Astrophysics Graduate Course
Late Stages of Stellar Evolution
(Ph. Podsiadlowski, Oxford, HT07)

Please do either all of the problems in Part A or *one* of the literature review problems in Part B.

Part A: Problems

(1) Fermi Acceleration and Cosmic Rays

Explain what is meant by the Fermi acceleration mechanism and how it is thought to produce cosmic rays in supernova remnants. [Ref.: e.g. High Energy Astrophysics, Volume 2, Longair.]

(2) Sedov-Taylor Blast Wave

Consider a spherical blast wave (e.g. caused by a nuclear explosion, supernova) in a medium of constant mass density ρ_0. Dimensionally, the time evolution of the blast wave can only depend on ρ_0, the energy of the explosion E, the time t since the explosion and the radius r. Using dimensional analysis, show that the radius of the blast wave must evolve with time as

$$r(t) = \xi_0 \left(\frac{\rho_0}{Et^2} \right)^{-1/5},$$

where ξ_0 is a dimensionless constant. Assuming that ξ_0 is of order 1, estimate the age of a supernova remnant that has a radius of 10 pc. [Typical values for E and ρ_0 are $E = 10^{44}$ J and $\rho_0 = 1 \times 10^{-21}\,\mathrm{kg\,m^{-3}}$, respectively.]

(3) Rankine-Hugoniot Relations

What are the Rankine-Hugoniot jump conditions? Derive these relations from first principles for a perfect gas where the specific internal energy is given by $U = \frac{1}{\gamma-1}\frac{P}{\rho}$. Here P and ρ are the pressure and the density, respectively, and γ is the adiabatic index of the gas. What is the change in density across a strong shock for a $\gamma = 5/3$ and a $\gamma = 4/3$ gas?

(4) The Cas A Supernova (Remnant)

The supernova that produced the supernova remnant in the constellation Cassiopeia, known as Cas A, occurred around 1700, but surprisingly there is no historical record of the supernova despite its relative closeness. This suggests that the supernova was very underluminous compared to a typical supernova. While this could have been explained by a faint supernova associated with the formation of a black hole, observations with the *Chandra Observatory* have revealed a faint neutron star at the centre of the remnant, very likely the compact remnant produced in the supernova. Moreover, the kinetic energy in the supernova remnant has been estimated to be $\sim 2 \times 10^{44}$ J, quite typical for a normal core-collapse supernova. It has also been suggested that the neutron star is a magnetar, i.e. a neutron star with a very high magnetic field (with $B > 10^{11}$ T).

One speculation that could explain these apparently contradictory "facts" is that the supernova was indeed underluminous, but that the gas in the supernova remnant was accelerated after the supernova by the spin-down of the magnetar. Assuming that the spin-down timescale was less than 100 yr, estimate the initial properties of such a magnetar, i.e. the initial spin period and the magnetic field. Speculate on how this hypothesis might be tested.

Part B: Literature Review

(7) Pair-Instability Supernovae

Examine the recent literature to summarize what the present status of pair-instability supernovae is. Specifically answer questions such as: What is the physics behind pair-instability supernovae? For what types of stars are they believed to occur? What are their characteristics (e.g. energetics, chemistry)? What are their chemical signatures and are these consistent with the observed abundances of the elements?

[Potentially useful authors to search: Stan Woosely, Ken Nomoto, Alexander Heger.]

(8) The First Stars

Examine the recent literature to summarize our present understanding of the first stars (i.e. stars essentially without any metals). Specifically answer questions such as: What are the physical differences in their evolution (compared to stars with metals)? How low does the metal content have to be? What are the differences in their formation? What are their chemical signatures? What is the observational situation of discovering the first stars or extremely metal-poor stars?

[Potentially useful authors to search: Tom Abel, Ken Nomoto, Alexander Heger, Christopher McKee, Anna Frebel.]

(9) The Gamma-Ray Burst – Supernova Connection

Examine the recent literature to summarize our present understanding of the connection between long-duration gamma-ray bursts and supernovae. Specifically answere questions such as: What is the observational evidence? Are all supernovae hypernovae (i.e. very energetic supernovae)? Are their GRBs without supernovae (e.g. GRB 060614?)? What is the physical relationship between the supernova event and the GRB event? What is the chemical signature of hypernovae? What are their progenitors?

[Potentially useful authors to search: Paolo Mazzali, Ken Nomoto, Stan Woosely (2006 ARA&A papers), Neil Gehrels, Nature papers in 2006.]