Ay 1 – Spring 2026 – Summary of the key points in each lecture

Lecture 1: Astronomy as a science

- Astronomy has a long and venerable history, starting from the Neolithic era, starting with the calendar and agriculture predictions, aside from astrology and religion
- Hypparcos/Ptolemy geocentric system of the world was replaced by the Copernican heliocentric one. Tycho Brahe and Johannes Kepler obtained the first systematic post-antiquity observations. Astronomy as a science started with Galileo and his pioneering use of a telescope, and got its theoretical backing by Newton's optics and theory of gravity
- Experimental basis of astronomy is through observations and repeatability, and their interpretability through physics. It is driven by the progress in technology (optics, electronics, detectors, computing)
- Astronomy today is a branch of physics, and offers the means of studying phenomena that cannot be studied in the lab: extreme relativistic energies, extreme gravity, extreme states of matter, vastly greater spatial scales, etc. It also opens new physics, e.g., with the nature of dark matter and dark energy
- Astronomical observations have some fundamental limitations:
  - Not being able to interact directly with our objects of study, but just to observe
  - Our time scales are up to decades, vastly smaller than the age of the universe and stars
  - Signal-to-noise Poissonian and quantum limits of detection
  - Geometrical optics limits of angular resolution
  - Opacity of the Earth's atmosphere and the Galactic ISM
  - Obscuration by dust in galaxies
  - Turbulence of the atmosphere/ISM: erasing the spatial information
  - Convolved backgrounds and foregrounds
- We collect observations from the entire electromagnetic spectrum, radio to γ–ray, from ground and from space, and even underground/underice, and from non-electromagnetic channels (cosmic rays, neutrinos, gravitational waves) – a multi-messenger astronomy. Each channel has its own limitations and biases, and together they paint a more complete picture

Lecture 2: Starting the exploration

- Some commonly used units:
  - Astronomical unit: the Earth-Sun distance, 1 au = 1.496×10^{13} cm ~ 150 million km
  - Light year: c × 1 yr, 1 ly = 9.463×10^{17} cm ~ 10^{18} cm
  - Parsec: the distance from which 1 au subtends an angle of 1 arcsec, 1 pc = 3.086×10^{18} cm ~ 3×10^{18} cm, 1 pc = 206,264.8 au ~ 2×10^5 au

- Solar mass: 1 $M_\odot$ = 1.989 × 10^{33} g ~ 2 × 10^{33} g
- Solar luminosity: 1 $L_\odot$ = 3.826 × 10^{33} erg/s ~ 4 × 10^{33} erg/s

- Common coordinate systems are Equatorial (RA ~ longitude, Dec ~ latitude), Alt-Az (altitude and azimuth), Ecliptic, and Galactic
- Common time systems are synodic (based on the solar noon) and siderial (based on the stars, has an extra day in a year, due to the Earth's orbit around the Sun)
- Earth's rotation axis is tilted by 23.4^o, and its precession has a period ~ 26,000 yrs
- Parallaxes are the only real, geometric measure of distance in astronomy

Lecture 3: Telescopes and detectors for multimessenger astronomy

- Difraction-limited imaging depends on the aperture and the wavelength, 1.22 λ/D
- Adaptive Optics is used to compensate for the atmospheric turbulence in Vis/IR
- Radio telescopes come as single dish, or as interferometers, which can reach a high angular resolution, even with a modest collecting area
- X-ray telescopes (always space-based) use grazing incidence mirrors to focus
- γ-ray telescopes (always space-based) use various particle detectors
- Ultra-high energy cosmic ray and γ-ray observatories (ground-based) use particle showers and Cherenkov radiation created by incoming particles
- Neutrino observatories use large volumes of water/ice to detect Cherenkov flashes
- Gravitational wave observatories use laser interferometers
- Modern detectors from IR to X-ray use solid state physics devices, like CCDs or CMOS arrays. Different semiconductors are used at different wavelengths

