QUASI-STATIC AND STEADY-STATE PICTURES FOR COLLAPSING CORE OF TYPE II SUPERNOVA

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1. Introduction: Explosion of type II supernova is, in principle, a difficult process: The presupernova star was in gravitationally bound state with negative energy but it has to be divided into two parts, the collapsed core of still lower (negative) energy and the ejected envelope of positive energy. This process is against nature in the sense most of the phenomena in nature proceed towards equipartition of energies. Thus, some finely tuned mechanism should be necessary for successful explosion. Two different mechanisms have been proposed; one is the prompt explosion where the gravitational energy release by the core collapse is transferred to the mantle by a shock wave, and the other is delayed explosion where it is transferred slowly by neutrinos diffusing out of the core. In what follows we shall concentrate in the case of the delayed explosion.

2. Slow Timescale and Quasi-Homologous Collapse: According to Wilson's calculation (Wilson 1982; Wilson et al. 1985; Bethe and Wilson 1985) the core collapse proceeds typically with the timescale of $t_{coll} \sim 0.05$ sec while the free-fall time in the central core is $t_{ff} \sim 0.01$ sec. Since the ratio of the inertial term to the graviational accerelation is $(t_{ff}/t_{coll})^2$, it is as small as $\sim 1/25$. This implies that the well known concepts and theories of quasi-static stellar structure are applicable. If we plot Wilson's (1982) numerical model of 10 $M_{\odot}$ star on a plane of homology invariants we see that the structure of the core stays very close to that of polytrope of index N=3 except for the very outer mantle.

It may be due to the equation of state for which the deviation of the adiabatic exponent from 4/3 is small, i.e., $\varepsilon = 4/3-\gamma < 0.05$. However, we have to show that this proximity to N=3 should be practically be kept even during the collapse. For the structure close to N=3 the linearized stability theory for stellar structure has a wider applicability, since the polytrope of N=3 with $\varepsilon = 0$ has the eigen value of $\omega_0^2 = 0$ and the eigen function of ξ_0=constant (to be normalized as unity). For the deviation in the equation of state we expanded the linearlized stability equation still to the order of ε by putting $\omega^2 = \omega_0^2 + \varepsilon\omega_1^2$ and $\xi(r_0) = \xi_0(r_0) + \varepsilon\xi_1(r_0)$.

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We solved it and obtained $\omega_1^2 = -19.9(2GM/R^3)$, and, thus, $t_{coll} = 1/i\omega = 0.22\varepsilon^{-1/2} t_{ff}$(at M_r=M). Note that the free-fall time calculated at the surface (M_r= M) is appreciably longer than that in the bulk of the core. Here we see that the factor $\varepsilon^{-1/2}$ brings about the relatively slow collapse. As for the eigen function the value of $-\xi_1(r_0)$ remains as small as 3 within the inner 90 percent of the mass of the core though it grows from 5 to 13 within the outer 2 percent. If we multiply it with ε, we see how small is the deviation from the homologous contraction for the inner core.

3. Later Quasi-Steady Expansion: After the core collapse a weak shock is generated. It heats the outer core and the structure of the region with M_r>0.6 $M_\odot$ deviates greatly from N=3. The shock wave once stalls but after about 0.3 second it revives (Bethe and Wilson 1985). Then the structure of the outer core becomes close to N=3 again up to the neutrino sphere ($M_r \simeq 0.4M_\odot$). This is due to the trapped neutrinos.

In the layers exterior to the neutrino sphere, the temperature gradient is less steep. It is characterized by the thermal balance of neutrino heating and cooling. The heating rate is proportional to T_ν^6/r^2 where T_ν is the effective temperature of the neutrino sphere and r is the radial distance, and where the neutrino opacity proportional to the square of the neutrino energy is taken into account (Bethe and Wilson 1985). The cooling rate is proportional to T_m^6 where T_m is the matter temperature. Balancing them, we obtain $T_m \sim r^{-1/3}$.

In order to realize this thermal balance the outer layers have to expand against the gravity by absorbing energy. It results in a small deficit in energies in still outer layers and thus somewhat stronger temperature gradient. Finally, the quasi-steady mass loss is realized which is described by Parker-type neutrino-driven stellar wind having temperature gradient of $T \sim r^{-2/3}$ (Duncan et al. 1986).

The rate of mass loss is proportional to T_ν^{10} (Duncan et al. 1986). Thus, an analogue of HR diagram with neutrino luminosity versus neutrino effective temperature is desirable to represent numerical results. If we assume the structure of polytrope with N=3 and take account of the definition of the neutrino sphere, we can calculate a neutrino Hayashi-line analogously to that for red giant stars. We have shown that numerical results could be understandable if analyzed with appropriate concepts.

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