Initiating Core Collapse

As discussed in *Handout* XXVIII, stars with masses $M \gtrsim 10\,\mathrm{M}_\odot$ are destined to burn all the way through to form an iron core. Soon (a matter of a day or so) after an iron core forms, it begins to collapse under the force of its own gravity. The collapse is initiated by a pair of important processes. First, as the core temperature rises toward 10^{10} K, *photodisintegration* begins to break the ^{56}Fe nuclei into ^{4}He nuclei, and from there into protons and neutrons:

$$^{56}\mathrm{Fe} + \gamma \longrightarrow 13\,^{4}\mathrm{He} + 4\,n, \qquad ^{4}\mathrm{He} + \gamma \longrightarrow 2\,p + 2\,n \tag{1}$$

Second, at the very high densities found in the core, electron captures convert the protons liberated by photodisintegration into neutrons (a process known as *neutronization*):

$$p + e^{-} \longrightarrow n + \nu_{\mathrm{e}} \tag{2}$$

Both processes abruptly decrease the pressure support of the core[1], initiating its collapse.

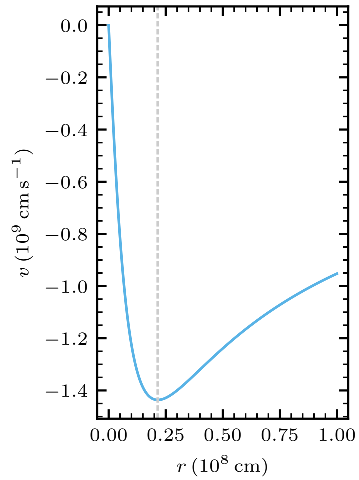

Figure 1: A typical velocity profile at the center of a massive star during core collapse. The vertical dotted line marks the boundary between the inner core (to the left; $v \propto r$) and the outer core (to the right; $v \propto 1/\sqrt{r}$).

[1] Photodisintegration decreases the radiation pressure, while neutronization decreases the electron degeneracy pressure.

Collapse Dynamics

During the collapse, the inner part of the core contracts *homologously*, meaning that the velocity at any instant in time is proportional to the distance from the origin: $v \propto r$. At sufficient distances from the center, the homologous collapse velocity exceeds the local speed of sound, and the velocity transitions over to a free-fall profile $v^2 \propto 1/r$ (see Fig 1). As a result, the inner core (having a typical mass ~ 1–$2\,\mathrm{M}_\odot$) decouples from the outer core, leaving it behind.

A few tenths of a second after the start of the collapse, the density in the inner core becomes comparable to that of atomic nuclei, causing the equation-of-state to 'stiffen' [2]. The collapse is abruptly halted, and the inner core springs back a little. This *core bounce* launches a shock wave that begins to propagate outwards through the still-infalling outer core.

[2] I.e., the material becomes much more resistant to compression. This is a consequence of the repulsive nature of the strong nuclear force at short ranges.

As it travels outward, the shock wave heats and compresses the outer-core material that it passes through. This results in further photodisintegration and neutronization, which robs the shock of energy and causes it to stall[3]. However, the densities interior to the shock are so high that neutrinos formed in the inner core[4]cannot escape from the star, and are instead re-absorbed below the shock. This injects sufficient energy that, after ~ 0.5 s, the shock re-energizes and resumes its march out through the star. As it passes through the outer core and envelope of the star, the shock sends the material

[3] Another important effect is the creation of new elements via capture of the neutrons produced by neutronization. Unlike the s-process neutron capture that occurs on the AGB (see *Handout* XXV), the neutron capture rate in this instance is so rapid that there is little time for radioactive decay to occur between captures. This *rapid* or *r-process* neutron capture is responsible for creating all of the elements beyond ^{209}Bi.

[4] These neutrinos are a result of further neutronization, as described by eqn. (1).

outward with a velocity in excess of the star's escape velocity — resulting in *core-collapse supernova* explosion.

Core-collapse supernovae are classified as type Ib, Ic or II, depending on the absorption lines in their spectra (see *Handout* XXXIV). If the progenitor star still retains its hydrogen envelope, it produces a type II supernova. However, if it lacks this envelope (e.g., due to wind mass-loss during its evolution), it produces a type Ib. If it also lacks a helium envelope, it produces a type Ic.

Unlike type Ia supernovae, which are powered by thermonuclear reactions, the energy source in core-collapse supernovae is gravitational. We can estimate the total energy budget by calculating the gravitational energy released as the inner core collapses from its initial radius $R_{\rm c,i}$ to its final radius $R_{\rm c,f}$:

$$\Delta U \approx \frac{GM_{\rm c}^2}{R_{\rm c,f}} - \frac{GM_{\rm c}^2}{R_{\rm c,i}} \tag{3}$$

With a core mass $M_{\rm c} \sim 1\,{\rm M}_\odot$, and typical values $R_{\rm c,i} \sim 10^9\,{\rm cm}$ and $R_{\rm c,f} \sim 10^6\,{\rm cm}$, the energy release is $\Delta U \approx 3 \times 10^{53}\,{\rm erg}$. Almost all of this energy is in the form of neutrinos, with about 1% absorbed to re-energize the shock wave (the remaining neutrinos escape into space). Of this 1%, corresponding to a few times 10^{51} erg, most ends up as kinetic energy of the ejecta; however, around 1% in turn[5]is converted into electromagnetic radiation, and is responsible for the immense peak luminosities $\sim 10^9\,{\rm L}_\odot$ of core-collapse supernovae.

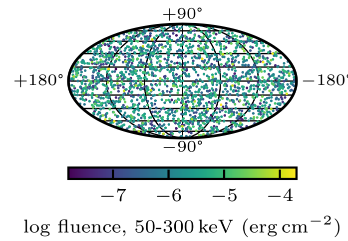

Figure 2: Distribution of GRBs on the sky, plotted in galactic coordinates using a homolographic (equal-area) projection. The data are from the Burst and Transient Source Experiment (BATSE) instrument on board the *Compton Gamma Ray Explorer* satellite. The fluence values indicate the total amount of energy received, per unit area, during the burst.

[5] I.e., a few times 10^{49} erg.

Gamma-Ray Bursts

In the 1960's, the US government initiated the *Vela* satellite program, to look for gamma rays originating from atmospheric nuclear weapon tests. Although none were found, the satellites discovered a new kind of astrophysical phenomenon: brief, intense flashes of gamma rays known as *gamma-ray bursts* (GRBs). The distribution of GRBs is uniform on the sky (see Fig. 2), indicating that they must originate from outside the Milky Way galaxy. In fact, we now believe that 'long' GRBs (with a duration of a few seconds) originate in core-collapse supernovae of rapidly rotating stars[6]. The rapid rotation focuses the explosion energy along a polar jet, and if this jet is directed toward Earth, we observe an intense flash of gamma rays as the jet breaks through the stellar surface.

[6] By contrast, 'short' GRBs (with durations of less than a second) originate from merging neutron stars.

Further Reading

Kippenhahn, Weigert & Weiss, §§36.3,36.4; *Ostlie & Carroll*, §15.3, *Prialnik*, §§10.2,10.3.