Lecture 4: Electromagnetic radiation processes

- Electromagnetic radiation can be discrete (between energy levels in quantum systems) , or continuous (due to the deceleration of charged particles). Continuous can be thermal (blackbody or brehmsstrahlung) or non-thermal (synchrotron, for particles moving in a magnetic field, or Cherenkov, for particles moving faster than the speed of light in a given medium)
- Kirchhoff's Laws specify the type of a spectrum that will be observed depending on the source and the medium between it and the observer, emission or absorption
- Blackbody radiation is in a *thermal equilibrium* with matter at some temperature T, and is completely defined by it, and described by the Planck formula. It obeys the Wien's law. Its luminosity is given by the Stefan-Boltzmann formula

- We measure relative fluxes in magnitudes, $m = m_0 - 2.5 \log F$, with the zero point dependent on a particular bandpass
- Absolute magnitudes are a proxy for the luminosity

Lecture 5: Interstellar medium, the birth of stars and planets

- Major ISM components: cold, atomic and molecular gas and dust, concentrated in the Galactic plane, from which stars and planets form; warm, ionized by young stars in star forming regions; and hot, as a Galactic spheroidal corona, ejected and heated by SNe
- 21cm spin-flip line of neutral hydrogen is a significant tool to study the ISM
- Dust causes interstellar extinction, mainly at the short wavelengths. The process is exponential with the path length
- Stars form in giant molecular and dust clouds. Protostellar clouds collapse under their self-gravity, until thermonuclear reactions ignite in their core. Young, massive stars then ionize and clear out the remaining ISM, leaving a young star cluster
- Angular momentum conservation leads to a protoplanetary disk, in which planets form by agglomeration, dust ⟶ pebbles ⟶ planetesimals ⟶ planets, which then sweep the leftover material along their orbits
- Heavier elements lead to the formation of rocky planets closer to their star, while volatile materials condense and form gas giants further away from the star

Lecture 6: Kepler's laws, orbits, planets and their properties, the Solar system

- Planetary motions and orbits follow the **Kepler's laws**, and are **direct consequences** of **Newton's gravity**:
  1. Planetary orbits are ellipses, with the Sun at the focus
  2. Planet velocities vary along the orbit, but they sweep the same area per unit time
     - It is a consequence of the **conservation of angular momentum**
  3. Cubes of the semimajor axis are proportional to the squares of the periods
     - It is a consequence of the **conservation of energy**
- More generally, the **orbits are conic sections**, and **depend on the energy**: ellipses for the gravitationally bound planets ($E_{kin} < E_{pot}$), parabolas when $E_{kin} = E_{pot}$, and hyperbolas for the unbound ones ($E_{kin} > E_{pot}$)
- Orbit's **size** depends on the **energy**: the larger the energy, the larger orbit
- Orbit's **shape (eccentricity)** depends on the **angular momentum**; circular orbits have the maximum angular momentum for a given energy

- In our Solar system, there are 3 kinds of planets; rocky, closer to the Sun; gas giants, further out, and dwarf planets, even further out ant into the Kuiper belt. Asteroids and comets are leftover rocky and icy planetesimals from the formation era
- The Moon probably formed from the material ejected due to a collision of a smaller protoplanet with the young Earth, and it condensed in its orbit
- The larger moons of Jupiter and Saturn can have oceans under the icy crust, in particular Europa and Enceladus, and likely most, if not all of the rest
- Planetary atmospheres develop belt-like circulation cells due to the Coriolis force
- Planets reflect some of their star's flux (albedo), absorb the rest, and re-emit the energy in the thermal IR. In the absence of an atmosphere, planet's temperature depends only on its albedo and the distance from the parent star
- Atmospheric opacity prevents some of that energy escaping, creating a greenhouse effect, that leads to global warming

Lecture 7: The greenhouse effect, brown dwarfs, exoplanets, and life in the universe

