ASTRONOMY 220C

Nuclear Astrophysics and Explosive Stellar Transients

Stan Woosley - Winter, 2019

This is a one quarter course dealing chiefly with: a) nuclear physics and nuclear astrophysics; b) the advanced stages of the evolution of massive stars; c) nucleosynthesis; d) supernovae of all kinds, and e) other forms of explosive astrophysical transients that involve stars (novae, x-ray bursts, gamma-ray bursts). Our study of supernovae will include not only the mechanisms and evolutionary contexts for a wide variety of supernova-like explosions, but also their observables: nucleosynthesis, remnants, light curves, and spectra. Though the course is self contained, the student should be familiar with material presented in an upper lever or graduate stellar evolution course, and thus already knows the essentials of stellar physics and evolution. Low mass stars like the sun will not be covered.

The course material is extracted from a variety of sources. Much of it the results of local research. It is not all contained in any one text book. A strongly recommended book is Clayton, *Principles of Stellar Evolution and Nucleosynthesis*. Copies have been ordered at the campus bookstore. This is an old book. What it covers (basics of nuclear physics, equation of state, stellar structure, the s-process), it covers very well, but it is very dated. Additional texts of interest are Branch and Wheeler *Supernova Explosions* (Springer; current, but expensive); Kippenhahn and Weigert *Stellar Structure and Evolution* (Springer); and Pols free on line text book on stellar evolution (see notes). Considerable material, including background reading, will be given on the web.

Course performance will be based on four graded homework assignments and a final exam.

In general, the anticipated course material is given in outline form below, but you can expect alterations as we go along. The course will begin with material that is "classical" in nature, but advance, by mid-quarter to more current, and consequently less certain, results and challenges. Roughly 2 weeks will be spent on basic nuclear physics as applied to astrophysics.

1. **Introduction and overview**

   Course overview. On line resources. General principles of stellar evolution - time scales, temperature-density scalings, critical masses.

2. **Abundances in the cosmos**

   Abundances in the sun and meteorites. Abundances in other stars, Abundance evolutionary trends.

3. **Fundamental nuclear physics - 1**

   The nuclear force. Physics of the atomic nucleus. Binding energy. The liquid drop model.

4. **Fundamental nuclear physics - 2**

   The shell model. Nuclear stability.

5. **Fundamental nuclear physics - 3**

   Reaction rates and theory. Resonant and non-resonant reactions.

6. **Some key reaction rates in astrophysics**

   The pp-reaction, the three alpha reaction, $^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}$

7. **Hydrogen burning in massive stars**

   Main sequence evolution, the CNO tri-cycle, nucleosynthesis. Simple nuclear reaction networks. Novae. X-ray bursts.

8. **Uncertainties in massive stellar evolution**

   Overshoot mixing, semi-convection, mass loss, rotation, B-fields and angular momentum transport. Rotational mixing processes. Eddington-Sweet circulation. Wolf-Rayet stars.

9. **Explosive hydrogen burning**

   The rp and αp-processes. Nuclear physics in and models for classical novae and Type I x-ray bursts

10. **Helium burning and the s-process**

    Relevant nuclear physics. Solving the reaction rate equations. Computer models for helium burning stars. The s-process in in massive stars and in AGB stars.

11. **Neutrino losses and the advanced stages of massive stellar evolution - 1**

    Thermal neutrino losses - pair-, photo-, and plasma-processes. Nuclear physics of carbon, neon, and oxygen burning. Evolution at balanced power. Computer models.

12. **The advanced stages of massive stellar evolution - 2**

    Silicon burning. Nuclear statistical equilibrium and quasi-equilibrium. Electron capture and beta decay.

13. **Presupernova models, core-collapse and bounce**

    Outcomes for different masses and metallicities in the range 8 to 80 solar masses. Collapse instabilities. Photodisintegration, electron capture, the birth and death of the prompt shock. Protoneutron star formation.

14. **Neutrino powered explosions**

    Current models in 1, 2 and 3D. Limits of the mechanism. Role of rotation and magnetic fields. Mixing and fail back. Black hole formation. Neutron star and black hole birth mass function.

15. **Explosive nucleosynthesis**

    Conditions for an outcome of explosive silicon, oxygen and neon burning. Nucleosynthesis summary. The r-process - physics and sites.

16. **Supernova overview and Type II supernovae**

    Neutrino signals. Shock break out. Stages in UVOIR light curve. Gamma-ray line astronomy. The Effects of mixing.

17. **Some results of binary evolution**

    Type Ib and Ic Supernovae. Different outcomes from single stars.

18. **Type Ia supernovae - models**.

    Chandrasekhar mass explosions and sub-Chandrasekhar mass models. Turbulent flame ignition and propagation. Light curves, spectra, and nucleosynthesis - The width-luminosity relation.

19. **Unusual supernovae**

    Pair instability, and the pulsational pair instability. Magnetar and collisionally powered supernovae. Models, light curves, nucleosynthesis.

20. **Gamma-ray bursts and Gravitational Wave Astronomy**

    Observations. Relation to massive star death. Models and constraints.