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RAYLEIGH-TAYLOR CONVECTIVE OVERTURN AS A POSSIBLE SOLUTION TO THE SUPERNOVA PUZZLE *

Mario Livio and J.Robert Buchler

Department of physics and Astronomy University of Florida Gainesville, FL 32611 and
University of California Los Alamos Scientific Laboratory Los Alamos, NM 87545

Résumé.-Au cours du collapse stellaire, la neutronisation intense au-dessus de la neutrinosphère crée un gradient de la concentration des électrons qui cause une instabilité de Rayleigh-Taylor d'ordre ℓ=2. Il en résulte un chamboulement qui libère les neutrini emprisonnés dans le coeur de l'étoile qui eux à leur tour causent l'explosion violente de l'enveloppe stellaire.

Abstract.-Strong neutronization above the neutrinosphere produces a convectively unstable gradient of the electron to baryon ratio Y_e. An ℓ = 2 Rayleigh-Taylor overturn of the whole core is expected to ensue. As a result the trapped neutrini are released on a short timescale, thus providing the necessary boost to cause a violent explosion.
The final word for the growth of this instability calls for a full two-dimensional calculation. Such a study is now in progress. A one-dimensional hydrodynamic parametrization of the overturn shows that explosion results whenever mixing occurs significantly beyond the neutrinosphere. The main cause for explosion is energy deposition in the mantle by Comptonization as well as by absorption and re-emission.
The Rayleigh-Taylor overturn of the core could thus well resolve the present puzzle of only marginally exploding supernova models.

Recent studies of stellar core collapse are still unable to poduce a conclusive answer to the problem of supernova explosions. Hydrodynamic calculations indicate that the collapse is halted and reversed as a result of the sudden stiffening of the equation of state, at about nuclear matter densities. An outward moving shockwave results from this bounce (Wilson 1979a, Van Riper and Arnett 1978, Bruenn 1975).
Although the shockwave has been demonstrated to produce mass ejection under adiabatic conditions (Lichtenstadt et al.1979, Van Riper 1978) the explosion is still generally marginal (see also Mazurek 1979, Bruenn, Buchler and Yueh 1978) and too sensitively dependent on various parameters, in particular the adiabatic index γ and the density. Furthermore, the use of a more realistic equation of state in the calulation results in a standing shock (Wilson 1979b). The expectation that a large neutrino flux would impart enough energy (Colgate and White 1966) or mementum to the mantle, thus causing its ejection, has also not been realized. Neutrino transport calculations have demonstrated that the neutrini are trapped at densities above 10^{12} g/cc (Arnett 1977, Yueh and Buchler 1977, Mazurek 1977, Tubbs 1977). As a result, insufficient stresses are obtained.

Epstein (1978) has observed, that because of strong neutronization above the neutrinosphere (neutrino "photosphere") a convectively unstable gradient of the electron to baryon ratio Y_e develops.
An examination of the collapse calculations of Wilson (1979a), Arnett (1979) and Bruenn, Buchler, and Livio (1979), reveals, that the inversion in Y_e becomes even more pronounced after several bounces. This potentially unstable configuration led Colgate (1978) to suggest that a delayed Rayleigh-Taylor core overturn may occur. The effect of such an overturn may be in the enhancement of neutrino release on one hand the release of gravitational and thermal energy on the other (Colgate and Petschek 1979), both leading possibly to an explosion.

The two important questions that need, therefore, to be answered are: (i) Can a large scale Taylor mode really grow (how fast and what is the relevant wavelength)? and (ii) is such an overturn (provided it occurs) really capable of producing an

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explosion?

The final word concerning the first question calls for a full two-dimensional hydro dynamic calculation. Such a study is now in progress (Livio, Buchler, and Colgate (1979). At the present time we can only give an answer in terms of plausibility arguments. Lattimer (1979) has shown that neutrino losses from matter just above the neutrinosphere (even at the limit of zero kinetic energy) lead to a reduction in the pressure. This in turn means, that a convectively unstable situation will arise, provided that the (stabilizating) entropy gradient is not too steep and the pressure depends only weakly on the entropy. Cogate and Petschek (1979) argue, that since the nuclei have a very large specific heat, the thermal energy is primarily absorbed by the large number of nuclear excited states and thus has only a little effect on the pressure. In addition, they note, that according to the calculations of Lichtenstadt et al. (1979), a shock generated, large entropy gradient, can cause mass ejection in itself, even without any core overturn. They therefore conclude that the combination of Y_e and entropy gradients should be convectively unstable.