- Planet's temperature is determined only by its albedo and the distance to its parent star, but if there is any opacity in its atmosphere, some heat is retained, leading to a greenhouse effect. In our Solar system, Venus is an extreme case of this
- Habitable zone is the range of planet orbits radii where liquid water can exist on the surface. In the Solar system, this is $0.84 \text{ AU} < a < 1.7 \text{ AU}$
- Brown dwarfs are objects that are larger than planets, but insufficiently massive to ignite thermonuclear reactions, $M < 0.085\ M_\odot$
- Brown dwarfs and large planets can generate energy through the Kelvin-Helmholtz mechanism, conversion of the binding energy into heat as the object shrinks. Jupiter emits twice the amount of energy than it receives from the Sun
- *Planets are an expected byproduct of star formation*, from the leftover material in the protostellar/protoplanetary disk, and are now known to be common
- There are estimated to be between 100 billion and over 3 trillion planets in the Milky Way galaxy alone
- Search methods for exosolar planets include: direct imaging, Doppler shift as the planet and its star orbit the common center of mass, eclipses (transits) as a planet crosses the stellar disk, and gravitational microlensing
- Types of exoplanets include: gas giants, mini-Neptunes, super-Earths, and Terrestrial (rocky) planets. There are also rare types that do not exist in the Solar system. There are also rogue or interstellar planets that do not belong to any planetary system
- Architectures of exoplanetary systems can be very different from out own

- Water, oxygen, and various organic molecules have been detected in exoplanet spectra, and are also common in the interstellar medium, so life could be relatively common elsewhere in the Galaxy. In our Solar system, the most likely place for extraterrestrial life may be the larger moons of Jupiter and Saturn
- Searches for Extraterrestrial Intelligence (SETI) using radio have not yielded any results so far, but they have anthropocentric biases

Lecture 8: Stars, their structure, and our Sun

- The four basic factors of stellar structure are: hydrostatic equilibrium, thermal equilibrium, energy generation through thermonuclear reactions, and energy transport from the core to the surface
- Fusion of hydrogen into helium is the primary mechanism; other elements up to iron can be created in sufficiently massive stars, and heavier elements must be created in Supernova explosions or collisions of neutron stars
- High temperatures ($\sim 10^7 - 10^9$ K) and densities are needed in order to overcome the electrostatic repulsion of positively charged nuclei
- Two energy transport mechanisms are radiation diffusion, as photons are randomly scattered, absorbed, and re-emitted on the way from the fusion core to the surface; and convection, which happens when the plasma is too opaque for an efficient radiation transfer
- Intermediate mass (~ Sun-like) stars have a radiative core and a convection envelope, massive stars have a convective core and a radiative envelope, and low mass stars are fully convective
- Solar structure is: radiative core where the energy is produced, radiative envelope, convective envelope, photosphere (~ the visible surface, ~5800 K), chromosphere (where most of the Solar activity happens, $\sim 10^4$ K), and corona ($> 10^6$ K, heated by the chromospheric activity, source of the Solar wind and Coronal Mass Ejections)
- Solar activity is produced by the Solar magnetic field embedded in the solar plasma, and includes phenomena like Sun spots, Solar flares, and Coronal Mass Ejections (CME). It operates on a 11-year cycle
- CMEs bring high energy charged particles and magnetic fields, and can severely disrupt the Earth's magnetic field (geomagnetic storms), and cause aurorae
- About 2% of the Solar luminosity emerges in the form of electron neutrinos, generated through the inverse beta decay, as protons are turned into neutrons during the thermonuclear reactions
- En route to the Earth, neutrinos oscillate between three types, electron, muon, and tau, and thus the observed Solar neutrino flux is 1/3 of the initial one

