# CORE-COLLAPSE SUPERNOVA MECHANISM — IMPORTANCE OF ROTATION

A. Odrzywołek[b †], M. Kutschera[a,b], M. Misiaszek[b], and K. Grotowski[a,b]

[a]H. Niewodniczański Institute of Nuclear Physics
Radzikowskiego 152, 31-342 Kraków, Poland
[b]M. Smoluchowski Institute of Physics, Jagellonian University
Reymonta 4, 30-059 Kraków, Poland

*(Received July 17, 2002)*

An attempt is made to assess the significance of rotation in the core-collapse supernova phenomenon, from both observational and theoretical point of view. The data on supernovae particularly indicative of the role of rotation in the collapse-triggered explosion is emphasized. The problem of including the rotation of presupernova core into the supernova theory is considered. A two-dimensional classification scheme of core-collapse supernovae is proposed which unifies "classical" supernovae of type Ib/c and type II, "hypernovae" and some GRB events.

PACS numbers: 97.10.Kc, 97.60.–s, 97.60.Bw, 97.60.Jd

## 1. Introduction

The phenomenon of supernova amazed already ancient observers as some bright historical supernovae were visible on the sky even in the daytime. The absolute luminosity of supernovae has been properly estimated only in the 20-th century, when it was realized that supernovae belong to a very special class of astronomical events. In 1885 the nova S And appeared in the M31 nebula, now well-known as the Large Galaxy in Andromeda. At those times many astronomers accepted the in-Galaxy theory of M31 and other nebulae. After establishing that the real location of M31 is extragalactic, astronomers were forced to conclude that the nova S And[1] was much brighter than any usual nova [1] — it was a super-nova!

† aodrzywolek@poczta.onet.pl
[1] Now called SN 1885A.

The systematic supernova research began in the 20-th century. Unfortunately, there was no Galactic supernova event since the 17-th century. In spite of this astronomers have observed more than 2000 extragalactic supernovae. The number of observed events grows rapidly, from about 20 per year in the eighties to about 200 per year now. In contrast to the optical events, more than 600 supernova remnants have been found in the Galaxy. Also, a number of extragalactic remnants, mainly in the Local Group galaxies LMC, SMC, M31 and M33 [2] have been observed.

In 1942 Minkowski [3] introduced the modern classification scheme of supernova events into two classes. To the first class belong supernovae with no hydrogen absorption lines in the spectrum referred to as type I supernovae. The second class comprises the supernova events with strong hydrogen lines which are referred to as type II supernovae.

As for the physical nature of supernovae, Landau [4] in 1932, soon after discovery of the neutron, suggested the possibility of existence of dense stars composed of neutrons which are stabilized by very high pressure of the neutron gas. In 1939 Baade&Zwicky [5] proposed the gravitational collapse of a normal star to such a neutron star as the supernova energy source. This picture is generally accepted today. In 1960 Fowler and Hoyle [6, 7] pointed out that also nuclear reactions can serve as a source of the supernova energy. They proposed the thermonuclear explosion of a white dwarf or a giant star as an another possible supernova mechanism.

After several decades that passed since the original proposal of Zwicky and Baade, significant progress in understanding the supernova mechanism has been achieved. The detection of the neutrino burst correlated with the appearance of SN1987A proved that the theoretical research is on a right track. Unfortunately, the standard core-collapse supernova theory suffers from difficulties in producing a successful explosion under general conditions. This could be a consequence of suppressing star's rotation in the theory. In this paper we collect arguments in favor of the necessity to include rotation into the supernova theory. The paper is organized as follows: In the next section we review in some details the modern version of supernova classification. We wish to emphasize a division of observational data into these related to outer layers of the exploding star and the ones reflecting the physics of the engine mechanism. In Sect. 3 the essential features of the standard supernova theory are reminded. The problem of inclusion of the presupernova core rotation into the supernova theory is considered in Sect. 4. Finally, in Sect. 5, we introduce a two-dimensional classification employing some measure of the rotation as a second dimension.

