycles per second   Surface rotation velocity = $60000\,\mathrm{km\,s^{-1}}$
Matter accreting onto neutron star becomes hot and dense enough for H and He to fuse $\rightarrow$ Produce burst of x-rays
Neutron star has thin atmosphere of He, accreting matter contain He and H fusion forms He
Neutron degeneracy pressure has a limit of $3\mathcal{M}_\odot$ $\rightarrow$ becomes black hole
Escape velocity: $v_{\text{escape}} = \sqrt{\frac{2G\mathcal{M}}{r}}$
Schwarzschild Radius: Smallest distance from black hole such that light can escape $r_s = \frac{2G\mathcal{M}}{c^2}$
Non-rotating black hole: Singularity at center (0 size and infinite $\mathcal{D}$)   Event horizon: singularity centered with Schwarzschild radius
Tidal force for force at top and force at bottom: $F_1 - F_2 = \frac{2G\mathcal{M}_{\text{black hole}}\mathcal{M}\ell}{r^3}$
At event horizon, $F_1 - F_2 = \frac{c^6\mathcal{M}\ell}{4G^2\mathcal{M}_{\text{black hole}}}$ More massive black holes have smaller tidal force
Black hole strongly warps space-time in vicinity of event horizon
Gravitational Time Dilation: Clock near massive object appears to run more slowly
Gravitational redshift: Light is redshifted when moving away from massive object
Methods for hunting black holes:
Measure mass: Use orbital properties of companion or measure velocity and distance or orbiting gas
Compact object is black hole if it has mass $3\mathcal{M}_\odot$
Gravitational lensing: Multiple images or rings of distant objects as light bends
Einstein's ring: Seen when massive object is spherical   Einstein's cross: Seen when massive object has less regular shape
Gravitational waves: Massive objects undergoing rapid non-uniform motion emit gravitational waves (Binary black hole system)
Gamma ray bursts origin: Supernovae, hypernova, collision between neutron stars

Chapter 11 Our Galaxy

Galaxy: Spiral galaxy with (on average 10^{11}) stars in space, all held together by gravity and orbiting a common center.
Milky Way consists of disk with spiral arms, nuclear bulge and halos with globular clusters $d_{\text{Milky Way}} = 25000\,\text{pc} = 75000\,\text{ly}$
Sun is located about 27000 ly from galactic center
Disk: Contains gas and dust, hosts younger generation of stars, location of open clusters   Bulge: Mixture of both young and old stars
Halo: Contains very few gas or dust, hosts older generation of stars, location of globular clusters, a lot of dark matter
Star in disk orbit same direction with up-and-down motion due to gravity of disk stars pulling them toward the disk
Orbits of stars in bulge and halo have random orientation
Orbital Velocity Law: $\mathcal{M}_r = \frac{r \times v^2}{G} = \frac{4\pi^2 r^3}{Gp^2}$ Mass within Sun's orbit: $1 \times 10^{11}\mathcal{M}_\odot$
Galactic Recycling: Star-Gas-Star cycle   Gas from old stars form new stars
Multiple supernovae create giant bubble in which hot gas can blow out of it into halo   Gas clouds cooling rain back down onto disk
Atomic H gas forms as hot gas cools allowing electrons to join with protons

Molecular clouds form after gas cools enough to allow atoms to combine into molecules   Stars form in molecular clouds
Radiation from newly formed stars erode surface of clouds and glows   Densest gas resist the erosion and continue to form stars
Observation of star-gas-star cycle:
21 cm radio waves show where H gas cooled and settled in disk $2.6 - 1.3$ mm radio waves from CO show locations of molecular clouds
Long λ infrared ($60 - 100\,\mu$m) from star heated intestellar dust   Short λ infrared ($1 - 4\,\mu$m) shows stars behind interstellar materials
Visible light emitted by stars is scattered and absorbed by dust   X-ray emitted from hot gas bubbles and X-ray binaries (Point-like)
Gamma-ray emitted from collisions of cosmic rays with atomic nuclei in interstellar clouds
21 cm radio radiation: Electron orbiting proton with parallel spins has higher energy than one with anti-parallel
Hyperfine structure arises from coupling between magnetic moment of electron and nuclear magnetic moment
$2.6 - 1.3$ mm radio waves: Comes from rotational transition (3 rotational energy levels: 2 emit 1.3 mm, 2.6 mm to 0)
Easily detected CO radio emission lines are used to infer amount of H_2 (Only in Milky Way)
Emission nebulae, blue stars → O-going star formation   Star formation mostly happens in spiral arms
Spiral arms: Not fixed   Gas clouds get squeezed as they move into spiral arms → Star formation → Young stars
Center of Milky Way: Sagittarius A* Using radio frequency, infra and x-ray imaging with adaptive optics to identify center with precision and clarity
Enclosed mass density is too high to be compatible with anything other than single supermassive black hole ($4.3 \times 10^6 \mathcal{M}_\odot$)

