Neutrino mechanism of thermonuclear burning of carbon, formation of neutrino stars, and supernova outbursts

S. S. Gershteĭn, L. N. Ivanova, V. S. Imshennik, M. Yu. Khlopov, and V. M. Chechetkin

Institute of High Energy Physics

(Submitted June 15, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 3, 189–193 (5 August 1977)

Allowance for the neutrino energy transport in explosions of carbon nuclei of stars leads, at densities $3\times10^9<\rho_c<8.4\times10^9$ g/cm^3, to an expansion with kinetic energy up to 10^{51} erg (supernova of type II), and leads at $\rho_c>8.4\times10^9$ g/cm^3 to the production of neutron stars with $M\approx1.4M_\odot$ and to the envelope destruction typical of supernovas of type I.

PACS numbers: 95.30.Cq, 97.10.Cv, 97.60.Bw, 97.60.Jd

The theory of the later stages of stellar evolution leads to the conclusion that in all main-sequence stars with masses $(4-10)M_\odot$, there are produced at the center, after the helium has burned out, identical strongly degnerate cores with mass $M=1.4M_\odot$, in which, at central densities $\rho_c=3\times10^9$ g/cm^3 and temperature $T_c=3\times10^8$ K, explosive burning of carbon sets in[1].[1)] The hydrodynamic theory of thermonuclear explosions with the indicated parameters has shown that the star blows up completely with a kinetic energy $<10^{50}$ erg, which is rather small in comparison with the observed supernova outburst energies.[4] The explosion developes in a pulsating regime, and the thermonuclear energy released by the burning carbon combustion is offset to a considerable degree by neutron losses. The predominant neutrino energy-loss process is the capture of electrons by nuclei of the iron group, which are the products of the combustion of the carbon. Thus, although this explosion can serve as a model of a supernova outburst, its kinetic energy is not large enough, and no gravitationally bound remainder in the form of a neutrino star—pulsar—is produced in it.

It was suggested in[5] that a major role in the development of the explosion might be played by neutron energy transport from the central already burned regions of the star to the outer layers which have not yet burned out. The principal mechanism of such a transport is the scattering of neutrinos by relativistically degenerate electrons of the outer layers (under conditions of low opacity νe scattering). The neutrino transport ensures the ignition of new layers of carbon and the propagation of the combustion from the center of the star to its surface. We have included this transport in a self-consistent program for the computation[4,8] of the thermonuclear explosion of the carbon core of a star.[2)]

At the calculation parameters used in[4] ($\rho_c=3\times10^9$ g/cm^3), neutrino energy transport does not lead to a noticable change in the results, since the neutrino-radiation energy is low. According to the evolution theory, however, ρ_c can increase by several times[7] (with a certain decrease in temperature $T_c=1\times10^8$ K), if, for example, the star evolves as a tight binary system, where there is

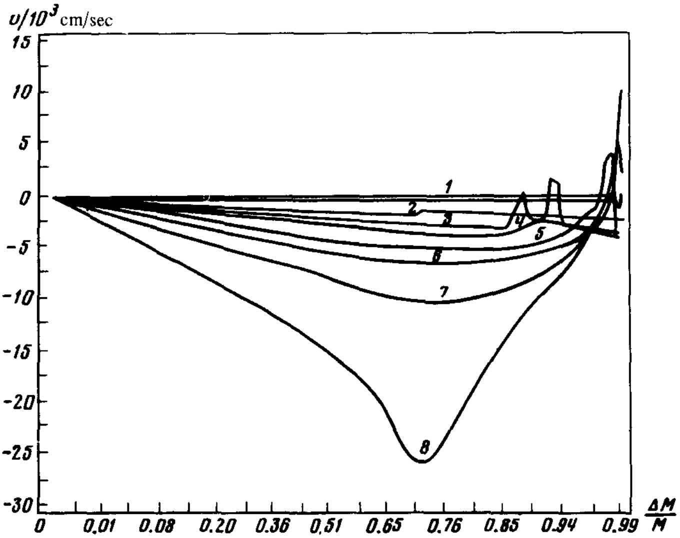

FIG. 1. Profiles of velocity v as functions of the fraction of the mass of the star nucleus $\Delta M/M(T=1.4M_\odot)$ for different successive instants of time 1—8.

mass exchange between the companions. It is natural therefore to consider the explosion of the carbon core of a star with increased density $3\times10^9<\rho_c<3\times10^{10}$ g/cm^3. (At $\rho_c>3\times10^{10}$ g/cm^3 the carbon core of the star collapses as a result of electron capture by the carbon nuclei themselves). In this region, obviously, a transition should take place from total blowup to a collapse initiated by the thermonuclear burning of the carbon. For the detonation regime, this transition has set in at $\rho_c=2\times10^{10}$ g/cm^3.[6] In our calculations, where the detonation combustion hypothesis is not used (without allowance for the neutrino heating), this limit turned out to be much lower: $\rho_c=5\times10^9$ g/cm^3.[8] At $\rho_c=5\times10^9$ g/cm^3, the iron core resulting from the total combustion of the carbon has collapsed without any envelope destruction whatever.

