

# ASTR:3772, 2019 Spring, Lecture Outline

Jan 14 - May 5, 2019 = 16 weeks - Spring Break week = 15 weeks = 30 lectures

Pre Spring Break = 9 weeks

Spring Break - Mar 18 - 22

Post Spring Break = 6 weeks

- **Post Main-Sequence Evolution**

- Low/Intermediate-mass star: evolution track on the HR diagram
  - Core collapse, protoplanetary disks, protostar (Hayashi-Henyey tracks)
  - MS evolution (depletion of H lead to the increase in mean molecular mass and  $T_c$ )
  - **derivation of mass-luminosity relation** of MS stars
  - post-MS evolution
    - SGB: core contraction after reaching S-C limit
    - RGB: H-shell burning
    - He core flash: fusion in conventional vs. degenerate cores
- post-MS evolution
  - HB, AGB, TP-AGB, Post-AGB, PN, Nebula Dissipation, Cooling of WD.
- **derivation of Schonberg-Chandrasekhar limit**
  - balance between required central pressure to maintain hydrostatic equilibrium and the maximum pressure an isothermal core can provide
  - textbook derivation conceptually incorrect when taking the partial derivative of  $M_{\text{core}}$  instead of  $R_{\text{core}}$ .
  - Application: color magnitude diagram of star clusters
    - Hertzsprung Gap (between MS and RGB) due to

rapid contraction of the core after it reaches the Schonberg-Chandrasekhar limit.

- **Kelvin Helmholtz** timescale

- e- degenerate gas
  - non-relativistic degenerate pressure
  - mass-radius relation of degenerate cores
  - relativistic degenerate pressure
  - **Chandrasekhar limit**

- **Fate of Massive Stars**

- Heavy mass loss and heavy metal shell burning
- End of fusion
- neutron capture processes: s-process vs. r-process
- Fe core collapse
- SNe classification
- SN light curve decay rate
- neutrino detection
- cosmic ray detection
- Type II has higher alpha/Fe ratio than type I

- **Degenerate Remnants**

- Neutron stars, predicted properties
- Pulsar-NS connection
- Pulsar-SN connection
- P-dP/dt plot

- **Close Binary Star Systems**

- Motivation: to better understand systems like the binary pulsar
- Celestial mechanics
  - co-rotating frame, a non-inertial reference frame
  - effective gravitational potential (added centrifugal potential)
  - Lagrangian/Libration Points
  - Roche Limit derivation

- Equipotential surface -> Roche Lobes (not axisymmetric)
      - think of the effective potential above the orbital plane
  - Orbital evolution due to mass transfer
    - Angular momentum conservation,  $dL/dt = 0$
  - Accretion disks
    - energy generation efficiency of gravitational accretion
    - temperature profile of a steady-state, optically thick disk (energy conservation),  $T(r) \sim r^{-3/4}$
    - Eddington Luminosity-limited growth rate
    - The requirement for seed BH mass of 100 Msun near Big Bang
  - Types of astrophysical objects related to close binaries
    - Blue stragglers, off-nuclear X-ray sources, Novae, CVs, SN Ia
- **The Milky Way Galaxy**
  - Scope of the Milky Way
    - Herschel's star count technique - finding the edges of the Milky Way
    - Effects of dust extinction - apparent distance < true distance
  - Direction of the Galactic Center
    - Shapley's GC method — RR Lyrae P-L relation
    - HI 21cm survey of the disk — symmetric point with zero radial velocity
    - Association of Sgr A\* to the SMBH at the Galactic Center
  - Distance to the Galactic Center
    - Proper motion of Sgr A\* using Solar system's motion in the Milky Way
    - Doppler shift measurements of stars orbiting around Sgr

