Lec 23: 11/16/2010

Type II Supernova:

For stars with $M > 8 M_\odot$ Carbon burning will be ignite at the Core and a variety of heavier elements will undergo nuclear burning.

Eventually, a host of nuclei centered around ^{56}Fe peak of the nuclear binding energy curve will be synthesized.

Once an Iron Core is formed at the center of a sufficiently massive star, the future evolution will be roughly as follows:

(1) Continued Silicon burning (and other shell burning) processes add to the Core mass and drive it to the limiting mass value M_{Ch}.
At the central conditions during this stage, neutrino interactions play a significant role, and neutrinos act as the main Cooling mechanism for the Core.

(2) At the very high central temperatures, energetic photons disintegrate the Iron nuclei into α particles and neutrons,

This process takes away the energy from photons, and hence lowers the pressure of photon gas.

(3) It becomes possible for the inverse β_- decay to produce neutrons and neutrinos by combining protons and electrons. The emission of neutrinos takes away energy from the star, and also leads to a rapid decrease in the the degeneracy pressure provided by the electrons.

(4) The reduction in the pressure support of the core triggers a rapid collapse of the core. The inner core collapses subsonically, while the outer core callapses supersonically (almost in free fall). This process is very fast, and the speeds in the outer core can be as high as 70,000 $\frac{km}{s}$.

(5) The collapse of the inner core continues until the density is $\sim 8 \times 10^{14}\, g\, cm^{-3}$ (which is three time the nuclear density). Models of nuclear structure suggest that nuclear interactions

can produce an effective repulsive force at such high densities. The collapse is halted, leading to a rebounding of the inner region, which sends a pressure wave outwards through the infalling material.

(6) The propagation of this shock wave is not completely clear from numerical simulation. There are two possible cases that can be envisaged;

(a) Prompt explosion; If the Iron core is not too massive, the shock can emerge at the outer region without too much of energy loss. An explosion can result ejecting material in the envelope.

(b) Delayed explosion; If the Iron core is fairly massive, the shock loses a fair amount of its energy and its propagation stalls. The accreting matter on the core will produce an accretion shock (similar to that in the case of protostar formation. Neutrinos can deposit their energy in the matter behind the shock leading to its revival. The explosion happens subsequently. This case relies heavily on the results of numerical simulations.

(7) The total kinetic energy of the outgoing shock is $\sim 10^{51}$ erg. The energy in the neutrinos (which is essentially the binding energy released in the collapse) is $\sim 10^{53}$ erg. When the outer material expands to $\sim 10^{15}$ cm, it becomes optically thin. An impressive optical display arises, which releases $\sim 10^{49}$ erg of energy in photons with a peak luminosity of 10^{43} erg s^{-1}. This is $\sim 10^{9} L_{\odot}$, and hence light from supernova explosion overwhelms the hosting galaxy.

(8) The nature of the remnant depends on its mass, thus the original mass of the star. If $M \lesssim 25\ M_{\odot}$,

the inner core, which is mostly made of neutrons, can be stabilized by the degeneracy pressure from neutrons. The resulting structure is called a neutron star. If $M \gtrsim 25 M_\odot$, the remnant mass is larger than the Chandrasekhar limiting mass. It will then collapse to form a black hole. For very large masses, $M \gtrsim 40 M_\odot$, the star can collapse into a black hole directly, without forming an explosion.

(9) A very clear signature of the core collapse, followed by the formation of a compact objects is the emission of $\sim 3 \times 10^{53}$ erg of energy in neutrinos. Therefore the detection of neutrinos from a supernova can be of significant help in testing the theoretical models.

We point out that ther exists another class of supernova (Type I) that are believed to arise because of the accretion of mass by one of the stars in a binary system. We will not discuss it here.

Now let us discuss various effects that are important in the core collapse supernova.

Formation of Iron Core:

Consider the Virial theorem:

$\Omega + 3 \int P \, dV = 0$

Here the total pressure P is the sum of electron pressure and the pressure from nuclei:

$$P = (\gamma - 1) n_e m_e c^2 \left[(1+x^2)^{\frac{1}{2}} - 1 \right] + n_N k_B T$$

$$x = \frac{P_F}{m_e c} \quad , \quad \rho = 0.97 \times 10^6 \, g \, cm^{-3} \left(\frac{A}{Z} \right) \left(\frac{P_F}{m_e c} \right)^3$$

Degeneracy pressure of the electrons is considered in the $T=0$ limit, and γ determines the corresponding equation of state ($\gamma = \frac{5}{3}$ in the non-relativistic regime, $\gamma = \frac{4}{3}$ in the extreme relativistic limit).