In this article we present some results of calculations of the thermonuclear explosion of the carbon core of a star with allowance for neutrino heating of the external layers via νe scattering. The variant with very large central density $\rho_c=1.4\times10^{10}$ g/cm^3 and $T_c=3\times10^8$ K has collapsed. Nonetheless, neutrino heating produced in the outermost layers a strong detonation wave and a short-duration expansion of the outer surface of the core of the star. The work performed on the outer envelope in this expansion was $\sim2\times10^{49}$ erg, which is quite sufficient for destroying such an envelope. Almost the same work was obtained for other collapsing variants: (a) $\rho_c=8.4\times10^9$ g/cm^3, $T_c=1\times10^8$ K; (b) $\rho_c=8.4\times10^9$, $T_c=3\times10^8$ K. Figure 1 shows for variant (a) the velocity profiles at different instants of time. It is seen how the collapse of the central regions develops with a characteristic position of the maximum with the negative velocity at $\Delta M\approx 1M_\odot$. Positive velocities are obtained for a number of later instants of time in a small fraction of the mass. (No positive velocities were produced anywhere in the absence of neutrino heating).[8]

For the variant $\rho_c = 8.4 \times 10^9$ g/cm^3 and $T_c = 3 \times 10^8$ K the results turned out to be quite sensitive to the details of the allowance for the neutrino losses (a small overestimate of the losses led to collapse, and an underestimate to a complete blow-up). The reason is that near the value $\rho_c = 8.4 \times 10^9$ g/cm^3, there is a boundary between the collapsing and expanding cores of the stars. Thus, the corresponding limiting density almost doubled when account was taken of neutrino heating (cf.).[8]

On the basis of our calculations we can advance a working hypothesis concerning the mechanism of supernova outbursts. Degenerate carbon cores, which at the instant of the explosion have sufficiently low central densities $3 \times 10^9 < \rho_c < 8 \times 10^9$ g/cm^3, explode like supernovas of type II with large energy variation 10^{50}—10^{51} erg in their outer, generally speaking, extended envelopes. The largest of them possibly are contained in close binary systems. (At $\rho_c = 5 \times 10^9$ g/cm^3, calculation yields for the expansion energy a value 1.7×10^{51} erg.)

Carbon stars with high density $\rho_c > 8 \times 10^9$ g/cm^3 are almost definitely companions of close binary systems. They probably do not have extended envelopes and certainly experience collapse with a release of energy $\sim 2 \times 10^{49}$ erg in the outer envelope. This energy is certainly sufficient for destroying the envelope (whose binding energy is smaller by one or two order of magnitude). The result is a neutron star with mass $M \approx 1.4 M_\odot$. This value of the mass agrees well with the mass range of neutron stars $(1.2$—$1.8) M_\odot$, determined from observations in binary systems.[9]

In this case, after formation of the neutron star, slow release of energy to the surrounding space can start.[10] The kinetic energy of the ejected envelope can increase by one order of magnitude. This process of two-stage envelope ejection can be set in correspondence with supernovas of type I (judging from the character of the brightness curves and the spectral singularities). We note that the second stage of this process is analogous to slow energy release of collapsing iron cores.[2]

The authors are sincerely grateful to L. G. Kaminskiĭ and V. N. Folomeshkin for help with the calculations, to Ya. B. Zel'dovich, A. A. Logunov, and D. K. Nadezhin for useful discussions, and to M. P. Khlopova for help in preparing the paper.

---

1) Stars with smaller masses are transformed into white dwarfs, while those with larger masses reach the final stage of the formation of the central iron core[1] and collapse into neutron stars (not excluding also the possibility of the production of black holes).[2] In the latter case there is no explanation for supernova outbursts.

2) We note that the neutrino transport mechanism ensures a deflagration combustion regime, which under suitable conditions goes over into detonation. The hypothetical detonation regime of combustion without deflagration then becomes superfluous (see, e.g.,).[6]

---

[1] Z. Barkat, Ann. Rev. Astron. Ap. 13, 45 (1975).

[2] D. K. Nadezhin, Preprint IPM Akad. Nauk SSSR No. 98, No. 106, 1975; No. 26, 1976.

[3] V. M. Chechetkin, V. S. Imshennik, L. M. Ivanova, and D. K. Nadyozhin, Supernovae, ed. D. N. Schramm, 1977, p. 159.

[4] L. N. Ivanova, V. S. Imchennik, and V. M. Chechetkin, Astron. Zh. 54, 354 and No. 3 (1977) [Sov. Astron. 21, 197 and No. 3 (1977)].

[5] S. S. Gershteĭn, V. S. Imshennik, D. K. Nadezhin, V. N. Folomeshkin, M. Yu. Khlopov, V. M. Chechetkin, and R. A. Eramzhyan, Zh. Eksp. Teor. Fiz. 69, 1473 (1975) [Sov. Phys. JETP 42, 751 (1976)].

[6] S. W. Bruen, Astrophys. J. Suppl. 24, 283 (1972).

[7] E. V. Ergma and A. V. Tutukov, Acta Astron. 26, 69 (1976).

[8] L. N. Ivanova, V. S. Imshennik, and V. M. Chechetkin, Astron. Zh. 54, No. 5 (1977) [Sov. Astron. 21, No. 5 (1977)].

[9] S. A. Rappaport and P. C. Joss, Texas Symposium, Boston, USA, 1976.

[10] D. K. Nadezhin and V. P. Utrobin, Preprint IPM Akad. Nauk SSSR No. 122, 1975; No. 85, 1976.