MODELS OF TYPE II SUPERNOVA EXPLOSIONS

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1. THE PROGENITOR STARS

Present stellar evolution codes predict that stars with He-core masses above approximately 2 $M_\odot$, corresponding to main sequence masses of at least 8 $M_\odot$ burn carbon non-violently. After hydrostatic core carbon burning all those stars contain O-Ne-Mg cores but their further evolution is strongly dependent on the stellar entropy and thus on the main sequence and the core mass. If the He-core mass is below 3 $M_\odot$ the O-Ne-Mg core grows due to carbon-burning in a shell and the crucial question is, whether or not it grows beyond the critical mass for Ne-ignition ($\cong$1.37 $M_\odot$). Stars with He-cores less massive than about 2.4 $M_\odot$ will never ignite Ne, but due to electron-captures, mainly on Ne and Mg, their cores will contract until O-burning begins. Since the matter of the O-Ne-Mg core is weakly degenerate O-burning propagates as a (subsonic) deflagration front and incinerates a certain fraction of the core into a nuclear statistical equilibrium (NSE) composition of iron-group elements (Nomoto, 1984). If, on the other hand, the mass of the O-Ne-Mg core is slightly larger than 1.37 $M_\odot$ Ne and O burn in a shell from about 0.6 $M_\odot$ to 1.4 $M_\odot$, but again the outcome is a NSE-composition (Wilson et al., 1985). In both cases the core-mass finally exceeds the Chandrasekhar limit because electron captures on free protons and heavy nuclei lower the electron concentration and consequently also the effective Chandrasekhar mass. The cores, therefore, continue to contract and finally collapse to neutron star densities with iron-core masses between 0.7 and 1.4 $M_\odot$.

More massive stars, M>12 $M_\odot$, burn all their nuclear fuel under non-degenerate conditions and via Ne-, O- and Si-burning form iron-cores which are more massive and have higher entropies than the ones discussed before. The mass inside the Si-burning shell depends again on the main sequence mass but also on the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. Evolutionary computations that take into account an increase of this rate by roughly a factor of 3 to 4 as indicated by recent experiments (Kettner et al., 1982; Rolfs, 1985) still predict small core masses for stars with $M_{MS}<20$ $M_\odot$ but significantly larger cores for more mass-

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ive stars. Typical values found range from 1.4 $M_\odot$ to more than 2 $M_\odot$ (Wilson et al., 1985; Woosley and Weaver, 1986). For these large iron cores the collapse is triggered by nuclear photo-dissociations rather than electron captures, but again the entropy is sufficiently low such that the collapse proceeds to neutron star density.

2. EXPLOSION MECHANISMS

During core-collapse the electron pressure will always be much larger than the pressure of the ions if the entropy per nucleon is smaller than about 2 k_B, where k_B is Boltzmann's constant. Since the pre-supernova stellar models typically have entropies of about 1 k_B per nucleon and the entropy increase during collapse due to non-equilibrium weak-interaction processes such as e^--captures and neutrino interactions is small, the entropy always stays low. Consequently the adiabatic index is close to the critical value of 4/3 of a relativistic electron gas. There are still uncertainties in the e^--capture rates and the equation of state but there is also general agreement that about a Chandrasekhar mass will collapse homologously (see Hillebrandt, 1982,1984 for reviews; Bowers and Wilson, 1982; Hillebrandt and Wolff, 1985; Bruenn, 1985). This finding is in agreement with analytical considerations (Goldreich and Weber, 1980). The Chandrasekhar mass is proportional to the square of the electron concentration and therefore decreases during collapse. At the time when the central density reaches nuclear matter density the homologous inner core of the collapsing star contains roughly 0.7 to 0.8 $M_\odot$, because the electron concentration has dropped to values of about 0.35 to 0.39. The outer layers of the original iron-core still move inwards with supersonic velocities. Beyond nuclear matter density nuclei dissolve into a fluid of free neutrons and protons, which now dominate the equation of state. Since typical temperatures are of the order of 10 MeV only, neutrons and protons are non-relativistic fermions and the adiabatic index will be at least 5/3 even if nucleon-nucleon interactions are neglected. As a consequence the inner core is stopped on a sound-travel time (<1 ms) as soon as the innermost mass-zones exceed nuclear matter density. Since the matter of the outer core has a velocity larger than sound-velocity a shock must form near the sonic point which in most numerical studies is at a radius of about 20 km and a mass of about 0.7 $M_\odot$. The unshocked inner core cannot expand against the ram-pressure of the infalling matter and comes to rest in less than 1 ms. From energy conservation one can estimate the energy that goes into the shock-wave from the binding energy of this proto-neutron-star and finds typically values in the range from 4 to 8×10^{51} erg. Again uncertainties arise from the way in which weak interaction processes are treated in the numerical models and also from uncertainties in the nuclear equation of state, but the general results of different investigations are in good agreement.