## 2. Modern classification of supernovae

With a simple classification of supernova events available, researchers were tempted to establish a direct relationship between the two proposed supernova mechanisms and the two observed supernova types. Unfortunately, the relation of the thermonuclear explosion mechanism and the core-collapse scenario to type I and type II supernovae is not as straightforward as it may seem. It turns out that type I supernovae with no hydrogen lines form a class of diverse events which can be further divided into more homogeneous subclasses. The spectra near the maximum brightness are used to distinguish type Ia events which show a strong SiII absorption dip at $\lambda$ 6150 Å and type Ib/c events with no or weak SiII lines. Further, a strong helium line at $\lambda$ 5876 Å is employed to distinguish type Ib events from those of type Ic. Type Ib/c supernovae occur in the same environment as do type II supernovae, namely in the star forming regions in spiral galaxies. Both are thus related to young population I stars. Type Ia supernovae are more common and they occur in all types of elliptical and spiral galaxies, and in the halo of our Milky Way galaxy. This location indicates they are related to population II stars. The main observational features used as a basis of modern supernova classification are presented in Table I.

A generally accepted hypothesis with regard to the relationship of the physical supernova mechanism and the observed supernova types postulates that thermonuclear explosions of white dwarfs produce type Ia supernovae and the core collapse of giant stars results in type Ib/c/II supernovae. Basic arguments in favor of this identification come from common locations of type Ia supernovae in old stellar systems and type Ib/c/II — in regions of active stellar formation in spiral galaxies.

Homogeneity of type Ia supernovae also indicates the same explosion mechanism. Type Ia events have similar spectral properties and obey a simple empirical relation (*e.g.* the Phillips relation [8]) between the maximum absolute brightness and the behavior of the light curve, which states that brighter events are longer. The observed scattering of absolute magnitudes at the maximum is about $2^m$, and further division of type Ia into subclasses is not excluded [9].

It was long believed that these differences are due to observational errors and all type Ia supernovae are almost identical. However, the maximum brightness and the decay time are possibly related to the amount of $^{56}$Ni synthesized during the explosion. The light curves clearly show that the beta decay of $^{56}$Ni into $^{56}$Co, and a subsequent decay of $^{56}$Co to $^{56}$Fe with a half-life of 77 days, are the main energy sources supporting the light emission during the late phase of the explosion. It is of great interest that the radioactive energy source from $^{56}$Ni and $^{56}$Co decays occurs in all types of supernovae in spite of very different explosion mechanisms.

TABLE I

Supernovae classification and properties.

| **Type** | Ia | Ib/c[d] | II |
|---|---|---|---|
| **Definition** | No hydrogen lines | | Strong hydrogen lines |
| **Location** | All type galaxies and halo | Spiral arms, star forming regions | |
| **Relative rate** Galaxy rate | 30%± 9% ∼1/200yr | 11%± 6% ∼1/500yr | 59%± 28% ∼1/100yr |
| **Absolute magnitude** | $-20^m$ homogeneous[a] | $-17^m \ldots -18^m$ $(-19.5^m)$[b] | $-16^m \ldots -19^m$ $(-20^m)$[b] |
| **Spectra at maximum** | Si II absorption at λ6355Å [c] | No or very weak Si II[d] | Strong Hα |
| **Late spectra (months after max.)** | [FeII]+[FeIII] emission | Forbidden [OI] + [CaII] emission[e] | |
| **Nebular remains** | Shell (Balmer-dominated) | Shell (Oxygen-rich) | Plerion (Crab-like) |
| **Compact remains** | None | Neutron star ( or a black hole ) | |
| **Progenitor** | Accreting white dwarf in binary system | Wolf-Rayet star | Giant star |
| **Main light curve energy source** | $^{56}$Ni → 6 days →$^{56}$Co → 77 days →$^{56}$Fe decay | | |
| **Explosion energy source** | Fusion C/O → Fe | Neutrino flux | |
| **Physical mechanism** | White dwarf thermonuclear disruption | Core-collapse | |

[a] Average $M_B \simeq M_V \simeq -19.8 \pm 0.03 + 5\log(H_0/75)$, but deviations do exist: SN1991bg $-16.5^m$, SN1991T $-20.5^m$. $H_0$ is Hubble const. [km/s Mpc$^{-1}$].

