STELLAR COLLAPSE AND NASCENT NEUTRON STARS

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The collapse of dense cores in massive stars proceeds as follows. Initially, leptons dominate the pressure because neutrinos become trapped at high densities. This results in the formation of a cool inner core that collapses homologously. At around nuclear densities the pressure from nucleons increases rapidly and halts the collapse, giving a core bounce. A shock forms at the surface of the inner core and propagates into the infalling envelope. These basic features have emerged in the hydrodynamic studies of collapse by various researchers. However, the question of final outcome of collapse is unresolved at present. The evolution of the core after the shock has propagated through the envelope has not been addressed in detail. This communication summarizes some current results of the author's ongoing study of stellar collapse.

The mass of the inner homologous core is found to vary with trapped lepton fraction. It typically is larger than the corresponding Chandrasekhar mass because of thermal and non-leptonic contributions to the pressure. Neutrino opacities determine the trapped lepton fraction. Calculations were performed with opacities that varied over an order of magnitude above their presently accepted values. The results were found to change only mildly. Masses of inner cores and trapped lepton fractions for different calculations all fell in the ranges: $.6 \lesssim M/M_\odot \lesssim .8$ and $.25 \lesssim X_\ell \lesssim .35$. The shock strength also varied with the mass of the inner core, being stronger for smaller core masses. Post-shock entropies ranged between 5k and 8k per baryon. In all cases, the shock died out before mass ejection could occur. However, this may be an artifact due to the finite zoning effects in the numerical study.

The collapsed core becomes essentially hydrostatic after one bounce. Its structure consists of a cool central region that collapsed homologously and an overlying shock-heated mantle of about half a solar mass. Neutrinos remain trapped on dynamic time scales for all densities above $\sim 10^{12}$g cm^{-3}. Below this density electron capture depletes the lepton fraction to values around 0.1. These results define a possible structure for neutron stars at birth. The evolution of this structure to the final state of cold neutron stars needs to be examined.

D. Sugimoto, D. Q. Lamb, and D. N. Schramm (eds.), Fundamental Problems in the Theory of Stellar Evolution, 322–325.

DISCUSSION

Schramm: If neutrinos oscillate (for example $\nu_e \leftrightarrow \nu_\tau$), how would that effect the X_e at the time of the bounce?

Mazurek: If neutrinos oscillate on time scales greater than those of dynamic collapse (~10 ms), it would have little effect on the trapped lepton fraction. If subsequent oscillations occur only between three types of neutrinos (e.g., ν_e, ν_μ, and ν_τ), then the effects on the equation of state would be moderate. The electron fraction X_e would decrease somewhat (from ~0.25 to perhaps ~0.20). However, I would guess that the effect on the pressure would be small, since this decrease in the electron fraction would not be sufficient to dissolve the heavy nuclei. On this basis, I do not think that neutrino oscillations would lead to new, dramatic effects. They could, however, aid the shock, in the sense that lower trapped lepton fractions give stronger shocks.

A further caveat is in order. Even if neutrino oscillations do occur in vacuum, I have been told by experts that such oscillations will be strongly supressed when the neutrinos find themselves in the presence of high density matter. The most pertinent point however, is that at present we do not know the properties of neutrino oscillations, if they occur. Such oscillations may have unforeseen properties that could have dramatic effects.

Sato: Previously, you pointed out the possibility that a supernova explosion could be produced when the degenerate neutrinos diffuse out of the core, because the energy of the degenerate neutrinos goes into thermal energy as they escape from the core. Now, you have carried out extensive numerical calculations of the collapse of the core. Have you been able to confirm the above possibility?

Mazurek: The mechanism you refer to can operate only on the long time-scale of neutrino diffusion. The situation is the following. The initial postshock core has a large fraction of its internal energy in the form of relativistically degenerate leptons. Being relativistic, the leptons exert only one-half of the pressure that a non-relativistic gas would exert if it has the same amount of energy. As the neutrinos leak out, reducing the lepton concentration, they take with them only a small fraction of their original energy (10 MeV out of ~70 MeV). Thus the energy in leptons will be transferred to nucleons which are non-relativistic. This will increase the pressure and will lead to a large, longterm expansion of the compact core. This longterm expansion may produce a piston-like shock that results in an explosion. However, to confirm this conjecture one needs to study the evolution of a core from its initial lepton-rich state through lepton depletion. To date, this is a fundamental problem that has not been addressed in adequate detail.

Tscharnuter: What are the reasons that the shock wave generally dies out? Is it, because some poorly understood physical processes are going on in the shock region or simply because the numerical grid is too coarse?

Mazurek: At the present time, it is not certain why the shock dies out.

There are reasons for believing this behaviour is physical. As I noted earlier, the core is essentially static after the "bounce". Its initial infall energy plus the work it does in a small expansion go into the shock. The shock loses energy to dissociation of nuclei and to neutrino losses. In the present numerical work, the energy that the core gives to the shock is roughly equal to the total nuclear energy of dissociation and of neutrino losses. However, the limits on precision imposed by the finite zoning are not good enough to firmly establish this. The discrepancy in energy between input and output is sufficiently large so that it could power a supernova. Thus models with much finer zoning than the calculations I described will have to be computed. Unfortunately, such models are extremely time-consuming in terms of the computing required. However, if semi-analytic solutions cannot be found, such calculations must be performed.

Wheeler: Your cold homologous core is below the expected maximum mass limit for a neutron star. Do you foresee a way to change the astrophysical conditions slightly and get an explosion with a black hole remnant, as opposed to a neutron star and an explosion?

Mazurek: At the present time we do not know how the shock ejects the matter, assuming that it indeed does so. However, you will recall that in the calculations I presented, the post-shock stationary core is composed of $\sim 0.5\ M_\odot$ hot mantle in addition to the cold homologous core of $\sim 0.7\ M_\odot$. In view of our lack of understanding of the shock ejection mechanism, one can envisage a situation where mass ejection occurs after the mantle is sufficiently large to result in a black hole on cooling. However, such an occurrence would demand addition of mass that is initially outside the $\sim 1.5\ M_\odot$ degenerate core. In this case, the mechanism of explosion is likely to be somewhat more complicated than a "bounce" followed by shock ejection of the envelope as is usually discussed at present.

Tsuruta: Would you say that the expected core mass of $\sim 0.6 - 0.8\ M_\odot$ is the final mass of the remnant neutron star, or that mass will keep falling onto the core? In the latter case, what is the expected final mass of the neutron star?

Mazurek: The final mass of neutron star will certainly be greater than the mass of the inner core that collapses homologously. The mass of this core falls in the range you quote. In the particular numerical example I presented, the inner core of $\sim 0.7\ M_\odot$ had a hot a mantle (which would not be ejected even if the shock continued to propagate) of $\sim 0.5\ M_\odot$. I believe that this particular case is representative of what can be expected in general when the core that initially collapses is an electron degenerate dwarf of around $1.5\ M_\odot$. On this basis, I would expect the initial mass of the neutron star to be greater than $\sim 1.1\ M_\odot$.

Wheeler: Does the cold core you form have any affect on the subsequent rate of cooling of the neutron star, by setting up initial conditions which are different than assumed by Tsuruta, Lamb, or Sutherland?

Mazurek: No. The core configuration I have described will relax to the initial conditions assumed by Tsuruta, Lamb, and Sutherland on time scales of around a few seconds.

Cuyper: What will be the influence of rotation?

Mazurek: I don't know. Such effects are outside of the scope of the work I presented.