Ch 1 **Outline of Universe**
Hierarchy: nuclei/atoms/stars/galaxies
Solar System
Nearby Stars, Our Galaxy
Galaxies and the visible Universe
Lengths: AU, light year, parsec
Angles: degree, arcmin, arcsec

App.A Units, Powers of 10

Ch 6.1 **Nature of Light**
Speed of light = $c = 300,000$ km/s.
Spectrum (blue = 400nm, red = 600nm)
Electromagnetic waves
Electromagnetic Spectrum:
  Radio, microwave, infra-red, optical,
  ultra-violet, X-ray, gamma-ray
Atmospheric windows (transparency/opacity)
Wavelength (λ), frequency (f), $c = f\lambda$
  f measured in Hertz (Hz) ie "per sec"
Photons: $E = hf = hc/\lambda$
  h = Planck's constant = 6.6×10^{-34} J s

Ch 7 **Creation of light:** accelerated charge
Thermal radiation: hot solids, liquids, dense gases
Temperature scales: Kelvin (K),
  Celsius (C), Fahrenheit (F) [0 K = −273 C]
Blackbody (perfect) emitter/absorber
Blackbody spectrum shape
Stars (dense gas) approximate blackbody spectra
Higher Temp, shorter (bluer) peak,
  $\lambda_{\rm peak}(\rm nm) = 3 \times 10^6/T$ (Wein's Law)
Star color → star temperature
Higher temp, more emission
  E/unit area = σT^4 (Stefan-Boltzmann Law)
Line radiation created by atoms
Atomic structure: protons, neutrons, electrons
  protons and neutrons in nucleus
  electrons in orbits
  # of protons → element
  # of neutrons + protons → isotope
  # electrons = # protons (neutral atoms)
  # electrons ≠ # protons (ions)
Bohr picture of electron orbits
  only certain permitted orbits
  orbit levels → energy levels
  electrons can jump between levels
  jump up → absorption of photon
  jump down → emission of photon
  jump out (lost) → ionization
Hydrogen atom energy levels (n=1,2,3...)
  Lyman (n=1), Balmer (n=2), etc series of lines
Kirchoff's Laws: conditions for
  creating Emission/Absorption lines
Stellar spectra
Absorption lines from photosphere
Hydrogen Balmer series changes in strength
  weak at low temp: all in ground state (n=1)
  weak at high temp: all ionized
  strongest at ∼ 10000 K
Classification of absorption spectra
  O B A F G K M
  subdivided by #s 0 to 9
Temperature (spectral) sequence
  O stars 50,000 °K, M stars 2000 °K
  T decreasing: ions → atoms → molecules
Composition of stars: 74% H, 24% He, 2% all others
  abundances decrease for heavier elements
Doppler shift: $v/c = (\lambda - \lambda_o)/\lambda_o$
  v is radial velocity (RV) only
  redshift (away), blueshift (towards)
  no shift (transverse)
Line broadening:
  high pressure → wide lines.

Ch 8 **The Sun:** an average star
Global properties
  size, mass, density, luminosity,
  temperature, composition, rotation
Photosphere ('surface')
Granulation (convection cells)
Chromosphere (He discovery)
Corona (hot)
Solar wind → aurora, comet tails
Sunspots, sunspot cycle
Magnetic field, magnetic cycle
Prominences, flares
Solar interior: helioseismology
The Sun's Energy Source & Structure
Nuclear binding energy curve (fusion/fission)
Nuclear (hydrogen) fusion, p-p chain
$E=mc^2$: energy from mass
$4H \rightarrow {}^4He$ + Energy (0.7% efficient)
Solar neutrinos; detectors; discrepancy