[b] Extremly bright events called **hypernovae**.

[c] Doublet λ6347Å, λ6371Å blueshifted (velocity up to 30000 km s$^{-1}$) to ∼λ6150Å.

[d] Absorption of HeI (λ5876Å) defines type Ib; lack of HeI – type Ic.

[e] Hα always dominates in type II SNe.

Significant constraints on the supernova theory are imposed by observations of the nebular remnants. Unfortunately, in spite of known positions of SN1006, SN1054, SN1572 and SN1604 we cannot firmly classify these historical supernovae. In effect, it is not perfectly clear what remains after type Ia/b/c and II supernova explosions. We can distinguish three basic types of remnants:

- Balmer-dominated shell,
- oxygen-rich shell,
- plerion (Crab-like nebula).

A classical example of a plerion is M1, the Crab nebula. Because the pulsar is found in its center we connect plerions to type II events. They are sometimes surrounded by weak shells. The Balmer-dominated shell is usually connected to type Ia, and its emission can be explained as a result of the interaction between the shock wave and the interstellar hydrogen. Arguments confirming this identification come from the analysis of SN1572 and SN1604 remnants, which both probably were type Ia supernovae. In addition, we can not see any compact stellar remnant, such as a pulsar or a neutron star, inside or near outside the shell. Finally, type Ib/c supernovae are supposed to leave as a nebular remnant the oxygen-rich shell. This identification is supported by the theory of origin of type Ib/c supernovae from stars stripped off hydrogen and helium layers. The lost matter at least partially fills in the space around donor stars. If extensive mixing and core dredge-up took place at some evolution phases of these stars, we expect some enrichment of CircumStellar Medium (CSM) in heavy elements. The shock interacts with CSM whose composition is a relic of star's earlier evolution and excites atoms of heavier elements, like *e.g.* oxygen.

Observed spectral differences between various types of core-collapse supernovae are in significant part a result of the differences in the outer shells. Classification of core-collapse events clarifies and becomes more elegant when we use the lost mass as a basic ordering parameter [10]. Stars with very massive hydrogen layers at the onset of the explosion produce type II-P supernovae with the light curve plateau. An extreme example of such a light curve was provided by the SN1987A. If the star has not very massive hydrogen shell the explosion is classified as type II-L with fast, linear decay of the light curve. In case of a very thin H shell the explosion is type IIb and if the whole hydrogen is lost, the event is classified as Ib. If in addition the helium layer is also removed we can see type Ic supernova. This ordering of core-collapse supernovae is displayed schematically in Fig. 1.

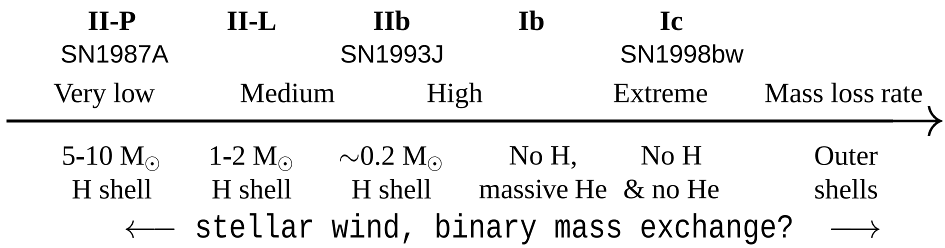


Fig. 1. Unification of the core-collapse events within a one-dimensional family of the growing mass loss rate.