Lecture 9: HR diagram, star clusters, and stellar evolution

- The Hertzsprung-Russell (HR) Diagram plots stellar luminosity vs. surface temperature (or spectral type or color). It is the principal tool to study stellar structure and evolution
- Stars form 1-D sequences as a function of mass, which represent different stages of thermonuclear burning. They spend most of their lifetime on the Main Sequence, where they burn H into He in their core
- Stars are always born in clusters. Galactic (disk, or open) clusters are young, confined to the disk, typically have 10^2 - 10^3 stars, and ages ~ 10^7 - 10^9 yr. Globular clusters are old, live in the stellar halo, typically have 10^4 - 10^7 stars, and ages ~ 10 - 13 Gyr
- Both kinds are gradually dissolved due to tidal encounters with giant molecular clouds in the disk, or passages through the disk or the Galactic bulge
- The range of stellar masses is limited by the ability to burn H into He on the low mass end, and by the balance of radiation pressure and gravity on the high mass end
- At the end of their thermonuclear evolution, massive stars explode as Supernovae

Lecture 10: The end points of stellar evolution

- After exhausting hydrogen in their core, stars ascend the red giant branch, with hydrogen burning in a shell and inert helium core
- In stars with $M < 2\ M_\odot$ the thermonuclear reactions stop, the core shrinks and becomes a hot, dense, passively cooling white dwarf, and the envelope dissipates, ionized by the central star, becoming a planetary nebula
- White dwarfs consist of degenerate gas, supported by a quantum-mechanical pressure. They do not generate energy, but cool passively, becoming black dwarfs
- In intermediate mass stars, He ignites in the core, burning into carbon, and the star moves to the horizontal branch
- For more massive stars, the process repeats and the star moves to the asymptotic giant branch
- For the most massive stars, the process repeats until Si burning into Fe
- When the Fe core becomes too massive to be supported by the electron degeneracy pressure, the core collapses, leading to a Type II Supernova, with a neutron star or a black hole as the remnant, depending on the star's mass
- If a white dwarf exceeds $1.4\ M_\odot$ (Chandrasekhar mass) through accretion or merging, it explodes as a Type I Supernova
- Neutron stars inherit their progenitor's angular momentum and spin fast, and magnetic fields that accelerate plasma, creating a lighthouse-like radio beam (pulsars). Some neutron stars can also generate Fast Radio Bursts (FRBs)
- Similarly, formation of a stellar black hole can lead to a relativistic beam that causes a Gamma Ray Burst (GRB)

- Any compact remnant (whit dwarf, neutron star, black hole) can have a binary companion, with accretion causing luminous bursts (visible or X-ray)
- In all cases, chemically enriched material from the progenitor star returns into the ISM, and is incorporated into the next generations of stars

Lecture 11: Our Galaxy, the Milky Way

- Milky Way Galaxy is a fairly typical barred spiral, with the Solar system ~ 8 kpc from the center, with the orbital speed of 220 km/s. Its major components are:
  - Thin stellar disk, embedded in a thicker stellar disk, and with the gas and active star formation concentrated towards the disk plane
  - Elliptical-like central bulge and a bar, composed of old, metal-rich stars
  - Spheroidal, metal-poor stellar halo, also containing globular star clusters
  - Hot gaseous corona created by Supernova ejecta from the Galactic plane
  - Dark matter halo, with a flat rotation curve, and density distribution $\rho(r) \sim r^{-2}$ (singular isothermal sphere) that dominates the total mass
  - A supermassive (4 million $M_\odot$) black hole in the center
- Spiral structure represents density waves propagating in a differentially rotating disk. They can compress the molecular gas clouds, causing star formation

Lecture 12: Galaxies and their properties

- Hubble Sequence is the original morphological classification of galaxies. Many, but not all important properties of galaxies correlate with the Hubble type. On the elliptical galaxy end, stellar populations are older, there is little or no star formation, colors are redder, dynamical support is mainly random motions (pressure), and densities are higher. On the spiral end, stellar populations are younger, bluer, star formation is active, and disks are supported mainly by rotation
- Most of these trends can be understood as a sequence of star formation histories, with the order of galaxy assembly and star formation
- Galaxy mergers, due to dynamical friction, play a major role in galaxy assembly. Generally, mergers *turn the rotationally supported disk galaxies into pressure supported ellipticals*, and may cause bursts of star formation
- Galaxy disks have exponential density profiles, bit in radius and vertically. Stellar disks have cutoffs, with has extending beyond them, suggestive of an inside-out galaxy formation
- Ellipticals and bulges have $R^{1/4}$ projected density profiles and triaxial shapes due to an anisotropic velocity dispersions