A\*

- Kepler's first law -> inclination angle
- Key problems:
  - How fast are we moving relative to Galactic center?
  - How does the Galaxy rotate at different radii?
- Kinematics of stars in the Solar neighborhood ( $d < 0.1-1$  kpc)
  - Cylindrical motion coordinates ( $\Pi$ ,  $\Theta$ ,  $Z$ )
  - LSR definition - centered on the Sun
    - $\Pi_0 = Z_0 = 0$ ,  $\Theta_0 > 0$
  - Peculiar Motion ( $u$ ,  $v$ ,  $w$ ) - relative to LSR
    - $\Pi$ ,  $\Theta - \Theta_0$ ,  $Z$
  - Observed Peculiar Motion ( $du$ ,  $dv$ ,  $dw$ ) - relative to Solar motion
    - Estimate solar motion relative to the LSR
  - Velocity ellipsoids ( $u$  vs.  $v$  plot)
    - Velocity - metallicity relation
    - **$\Theta_0 = 220$  km/s**
- Kinematics of stars beyond Solar neighborhood
  - Observations
    - $v_r$  - radial velocity = Doppler shift
    - $v_t$  - tangential velocity = proper motion
    - Both  $v_r$  &  $v_t$  of stars at given distance follow sinusoidal functions of Galactic longitude
      - **$v_r \sim \sin(2l)$ ,  $v_t \sim \cos(2l)$**
  - Oort (1927) Explanation
    - **Oort's diagram**
    - **Oort's constants** - the normalizations of the sinusoidal functions
    - Results imply differential Rotation of the Milky Way
- Applications of Oort's constants
  - $\Theta_0/R_0 = A-B \Rightarrow R_0 = \Theta_0/(A-B)$
  - $d\Theta/dR @ R_0 = -(A+B) \Rightarrow$  nearly constant velocity

- Rotation curve of the MW
  - Point of maximum radial velocity is the tangent point
    - $R_{\min} = R_0 \cdot \sin i$
    - $\max(v_r) = (\Omega[R_{\min}] - \Omega_0) \cdot R_{\min} = \Theta(R_{\min}) - \Theta_0 \sin i$
    - **$\Theta(R_{\min}) = \max(v_r) + \Theta_0 \sin i$**
  - Rotation curve from HI 21cm line survey
  - Use the rotation curve to infer the spatial distribution of the HI gas in the disk
  - Rotation curve beyond the Solar circle
- Density Profile inferred from rotation curves
  - Constant rotation
  - Keplerian rotation
  - Rigid-body rotation
- **Understanding Star Formation in Normal Galaxies (2 lectures)**
  - morphology, color, luminosity, and kinematics
  - Galaxy morphologies
    - CMD and color-morphology correlation
    - Hubble tuning fork
    - morphology-density relation
  - CMD vs. HRD
  - from CMD to Star-forming Main Sequence
    - How to measure  $M^*$ ?
    - How to measure SFR?
    - Blue cloud => an evolving narrow SF sequence
      - (dust correction is key)
- **Midterm Exam and Spring Break**
- **Understanding Star Formation in Normal Galaxies (3 lecture)**
  - Mass-Metallicity Relation
    - How to measure [O/H] and Z?
  - Kennicutt-Schmidt Relation

- How to measure gas mass?
  - Tully-Fisher relation -  $L \sim V^4$ 
    - circular velocity enclosed mass
    - constant M/L ratio, same stellar population distributions
    - constant luminosity surface density,  $L/R^2$  (incompressible)
  - Fundamental plane  $\sim L \sim \sigma^{2.65} r_e^{0.65}$ 
    - Faber-Jackson relation
    - Derivation: virial theorem
- **Mutel Guest lecture: BH mass and distance measurements of NGC 4258**
  - Moran08, Herrnstein99, Miyoshi95
  - Condon book Sec 7.5
- **Equilibrium Stellar Dynamical Systems (3 lectures)**
  - The unimportance of two-body relaxation
    - strong close encounters
      - $l = 1/n \sigma$
      - $Gm/r \sim mv^2/2 \Rightarrow r_s = 2Gm/v^2$
      - $t_s = l/v \sim v^3/(m^2 n)$
    - weak distant encounters
      - impulse approximation
        - $dV = Gm/b^2 * 2b/v = 2Gm/bv$
        - $dV = V \Rightarrow b_{min} = 2Gm/v^2$
      - $t_{relax} = t_s / 2 \ln(b_{max}/b_{min})$
    - application of virial theorem
      - $R = GNm/v^2 = N b_{min}/2$
    - two-body relaxation timescale
      - $t_s = N t_{cross} / 4 \pi$
      - $t_{relax} = N t_{cross} / 8 \ln(N)$
    - applications
      - galaxies are collisionless systems
      - star clusters are collisional