Ch 9 **Stars**
Star distances:
  stellar parallax (p)
  d(pc) = 1/p(arcsec)
  1pc = 3.26 light years
  difficult beyond 1000 pc
Star motion (few arcse/century; few km/s):
  proper (transverse) & doppler (radial)
Star luminosity, L, intrinsic (Watt)
Star brightness, b, at earth (Watt/m^2)
  brightness depends on distance and luminosity
  inverse square law: $b \propto \frac{1}{d^2}$; $b = \frac{L}{4\pi d^2}$
  e.g. Sun: $L = 3.8 \times 10^{26}$ Watt, $b = 1400$ Watt/m^2
  Sirius: $L = 9.1 \times 10^{27}$ Watt, $b = 1.14 \times 10^{-7}$ Watt/m^2
Apparent magnitude, m
  Hipparchus, 1 ⟶ 6 (brighter ⟶ fainter)
  difference of 5 mag is ×100 in brightness
  difference of 1 mag is ×2.512 in brightness
  absolute magnitude (M) = m at 10pc
Star sizes: large range

surface area of star (sphere) = $4\pi R^2$
Luminosity of star: $L = 4\pi R^2 \sigma T^4$
H−R diagram (Luminosity vs Temp)
Main sequence (MS), giants, white dwarfs
Luminosity/size class (width of absorption lines)
large R → low pressure → narrow lines
→ Luminosity Class (LC) & star size
LC I, III, V = supergiants, giants, main sequence
e.g. Sun: G2V, Arcturus: K2III
Binary stars
visual; spectroscopic; eclipsing
Star Mass determination from binary orbits:
stars orbit about center of mass
$k\ (M_1+M_2) = \frac{a^3}{P^2}$ (Kepler's 3rd Law)
$k = 1$ if M in $M_\odot$, a in AU, P in years
mass ratio $M_1/M_2 = V_2/V_1$
Mass−Luminosity relation for MS stars
$L \propto M^{3.5}$, eg M0 = 0.5 $M_\odot$; A0 = $4M_\odot$
Mass−Lifetime relation for MS stars ($t \propto M^{-2.5}$)
Mass limits: max ∼ 50 $M_\odot$, min ∼ 0.08 $M_\odot$
Luminosity function (census by brightness):
lower luminosity stars more common
night sky stars usually luminous

Ch 10 <u>Interstellar medium (ISM)</u>: low density gas & dust
Galactic "atmosphere", ∼ 5% mass in stars
Dust: composition/absorption/reddening
cold, so thermal emission in IR
Three kinds of nebulae: dark/reflection/emission
HI: electron spin flip → 21 cm (radio) photon
Molecules: e.g. CO "visible" in radio (not H_2)
X-ray emitting (hot) gas from supernova explosions
four phases (approximate pressure balance):
1) cold (∼ 20K) "dense" (∼ $10^3/cm^3$) molecular clouds
2) warm (∼ 500K) neutral hydrogen, HI clouds
3) hot (∼ 10^4K) ionized hydrogen, HII regions
4) v. hot (∼ 10^6K), low density ($0.01/cm^3$), pervasive
cycle: gas → stars → gas

Ch 11 <u>Star Birth</u>
Gas (molecular) clouds usually supported:
thermal+magnetic pressure/turbulence/rotation
Can collapse if triggered by shock
supernovae; stellar winds; spiral arms; cloud collision
core heating from gravity: "protostars"
hidden cocoon phase (IR sources), disks & jets
planets form; discovering extrasolar planets
Hydrogen fusion begins: star is "born"
evolutionary tracks on H-R diagram
Zero Age Main Sequence (ZAMS)
location on MS mass dependent (O high, M low)
formation time mass dependent (O short, M long)
Brown dwarf: failed star, $M_\star < 0.08M_\odot$, no fusion
HII regions, O&B stars ionize H, pink (Hα) color
Star winds & supernovae remove gas → young star cluster
Star Structure:
Hydrostatic equilibrium:
gravity inwards = pressure outwards
Energy source: p–p chain; CNO cycle
Energy transport:
radiation, convection, (conduction)
regions depend on mass
Star stability: stellar thermostat