Chapter 12   Galaxies, the Foundation of Modern Cosmology and Galaxy Evolution

Cosmology: Study of structure and evolution of universe
Spiral Galaxy: Disk component: Stars of all ages, many gas clouds
Bulge: Mixture of both young and old stars   Halo: Old stars, globular clusters, few gas clouds, lots of dark matter
Barred spiral galaxy: Bar of stars across the bulge
Elliptical galaxy: Spheroidal shape, no disk component
Lenticular galaxy: Has disk like spiral galaxy, but much less dusty gas and lack spiral arms (Intermediate between spiral and elliptical)
Irregular galaxy: No particular shape
Spiral galaxies found in groups of galaxies   Elliptical galaxies found in huge clusters of galaxies
Cosmic Distance Ladder: Stellar parallax limit to 200 pc, use properties of nearby stars for further stars
Radar ranging (1 AU), stellar parallax (200 pc), spectroscopic parallax (10000 pc), variable stars (50×10^6 pc)
Variable stars: Standard candle: Object with known luminosity
Variable stars pulsate because of changing balance between thermal pressure and gravity near equilibrium configuration
Happens in energy absorbing layer in outer envelope where He is partially ionized
Absorbing and releasing of energy lead to oscillation of star size, hence $\mathcal{L}$ and surface $\mathcal{T}$
Stars with higher $\mathcal{T}$: Layer cannot be formed   Stars with lower $\mathcal{T}$: Layer locate very deep in envelope, not significant variation
Period of variable star tells average $\mathcal{L}$, we can use the stars as standard candles
Apparent brightness of white-dwarf supernova tell us distance of its galaxy (3066×10^6 pc)
Type Ia Supernova always give same amount of energy ($M = -19.3$)
Hubble: Virtually all galaxies are redshifted (Moving away from us)   Redshift and distance are related
Hubble's Law: $d = \frac{v}{H}$ (Hubble constant $H = 64000\,\mathrm{m\,s^{-1}\,Mpc^{-1}}$)   Implies expanding universe
Universe age $t = \frac{d}{v} = \frac{1}{H}$ Cosmological Principle: Universe looks about the same on very large scales no matter where you are in it
Matter is almost evenly distributed on very large scale   No center and no edge
Cosmological redshift: Expansion of universe stretches photon λ
Galaxy formation: Start from protogalactic clouds, H and He gases formed first stars
Supernova heated surrounding interstellar gas, slowed down collapse of protogalactic clouds
For spiral galaxies, leftover gas settled into spinning disk
High $\mathcal{D}$ cloud form stars faster → Elliptical galaxy   Low $\mathcal{D}$ cloud form stars slower → Spiral galaxy
Galactic Cannibalism: Massive galaxies eat small ones due to larger gravity (Milky Way eats up large and small magellanic clouds)
Galactic collisions: More likely early in time   Trigger burst of star formation   Form elliptical galaxies
Starburst galaxies: From collision or near collision   Form stars so quickly that they use up all gas in less than billion yrs
Redshift $z = \frac{\lambda_{\text{shift}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}}$ Recessional speed $v_r = c\frac{(z+1)^2-1}{(z+1)^2+1}$
Quasars: $> 10^{12}\mathcal{L}_\odot$ Vary in brightness on timescale of hours, days or weeks
Highly redshifted spectra of quasars indicates large distance   Contains very wide range of λ (Contain matter with wide range of $\mathcal{T}$)
Active galactic nucleus (AGN): Unusually bright center of galaxy
Normal galaxy: $> 90\%$ of galaxies, $10^6 - 10^{10}\mathcal{L}_\odot$
Active galaxy: $> 10^{12}\mathcal{L}_\odot$, strong radiation from radio frequency to x-ray
Radio galaxy: Contain active nuclei shooting out jets of plasma that power lobes' radio radiation through synchrotron radiation
Charged particles in synchrotron radiation moves near speed of light but decelerating due to interaction with intergalactic medium
AGN shoot out blobs of plasma at speed of light → supermassive black hole is present
Accretion disks of some radio galaxies blocked by dusty gas clouds, look like quasar viewed along direction closer to jet axis
Power source of quasars and AGN: Accretion of gas onto a supermassive black hole at the center