The $\ell = 2$ unstable mode, corresponding to an eddy size $\lambda \sim \pi R$ is expected to have the largest initial amplitude, since it is excited by stellar rotation. This mode will also have the largest potential energy available and therefore lead to higher velocities. The important thing to note is that the development of such an unstable mode will involve an overturn of the whole core rather than just the unstable region. The growth time of a perturbation of wave number K is given by $\tau \sim \left[(\rho_2-\rho_1)\ Ka/(\rho_2+\rho_1)\right]^{1/2}$, where a is the acceleration and K the wave number and is of the order of a few milliseconds for the $\ell = 2$ mode. In the non linear regime the growth time is given roughly by the core traversal time which is of the order of 0.3 ms (Colgate and Petschek 1979). Thus, the growth rate is fast compared to the deleptonization time of the outer portion of the core, which is of the order of 30 ms (Wilson 1979a). One therefore expects that the neutrini that have been trapped in the core prior to the overturn will be dredged into the semitransparent regions, enabling them to impart energy and momentum to the mantle. In addition, the release of gravitational energy by the plume can also assist in ejecting the mantle.

In order to answer the second question (whether the overturn supplies enough energy for the explosion), Bruenn, Buchler and Livio (1979) have developed the following scheme : the convection is parametrized by mixing leptons, starting a time Δt after the bounce. The mixing is performed out to a radius R_{mix}, on a time scale t_{mix},

$$\frac{dY_L}{dt} = - \frac{Y_L - \langle Y_L \rangle}{t_{mix}} \qquad (1)$$

where Y_L is the lepton to baryon ratio and the average is mass weighted to ensure lepton conservation in the process. Inside the neutrinosphere, defined by a density ρ^* local beta equilibrium is assumed between electrons and neutrini. Outside the neutrinosphere, the neutrino dilution is approximated with the relation

$$n_L\ (r) = n_L(r^*) \left(\frac{r^*}{r}\right)^d \qquad (2)$$

where d is a dilution parameter which should be between 2 (decoupled neutrini) and 3 (volumic expansion). The spectrum of the neutrini is chosen as the one they had at the decoupling point r^* (corresponding to ρ^*). Neutrino transport has been treated by the multigroup diffusion scheme (Bruenn Buchler and Yueh 1978) and a 1-D hydrocode (Bruenn, 1975) followed the evolution. All calculations started as an iron core polytrope of index 3. The central density was $\rho_c = 5\times10^9$ g/cm^3 and temperature $T_c = 1.1\times 10^{10}$ K. This particular model, when colapsed and followed through several bounces did not produce an explosion; it will serve us as a reference model.

As we have already mentioned the mixing time is expected to be of the order of a few milliseconds; its value has been varied between 1 ms and 30 ms. Since the exact density of neutrino decoupling is not clear, ρ^* has been varied in the range 10^{11}-10^{12} g/cm^3. At the onset of the mixing process their model had 10 zones between r^* and the shock. R_{mix} has been varied from 2 zones beyond r^* to 2 zones behind the shock. All models that have been mixed significantly beyond the neutrinosphere result in an explosion. Although neutrino stresses are increased, typically by a factor of 5, the main factor in causing the explosion is energy deposition (both by comptonization and by absorption and re-emission). A tremendous strengthening of the shock as a result of the deposited energy is obtained. Two non exploding models had unrealistically small values of ($R_{mix}-r^*$), demonstrating the importance of neutrino dredging to the semitransparent regions outside the neutrinosphere. The total energy of the outward moving zones in the exploding models is in the range $4.1 \times 10^{51} - 7.0 \times 10^{52}$ ergs.

We regard as very encouraging the fact that we can answer affirmatively the second question we have posed. Taylor overturn (if it occurs) could therefore well be the answer to the present supernova impasse. The conclusive answer concerning the growth of the instability, however, will hopefully be given by a two dimensional hydrodynamic calculation (Livio, Buchler and Colgate 1979).

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