- ISM is collisional
  - star clusters
    - Maxwellian distribution function in 6-dimensional (x,v) phase space
    - evaporation
    - mass segregation
    - **collisionless systems with Maxwellian velocity distribution** is equivalent to **isothermal collisional gas, because** Poisson's Equation = Hydrostatic Equilibrium Equation
- Singular isothermal sphere (SIS / SIE) vs NFW
  - solutions to the Poisson equation
  - $\rho \sim r^{-2}$  compare to NFW profile
- M-sigma relation
  - why is it surprising?
  - King (2003) superwind model
- Resolving SMBHs in galaxies
  - Sphere of influence of SMBHs vs Schwarzschild radius
  - observability limited by spatial resolution
- SMBHs and AGN (3 lectures, all slides)
- Galaxy Evolution (2 lectures)
  - DM + baryon simulations
    - Star formation
  - Galaxy mergers
    - Merger tree
    - Dynamical friction timescale
  - A simple analytical model for galaxy evolution
    - Continuity equation
    - Stellar Feedback
    - AGN feedback
- Cosmology (2 lectures)
  - Newtonian derivation of Friedmann equation

- Critical Density  $\Leftrightarrow$  Hubble parameter
    - Density parameters
  - Expansion Histories  $R(t)$ : Solutions for  $k = 0$ 
    - matter/radiation/lambda-dominated flat universes
    - $\Omega_0 = \Omega_{m,0} = 1$ 
      - $R \sim (t/t_H)^{2/3}$
    - $\Omega_0 = \Omega_{rel,0} = 1$ 
      - $R \sim (t/t_H)^{0.5}$
    - $\Omega_0 = \Omega_{\lambda,0} = 1$ 
      - $R \sim \exp(t/t_H)$
  - Adiabatic expansion of photon gas (relativistic particles): why  $T \sim 1/R$ ?
    - First Law of Thermal Dynamics
  - Robertson-Walker metric
    - Introduce time-independent curvature:  $k = K(t) R(t)^2$
    - Cosmological redshift: why  $R = 1/(1+z)$ ? Link to observations.
  - Friedmann Equation
    - Add relativistic particles
    - Add cosmological constant
  - Full solution of the Friedmann equation for a three-component Universe
    - $H(R)$ ,  $\Omega(R)$ : analytical solution exists for any  $k$  or  $\Omega_0$
    - $t(R)$ : analytical solution for  $k=0$  or  $\Omega_0 = 1$
- Structure of the Universe (2 lectures)
  - Distance ladder
    - geometric / standard candle / standard ruler
    - relative distance vs. absolute distance
    - mutual calibration
  - Hubble's law
    - correct interpretation,  $z = H D/c$

- $H(t) = d \ln(Ru)/dt$
- Hubble time:  $t_H = 1/H(t)$
- Discovery of dark energy
- How to constrain  $\Omega(\text{baryon})$ ?
  - BB nucleosynthesis
  - Primordial abundances of light isotopes (He-3, Li-7)
- Use X-ray emission to estimate ICM (intra-cluster medium) mass ( $M_x = L_x/n$ )
- Use weak lensing to get gravitational mass
- Bullet cluster example
  - Spatial segregation of DM and ICM
- DM-only simulations vs. observed LSS traced by galaxies
  - Cold vs. Hot DM