- Galaxy scaling relations, mainly the Tully-Fisher relation for spirals and the Fundamental Plane relations for ellipticals, can be used as distance indicator relations, and provide some insights into galaxy formation
- Dwarf galaxies follow qualitatively different correlations, driven by the mass loss due to Supernova winds and adiabatic expansion

Lecture 13: Galaxy formation and evolution

- Galaxy formation and evolution processes consist of the mass assembly through mergers (dissipationless) and evolution of stellar populations and gas (dissipative)
- Observations are usually based on deep imaging surveys over many wavelengths, followed by deep redshift surveys
- The history of star formation starts low and grows in time, peaks around the redshifts 2 to 3, and then declines, driven by dissipative merging and infall
- A half of all star formation was obscured by dust, and observable in FIR/sub-mm
- Intergalactic medium (IGM) consists mainly of primordial H+He clouds (seen as the Lyman-α forest), but some metallic line absorbers as well
- Chemical evolution of galaxies and IGM is coupled: gas flows into galaxies, and enriched gas is expelled to IGM due to stellar and SN winds
- Mechanical winds and ionizing radiation from young stars and AGN constitutes feedback that limits the growth of galaxies
- Energy output from galaxies is due to the release of binding energy, stellar nuclear burning, and formation of supermassive black holes by accretion
- We now observe young and forming galaxies at large redshifts with JWST

Lecture 14: Large scale structure: formation and observations

- Large Scale Structure (LSS) is on scales > galaxies; groups, clusters, filaments, walls, voids, superclusters are the elements of it
- It originates from density fluctuations in the early universe that evolve through self-gravity and hierarchical merging, driven by dark matter. Free-fall time scale characterizes the dissipationless structure formation
- Theoretical modeling of LSS and its evolution requires large numerical simulations
- To map and quantify the LSS (the large-scale 3-D density field) and compare it with the theoretical predictions), we need redshift surveys. It is quantified through two-point correlation function and the power spectrum of the LSS density field
- Primordial density fluctuations are damped/erased on the small scales first, and depend on the nature of the dark matter: cold dark matter fits all the data

- Dark halos form first, and the baryons flow into them, and make stars later
- Galaxy biasing implies that galaxies form first in the highest peaks of the density field
- Galaxy clusters are the largest bound structures known. Interactions in them can alter galaxy evolution

Lecture 15: Active Galactic Nuclei and supermassive black holes

- AGN are highly energetic manifestations in the nuclei of galaxies, powered by accretion onto supermassive massive black holes (SMBH)
- They emit energy over the entire electromagnetic spectrum, from radio to gamma rays, and most search methods are based on that
- Empirical classification schemes have been developed, on the basis of the spectra. AGN unification says that they are the same underlying phenomenon seen from a different angle
- AGN evolve strongly in time, and their evolution tracks that or the star formation
- Most or all massive galaxies contain a SMBH, and their masses correlate with the properties of the galaxy hosts, implying a co-evolution and feedback processes
- Schwarzschild radius defines the event horizon of a BH
- The luminosity comes from the release of binding energy of the material that accretes through a disk orbiting the BH, within a few Schwarzschild radii
- Released energy is both thermal emission from the accretion disk and from the obscuring torus, and synchrotron emission from relativistic electrons moving in magnetic fields
- Spinning SMBHs develop relativistic jets by twisting the magnetic fields that thread the BH itself or its accretion disk. The jets transfer the BH rotational kinetic energy
- Eddington limit is the largest luminosity an isotropically emitting AGN can have for a given BH mass, defined by the balance between the radiation pressure and gravity
- Collective emission from AGN creates the diffuse X-ray and gamma-ray backgrounds
- SMBHs grow by accretion and by hierarchical merging. Both can be stimulated by dissipative galaxy mergers
- The origin of the initial "BH seeds" is uncertain; some may come from stellar BH remnants, some from gravitational collapse of dense star clusters or protogalactic clouds, and some may be primordial