Ch 12 <u>Star Evolution</u>
Computer model of Sun's interior:
centrally concentrated (core/envelope)
nuclear reactions in core (< 20%)
inner 80% radiative
outer 20% convective
Life on the Main Sequence (MS)
core H fusion (4H → He)
p-p chain (low mass), CNO cycle (high mass)
longest stage of life (eg sun 10^{10} yrs)
MS lifetime: Lower mass → Longer lifetime
Leaving MS, up Red Giant Branch (RGB) 1st time
H fuel exhausted in core
core contracts & heats
H burns in shell, powerful
envelope expands & cools
Red Giant ($R_\star \sim 1$AU), luminous ($L_\star \sim 10^3 L_\odot$)
Beyond RGB
He ignites in core, 3He → C (triple alpha)
($M_\star < 2M_\odot$ Helium flash)
lands on "Horizontal Branch" (HB)
He fuel exhausted in core
He & H shells burning, very powerful
envelope expands and cools
up RGB 2nd time (AGB)
red supergiant ($R_\star \sim 5$AU, $L_\star \sim 10^4 L_\odot$)
Star Clusters: groups of the same age
Globular clusters: old, halo, metal poor
Open clusters: young, disk, metal rich
Cluster H−R diagrams: isochrones (same age)
Young cluster isochrones
Main Sequence Turn Off point (MSTO)
measuring cluster age from MSTO
Variable stars
instability strip on H−R diagram
stellar pulsation, periods 1 − 90 days
RR Lyrae (fainter, lower mass)
Cepheids (brighter, higher mass)
period−luminosity relation
distance estimates

Ch 13 <u>Star Death</u>
Low mass stars ($< 0.4M_\odot$):
long lives; cannot ignite He
Intermediate mass stars (eg the Sun):
Large size → low surface gravity → mass loss
expanding envelope = "Planetary Nebula" (PN)
reveales hot core → White Dwarf (WD) star
UV ionizes PN → emission line glow
WD *slowly* cools → black dwarf

High mass stars ($M_\star > 10M_\odot$) DIFFERENT
- short MS lifetime
- heavier elements burn (He→C/O→Ne... etc)
- higher core temps & densities, shorter durations
- onion shell structure, core + shells
- iron core: no more energy (minimum in mass defect)
- core collapse (0.2 seconds; radius 3000km → 10km)
- protons + electrons → neutrons + neutrinos
- huge neutrino release
- core bounce → rising shock → star explodes

Type II supernova (eg SN 1987A)
- total energy ∼ 10^{46} Joules (gravity origin)
- energy emerges: 99% neutrinos, 1% kinetic, 0.01% light
- neutrino burst detected from SN 1987A
- light outshines galaxy for a week
- fades with decay ^{56}Co → ^{56}Fe ($t_{\frac{1}{2}} = 77$ days)
- expanding shell (supernova remnant)

Nucleosynthesis (origin of elements)
- α elements; r & s process (neutron addition)
- recycle into ISM → new stars (and planets and us!)
- gradual element enrichment of galaxy

Ch 14 Star Corpses

White dwarf (WD)
- dead core of intermediate mass star
- earth size, carbon/oxygen, hot (white), faint
- density ∼ 5×10^5 g/cm^3
- electron degenerate pressure support
- degeneracy pressure independent of temperature
- more massive WDs are smaller
- limiting mass $1.4M_\odot$ (Chandrasekhar mass)

Mass accretion onto WD from companion:
- nova: hydrogen detonation of surface layer
- Type I supernova: carbon detonation of entire star

Neutron stars:
- remaining core after Type II Supernova
- size ∼ 10km, density ∼ 10^{14} g/cm^3
- neutron degenerate pressure support
- mass limit about $3M_\odot$

Pulsars:
- rotating magnetized neutron stars
- conservation of angular momentum → rapid spin
- lighthouse model
- Crab nebula powered by pulsar (synchrotron)
- slowing down (young pulsars spin faster than old)

Mass accretion onto NS from companion:
- He detonation of surface → X-ray burster
- rapid spin-up → millisecond pulsars

Black Holes:
- escape velocity, $V_{esc} = \sqrt{2GM/R}$
- for $V_{esc} = c$, we get $R_s = 2GM/c^2$
- R_s = Schwarzchild radius = event horizon = $3M/M_\odot$ km
- $M > 3M_\odot$ collapse unstoppable → singularity

Near BH: time slows, light redshifted, strong tides

Spinning (Kerr) black holes, drag space around.