The crucial question is, however, whether the energy initially given to the shock-front is sufficient for a prompt explosion, because the shock will be damped by nuclear photodissociations and by neutrino losses. The matter that passes through the outwards moving shock-front is heated to entropies of more than 6 k_B per nucleon and therefore is dissociated into free neutrons and protons. The corresponding energy loss is 8×10^{18} erg per gramme which means that even the most energetic shocks found in numerical models can only dissociate less than 0.5 $M_\odot$ of heavy nuclei. Since the mass of the unshocked inner core is around 0.7 $M_\odot$ at best stars with initial iron-core masses of about 1.2 $M_\odot$ can explode by this mechanism. Such small iron-cores are at present only predicted for stars with He-core masses between 2 and 2.4 $M_\odot$ which translates into main sequence masses between 8 and 10 $M_\odot$. So even if we admit that the uncertainties in the numerical models are still large we have to conclude that prompt explosions by the core-bounce mechanism can only result from a very narrow mass-range around 10 $M_\odot$ (Hillebrandt et al. 1984).

There are several arguments why more massive stars should also explode and we have to discuss alternative explosion mechanisms for them. One possibility has recently been discussed by Wilson (1985) (see also Wilson et al., 1985), who found that neutrinos leaking out at the proto-neutron star may revive a stalling shock front. A few hundred milliseconds after core-bounce the shock has become a nearly standing accretion shock at a radius of several hundred kilometers if the original iron-core was too massive. The mass inside the shock front is then about 1.4 $M_\odot$, the density and the temperature just behind the front have dropped to roughly 10^7 g cm^{-3} and 1 MeV, respectively. The shocked matter is composed of free neutrons, protons, electrons and positrons and is irradiated by neutrinos with a luminosity of about $(2\text{-}4)\times10^{52}$ erg s^{-1} (Wilson, 1985; Hillebrandt and Müller, 1984). A small fraction of the neutrinos and anti-neutrinos are absorbed by free neutrons and protons, respectively, thereby heating the matter if their energy is sufficiently high (>4 to 5 MeV). The neutrino energies are determined at the neutrino-sphere from where they can stream freely outwards with constant energy. Wilson (1985) finds that the ν-sphere is at a radius of about 30 km several hundred milliseconds after core-bounce. Since the temperature there is about 5 MeV the neutrino-heating mechanism works and causes delayed explosions leaving behind rather massive neutron stars or black holes. It is interesting to note that for most stellar models considered the final explosion energy is to a large extent generated by burning in the oxygen shell and not by the original neutrino-mediated shock wave. As a consequence stars with masses around 15 $M_\odot$ will have low explosion energies (a few 10^{50} erg) whereas more massive stars ($M>20$ $M_\odot$) will give rise to rather energetic explosions (Wilson et al. 1985).

The quantity of key importance for the revival of the shock due to neutrino heating is the neutrino energy which in turn depends on the position and the temperature of the ν-sphere. If the neutrino temperature would be below 3 MeV an explosion caused by neutrino heating is unlikely (Lattimer and Burrows, 1984). In a recent computation I have tried to confirm Wilson's results but did not find an explosion for a

20 $M_\odot$ model of Weaver et al. (1985) which has a core-structure similar to that of a 15 $M_\odot$ star evolved with the revised $^{12}C(\alpha,\gamma)^{16}O$ rate (Wilson et al., 1985). The main difference between my computation and that of Wilson et al. (1985) seems to be that the ν-sphere remained at a radius of 70 km and the neutrino temperature dropped to about 3 MeV after 200 ms. Neutrino heating, therefore, was much less efficient. It is likely that these differences are caused by differences in the equations of state used in both simulations, and it seems to be an open question whether this explosion mechanism indeed works.

3. SUMMARY AND CONCLUSIONS

Although in recent years progress has been made towards a better understanding of the (type II) supernova phenomenon, most of the theoretical models are still quite controversial, and their predictions should be tested by observations. According to theory there should be at least two kinds of events, which differ in their energetics and also in the elemental abundances of the ejecta.

A first group is thought to explode by the core-bounce mechanisms. Their progenitor stars are likely to have main sequence masses of around 8 to 10 $M_\odot$ and the explosion energies will be larger than 10^{51} erg. From initial mass functions one can estimate that they may account for up to 80% of all events (Tammann, 1982). Their ejecta will be characterized by an enrichment of nitrogen, some depletion of oxygen and roughly solar carbon abundance. They will leave neutron stars behind and possibly Plerion-like remnants if the progenitor stars possess sufficiently strong magnetic fields. SN 1054 may have been a typical example.

The second group of type II supernovae is likely to be less energetic and may explode by neutrino-heating. In this case the progenitor stars will be more massive, $M>15\ M_\odot$, say, and the explosion energies will be around a few 10^{50} erg only. The ejecta will be enriched in oxygen and iron-group elements or, alternatively, in Si, S, Ar and Ca. The compact remnants can be either neutron stars or black holes. The supernova that led to Cas A may have been of this type.

These conclusions are definitely strongly model-dependent and are sensitive to details of the numerical simulations, such as the equation of state, weak and strong interaction rates, neutrino transport, etc. It is therefore almost hopeless to expect that one can prove them to be correct from theory alone.

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