The expression for P together with the Virial theorem gives,

$$\frac{k_B T}{m_e c^2} \simeq \frac{1}{3} \nu Y_e \left[\left(\frac{N_e}{N_{e_0}} \right)^{2/3} x + 3(\gamma - 1)\left(1 - \sqrt{1 + x^2}\right) \right]$$

Here N_e is the total number of electrons, Y_e is the number of electrons per nucleon, and:

$$N_{e_0} = \frac{m_{pl}}{m_u} Y_e \quad , \quad m_{pl} \equiv \left(\frac{\hbar c}{G} \right)^{1/2} \quad (m_{pl} \simeq 1.2 \times 10^{19}\ \mathrm{GeV},\ \text{Planck mass})$$

We note that if $N_e < N_{e_0}$, then T reaches a maximum as x increases, and will monotonically decrease after that. On the other hand, for $N_e > N_{e_0}$, T increases without limit as a function of x according to $T \propto x$. The mass corresponding to N_{e_0} is M_{Ch} (not surprisingly).

For $M \gtrsim 10 M_\odot$, the core mass M_{core} is driven toward M_{Ch} around the time of Silicon burning. Such stars therefore go through the entire sequence, having an onion like structure at late stages. Silicon burning requires a temperature of approximately $k_B T \sim 0.6 m_e c^2$, which requires an ignition mass of $M_{Core} \gtrsim M_{Ch}$. If $M_{Core} < M_{Ch}$, then the ignition is delayed until the shell burning of lighter nuclei increases the core mass.

As an example, detailed numerical simulations show that for a $M = 15\, M_\odot$ star, we have (at the onset of Silicon burning):

$Y_e = 0.42$, $\rho_c = 3.7 \times 10^9\ g\, cm^{-3}$, $T_c = 8 \times 10^9\ K$, $M_{Core} = 1.5\, M_\odot$

At these temperatures and densities, the emission of neutrinos becomes important, which we discuss next.

Neutrino Cooling:

Neutrinos have only weak interactions with other particles. Nevertheless, the rate for these interactions become large at high temperatures and densities. Neutrino production happens via two major sources:

- Nuclear: The main phenomenon is the so-called Urca process, which involves the following sequece of reactions,

$$\boxed{\begin{array}{ll} (Z, A) + e^- \rightarrow (Z-1, A) + \nu & \text{inverse } \beta_- \text{ decay} \\ (Z-1, A) \rightarrow (Z, A) + e^- + \bar{\nu} & \beta_- \text{ decay} \end{array}}$$

The net effect is a loss of thermal energy into a $\nu\bar{\nu}$ pair. The details of the process depend on the availability of a pair of nuclei (Z, A) and $(Z-1, A)$, with the latter having a slightly higher energy. The energy loss rate then increases monotonically with ρ and T.

- Leptonic: These processes occur without any nuclear reactions. The most important among these processes are the following;

$$\boxed{\begin{array}{ll} e^- + e^+ \rightarrow \nu + \bar{\nu} & \text{pair annihilation} \\ \gamma + e^- \rightarrow e^- + \nu + \bar{\nu} & \text{photoneutrino process} \\ \text{plasmon} \rightarrow \nu + \bar{\nu} & \text{plasmon decay} \end{array}}$$

In addition, it is also possible to emit neutrinos during the deceleration of an electron in the Coulomb field of a nucleus (analogous to bremsstrahlung).

The energy loss rate can be computed for all of these processes. To underline the importance of neutrino cooling at high temperatures and densities, let us consider the pair annihilation process. In the case of extreme relativistic degenerate gas of electrons, the energy loss rate per unit volume is given by:

$$\varepsilon_{pair} \simeq 1.2 \times 10^{15} \rho\, Y_e \left(\frac{E_F}{m_e c^2}\right)^2 T_{10}^4 \exp\left(-\frac{E_F}{k_B T}\right) \text{ erg cm}^{-3}\text{ s}^{-1}$$

Where $T_{10} \equiv \left(\frac{T}{10^{10}\,K}\right)$. Assuming that:

$\rho \simeq 10^9 \text{ g cm}^{-3}$, $k_B T \simeq m_e c^2$

We then find:

$$\varepsilon_{pair} \simeq 6 \times 10^{11} \rho \text{ erg g}^{-1}\text{ s}^{-1}$$

For a $1 M_\odot$ star, this corresponds to a luminosity of

$\sim 10^{11} L_{\odot}$. As a comparisont, the energy density in radiation is $aT^4 = 7.6 \times 10^{17}\, T_{10}^4$ erg cm^{-3}. The cooling of radiation thus happens extremely rapidly, with a time scale $\sim \dfrac{aT^4}{\varepsilon_{pair}} = 10^{-3}$ s.