Searching for black holes:
- rapid X-ray variability → small size
- Cyg X-1, accreting binary, $M_{BH} \sim$ few $M_\odot$

Ch 15 Our Galaxy

Appearance of Milky Way (MW) → slab geometry

Star counts → sun at center (Herschel)

Globular cluster distribution → sun off-center (Shapley)

Discrepancy: dust absorption in ISM (Trumpler)

Galaxy shape:
- radius ∼ 15kpc, sun ∼ 8.5kpc from center
- disk of stars + ISM, bulge, nucleus,
- large spherical halo with globular clusters

Motions:
- Halo orbits: elliptical; random orientation
- Disk orbits (eg sun): ∼circular in disk plane
- sun's speed ∼ 200 km/s
- sun's orbital period ∼ 200 million yrs
- about 70 rotations since birth of galaxy
- Kepler's law → M∼ $10^{11}M_\odot$ inside sun

Rotation curve:
- rapid rise, then constant (at ∼ 200 km/s)
- differential rotation (inner stars overtake)
- dark matter extends beyond stars (unknown)

Stellar Populations:
- Pop I: young, disk, enriched by heavy elements
- Pop II: old, halo, depleted in heavy elements

Galaxy Formation:
- collapse of protogalactic cloud
- + interactions/accretion of dwarf companions

Sprial structure:
- seen in HI 21cm maps
- seen in distribution of star formation regions
- arms follow star formation → brighter/bluer

Theories of spiral origin
- NOT simple rotation → windup too tight
- self-propagating star formation
- density wave theory: slow pattern speed
- density wave triggered by bar or passing neighbor

Galactic Nucleus, dense star cluster, star formation
- star orbits traced, periods ∼ 10 yrs
- → black hole with mass ∼ 2.6×10^6 $M_\odot$

Ch 16 Other Galaxies

Early work (1850s): Lord Rosse → Nebulae

Shapley−Curtis debate: nature of spiral nebulae
- Cepheids in M31 → external galaxy (Hubble)

Distribution & Total Number:
- Sload Survey of ∼ 10^6 galaxies: walls/sheets/voids
- Hubble Deep Field → 10^{11} galaxies total

Galaxy shapes: Hubble's classification
- tuning fork diagram
- spirals: Sa→c: big→small bulge, tight→open arms
- barred spirals: SBa,b,c ; have inner bar of stars
- ellipticals: smooth, round (E0)→ flat (E7), no ISM
- lenticular: like E plus disk but no arms or ISM
- irregulars (often smaller)

Galaxy distances

Cepheid variables (ok to ∼ 1Mpc)
further, need bright "standard candles"
eg brightest stars, HII regions, supernovae
Velocity of galaxies (almost all redshifts)
Hubble diagram: velocity (km/s) *vs* distance (Mpc)
straight line, $v \propto d$, or v = Hd (Hubble Law)
H: Hubble's constant 70± km/s/Mpc
(nearby galaxies dont follow the law)
use to estimate distance (v → d)
caused by universe expanding
Galaxy Properties: large range in size, mass, luminosity
Galaxy masses and mass/light ratios
rotation curves
dark (missing) mass
Galaxy interactions/collisions/mergers:
gravitational perturbations → distortion
gas clouds collide → strong star formation
no stars collide (too much space)
spiral + spiral → elliptical
Groups of galaxies: eg Local Group (3 spirals; 20 dwarfs)
Clusters of galaxies:
can contain thousands of galaxies
few big galaxies, many more smaller ones
often large central galaxy → cannibalized others
Doppler shifts → ∼ 500 km/s → 10^8 yr to cross
velocities → mass → dark mass dominates
gravitational lenses → dark mass dominates
Hot (10^7K) hydrostatic atmosphere → dark mass dominates
Galaxy Evolution
study distant (therefore younger) galaxies
find smaller building blocks (resemble LMC)
mergers → star formation, chemical enrichment
Hierarchical assembly: smaller → bigger