Lecture 16: Introduction to cosmology

- General Relativity (GR), as the theory of gravity, is the theoretical basis of the modern cosmology, connecting matter/energy, gravity, and geometry of space

- The universe expands, and the expansion rate is given by the Hubble constant. Two principal ways of measuring it are the "distance ladder" (parallaxes to Cepheids to Supernovae), and CMB fluctuations. They disagree slightly, but the difference is significant, and it is the cause of the "Hubble tension"
- While the full GR has 16 differential equations, symmetry assumptions (homogeneity and isotropy) reduce it to one, the Friedmann equation. Its solutions are cosmological models that give the past and the future expansion rates, and that are determined by the cosmological parameters, e.g., the densities of the various mass/energy components
- If the sum of all densities is equal to the critical density, the geometry of the universe is flat (Euclidean), and expands forever. If it is smaller, it is open, infinite, and also expands forever. If it is larger, the universe is closed and will recollapse
- Cosmological parameters, mainly the matter density and the dark energy, determine the overall geometry of the universe, and whether it will expand for ever
- There are many way of measuring them, but the principal ones are:
- Supernova Hubble Diagram, which uses the brightness of the Type Ia Supernovae as the "standard candles" to map the distance vs. redshift, which constrains the cosmological parameters
- CMB fluctuations, which serve as a "standard ruler" in the angular diameter test, based on the largest sound waves in the universe at redshift $z \sim 1100$, and require a theoretical and statistical analysis. These fluctuations are detectable in the galaxy clustering at lower redshifts, as Baryon Acoustic Oscillations (BAO)
- All current measurements intersect and agree in a small patch of the parameter space, which defines the standard cosmological model, ΛCDM, which is spatially flat, with matter contributing ~ 30% of the total density, and dark energy ~ 70% of it, and is 13.8 Gyr old

Lecture 17: Contents of the universe

- Main matter/energy density components of the universe are matter, radiation (mostly CMB), and dark energy (= cosmological constant, if it is constant)
- Their densities change differently as the universe expands: radiation dominates at first, then matter, then dark energy
- Visible (stars and gas) matter accounts for only 0.5% of the total; hot IGM adds another 4%, for a 4.5% total of the ordinary ("baryonic") matter
- Non-baryonic dark matter adds 26.5%. It is composed of as yet unknown particles that are outside the standard model of particle physics
- Gravitational lensing allows us to map the distribution of dark matter in the universe
- The remaining 69% is the dark energy, whose physical nature is unknown. It is unlike any other form of energy that we know

- These numbers come from a multitude of independent and consistent measurements, and are thus considered reliable

Lecture 18: The early universe

- These numbers come from a multitude of independent and consistent measurements, and are thus considered reliable
- As we look back in time towards the Big Bang, the universe was hotter and denser. At any given time, the temperature translates into a *characteristic mass or energies of particles* ($kT \sim mc^2$), which dominate that epoch
- As the energies increase, *different physical regimes* and different fundamental interactions come into play
  - Recombination at $z \sim 1100$ (atomic physics)
  - Nucleosynthesis at $z \sim 10^9$ (nuclear physics)
- The closer we get to the Big Bang (i.e., further away from the experimentally probed regime), the less certain the physics
- *Inflation* at $t \sim 10^{-33}$ sec solves important problems (flatness, horizon), but it is based on an *as-yet-unknown physics*
- Our extrapolations must break down by the epoch of $\sim 10^{-43}$ sec $\sim$ Planck time (?), where the quantum gravity must be important