Chapter 13 Birth of Universe, Dark Matter, Dark Energy, and Fate of Universe
Age of universe: about 13.8×10^9 yrs, but due to expansion of space, humans are observing objects that were originally much closer but are now considerably farther away.
Current Cosmic Model: Dark Matter 22%, dark energy 73%
Normal matter: $10\,\mathrm{g}$ in $10^{30}\,\mathrm{cm}^3$ Dark matter: Matter we infer to exist through gravitational effects but emit no detectable radiation
Evidence of existence: $\mathcal{M}$ of spiral galaxies: Far more $\mathcal{M}$ than we see in stars Flat rotational curves meaning lots of dark matter
$\mathcal{M}$ of elliptical galaxies: More massive galaxies have more gravity so stars are moving at faster orbital speed
More massive galaxies should have broader absorption lines
$\mathcal{M}$ in galaxy clusters: Measure velocities of galaxies from Doppler shift, $\mathcal{T}$ of hot gases, gravitational lensing
Possible dark matter: Massive Compact Halo Objects, weakly interacting massive particles, axions and neutrino-like particles
Olber's Paradox: If Universe if infinite, unchanging and everywhere the same, then night sky should be bright
Since night sky is dark, universe cannot be unchanging in time and infinite in space
Big bang: Hot and dense universe starts to expand
Earliest phases: Consists of radiation (photons) at $\mathcal{T} = 10^{32}\,\mathrm{K}$ and high $\mathcal{D}$.
$1\,\mathrm{s}$: $\mathcal{T} = 10^{10}$, protons, neutrons, electrons, neutrino emerged
Primordial Nucleosynthesis: H, He, Li, Be and isotopes formed
Cooler further: Formation of stars and galaxies (Formed He, C and heavier elements)
Hubble's Law: Redshift due to expansion of space-time
Cosmic Background Radiation (CBR): Freely streaming across universe since atoms formed at $\mathcal{T} = 3000\,\mathrm{K}$ (Become transparent)
When early universe was hot, it was radiation-dominated (Mostly electrons, ions, scattered photons), makes it opaque
When it expands, at age of 380000 yrs, cools enough for recombination of ions and electrons to form neutral atoms (Become transparent)
COBE: Satellite/thermometer to measure diffuse infrared and microwave radiation from early universe
BB model: Total expansion is 1000 time since universe became transparent Measured $\mathcal{T} = 3\,\mathrm{K}$ Observed $= 2.735\,\mathrm{K}$
Model also predict spectrum obey black-body radiation form
Early universe: Photon converted to particle-antiparticle pairs
At $10^9\,\mathrm{K}$, protons and neutrons fused into deuterium and helium $2\,\mathrm{p} + 2\,\mathrm{n} \rightarrow 1\,{}^4\mathrm{He}$ converted all free neutrons into He in 5 minutes
In very short time of He synthesis, there were 7 protons every neutrons (Explain why H/He mass abundance ratio is 3)
Model also works extremely well for other light elements Form ^{2}H, ^{4}He, ^{3}He, ^{6}He, ^{7}He in 5 minutes
BB model: basic framework of modern cosmology
Curvature of Universe: Universe cannot be perfectly uniform (Inhomogeneities show in CBR)
Angular size of $\mathcal{T}$ variation used to determine curvature of Universe (1° in angular size for flat universe) Data support Universe is flat
At age $10^{-32}\,\mathrm{s}$, Universe suddenly inflated by factor of 10^{78} due to high-energy to low-energy transition
Force of nature separated around cosmic inflation Small size of Universe before inflation allow $\mathcal{T}$ to equalize $\rightarrow$ isotropic
Flatness Problem: Inflation theory means tremendous expansion greatly dilutes initial curvature
Curvature of Universe $k = -1, 0, 1$ depends on total mass density ρ Critical density for $k = 0$ $\rho_c = \frac{3H_0^2}{8\pi G} = 10^{-29}\,\mathrm{g\,cm^{-3}}$
Density normalized to critical density $\Omega = \frac{\rho}{\rho_c}$
Dark energy: Causing universe expansion to accelerate (no idea what it is) Anti-gravity
Models without acceleration: Assume $\Omega_m = 1$ implies age only 9×10^9 yrs (Younger than some globular clusters)
Total energy density $\Omega_t = \Omega_m + \Omega_k + \Omega_\Lambda$ m: Ordinary and extraordinary matter k: curvature of space Λ: Dark energy
Since curvature of universe is flat, $\Omega_k = 0$ Geometrically flat: $\Omega_t = 1.02 \pm 0.02$
Mass of universe: $\Omega_m = \Omega_{DM} + \Omega_{\mathrm{atom}} \approx 0.3$ This means $\Omega_\Lambda \approx 0.7$
Concordance Cosmic Model (ΛCDM Model):
Type Ia supernovae: Cosmic acceleration depends on difference between repulsive Ω_Λ and attractive Ω_m, $\Omega_\Lambda > \Omega_m$
Galaxy clusters: $\Omega_m \approx 0.3$ CBR Ripples: $\Omega_m + \Omega_\Lambda = 1$
Before dark energy: $\Omega_m > 1$: Closed universe $\rightarrow$ Big crunch $\Omega_m < 1$: Open universe $\rightarrow$ Big freeze
After dark energy: $\Omega_m \approx 0.3$, $\Omega_\Lambda \approx 0.7$: Flat and accelerating universe $\rightarrow$ Big Freeze