Ch 17 <u>Active Galaxies</u>
Seyfert galaxies: bright varible nucleus
Radio galaxies: jets and lobes
Synchrotron emission: fast electrons in magnetic field
Supermassive black holes ($10^7 - 10^9$ $M_\odot$) in galactic nuclei
Accretion disk releases gravitational energy → luminous
High speed bipolar jets often created
jets can appear superluminal
Even non-active galaxies may have nuclear black holes
Activity triggered by galaxy interactions → gas inflow
Quasars:
Discovery history:
bright radio sources but faint galaxies or "stars"
("quasars": quasi-stellar radio source)
redshifts → very distant → VERY luminous
some brighter than 100 galaxies
variable ($\Delta t \sim$ months) → tiny source ($R < c\Delta t$)
energy source puzzle → distances doubted
Evolution; quasars more common in past (further away)

Ch 18 <u>Cosmology</u>: The Big Bang
Global Properties: isotropy; homogeneity;
expansion; universality of physical law
Hubble law: cosmic expansion (cake analogy)
linear expansion, gradient → H (Hubble's constant)
Cosmological (not Doppler) redshift: spacetime expands
No center: everyone sees same expansion
All together at one time → Big Bang
Time since BB: t∼d/v∼1/H eg H=70 → t∼13 Gyr
Lookback time = light travel time (eg 1Gly → 1Gyr ago)
Current limits are 80% lookback to BB (adolescent)
Particle horizon at 100% lookback to BB
Shape & size of universe:
matter curves spacetime (curvature $k = +1, 0, -1$)
curvature depends on average density
critical density (k=0) ∼ 9.5×10^{-27} kg/m^3)
measure k, use cosmic triangle → k=0 ("flat" geometry)
Contents:
Atoms (4%) Dark Matter (23%) Dark Energy (70%)
total adds to critical density (k=0)
Microwave background:
whole sky: thermal spectrum, T=2.7K
some distortion: earth's motion; MW foreground
Penzias & Wilson (1963) .... WMAP (2003)
recombination in 3000K gas; hot fog cools & clears
redshift factor ∼ 1000; 380,000 yrs after BB
First million years & Sound:
hot thin glowing gas → sound waves present
caused by gravity pulling on gas → dropping pitch
Accelerating Expansion:
measure expansion history using distant SN
slower in past → expansion speeding up
explain using Einstein's Λ parameter (vacuum energy)
gets more important → Universe expands for ever
Early History
$t \sim 50,000$yr: matter density = radiation density
t ∼ few minutes: conditions = stellar interior
nucleosynthesis: H fusion to He
predict 24%; observe 24% → evidence for hot BB
Deuterium abundance → baryon density (∼ 4%)
t < 1 second:
high Temp → matter created from particle collisions
threshold temps: electrons (10^{10}K) freeze out at 1sec
protons (10^{12}K) freeze out at 100 μs
protons break into quarks at T> 10^{13}K (t < 1μs)
Four eras: Quark; Hadron; Lepton; Radiation
Origin of Forces
four forces: gravity, weak, EM, strong.
strength/identity is temperature dependent
EM & weak join at 10^{-10}s (10^{15}K);
add strong at 10^{-35}s; add gravity at 10^{-43}s
Problems with standard BB theory:
Problems: Flatness; Horizon; Structure; Matter.
Inflation may solve all these
huge early expansion → k=0; smooth on large scales
quantum roughness → structures
GUT transition favour matter over antimatter
Exciting times !