Within this scheme, every type of core-collapse supernovae covers a range of outer shell masses of pre-supernova stars. For every pair of supernovae we may find a third one which could be placed between them in the classification scheme. For example, SN1993J in M81 was a missing link between type II and type Ib with a residual hydrogen shell, now distinguished as type IIb. The evidence of supernovae corresponding to stars with thin He layers is not clear yet, but candidates exist [11]. The fact this classification works indicates that mass loss rates in progenitors increase from type II to type Ic. Outer layers are expelled by strong stellar winds, but in extreme cases also stripping due to the mass exchange in close binaries occurs, as we indicate in Fig. 1.

This scheme clearly shows that the engine mechanism is not of major importance for the classification of supernovae based on light curves and spectra, which both are formed by processes occurring in outer layers of the exploding star. There are, however, a number of observations related to supernovae, such as pulsar initial velocities, asymmetry of explosions, "hypernovae", jets and possibly some gamma-ray bursts (GRB), which are likely related to processes in the inner part of the exploding star, in particular they can directly reflect physical conditions prevailing in the collapsing core. The detailed picture of the collapse depends on the mass of the core related to the ZAMS mass and the evolutionary track of the progenitor. In this paper we focus on the rotation of the progenitor core which can very significantly affect physics of the core collapse. Below, in Sect. 5, we discuss interpretations of the above observations as an evidence of rotation of the collapsing core. We propose a two-dimensional classification of the core-collapse supernovae which can accommodate "hypernovae" and GRBs. It is an extension of the scheme shown in Fig. 1, with the second dimension being some measure of the amount of rotation of the collapsing core, Fig. 4.

## 3. Standard supernova mechanism

In the standard scenario of the core-collapse supernova without rotation, a massive star at the onset of collapse is a red or blue super-giant, for example, the progenitor of SN1987A was a B3I spectral type star. It contains a number of shells, which correspond to the following stages of nuclear burning, given here in a simplified form:

$$\begin{array}{lcl}
\mathrm{H} & \longrightarrow & {}^{4}\mathrm{He} \\
{}^{4}\mathrm{He} & \longrightarrow & {}^{12}\mathrm{C},\ {}^{16}\mathrm{O} \\
{}^{12}\mathrm{C}\ (\ {}^{16}\mathrm{O}\ ) & \longrightarrow & {}^{20}\mathrm{Ne},\ {}^{24}\mathrm{Mg} \\
{}^{20}\mathrm{Ne}\ (\ {}^{16}\mathrm{O},\ {}^{24}\mathrm{Mg}\ ) & \longrightarrow & {}^{16}\mathrm{O},\ {}^{24}\mathrm{Mg} \\
{}^{16}\mathrm{O}\ (\ {}^{24}\mathrm{Mg},\ {}^{28}\mathrm{Si}\ ) & \longrightarrow & {}^{28}\mathrm{Si} \\
{}^{28}\mathrm{Si}\ (\ {}^{32}\mathrm{S}\ ) & \longrightarrow & {}^{56}\mathrm{Ni},\ {}^{56}\mathrm{Fe},\ {}^{54}\mathrm{Fe}
\end{array}$$

The synthesis of the most strongly bound nuclei near ${}^{56}$Fe ends the network of thermonuclear reactions. In Table II we show main evolutionary phases of a star of $25M_{\odot}$. One can notice that burning of neon begins about one year before the star's death.

TABLE II

The evolution of $25M_{\odot}$, $Z = 0.02$ star according to [12]. Duration of a given phase is defined here as time since central ignition of a given reaction until the central ignition of a next reaction. This includes phases of off-center burning, with no reactions in the center. The temperature and density correspond to the beginning of each phase.

| **Burning** | $T_c\,[K]$ | $\rho_c\,[g/cm^3]$ | **Duration** |
|---|---|---|---|
| **H** | $3.7 \times 10^7$ | 3.8 | 5.8 mln yrs |
| **He** | $1.6 \times 10^8$ | 200 | 85 000 yrs |
| **C** | $6.3 \times 10^8$ | $10^5$ | 280 yrs |
| **Ne** | $1.2 \times 10^9$ | $2 \times 10^6$ | 300 days |
| **O** | $1.7 \times 10^9$ | $4 \times 10^6$ | 134 days |
| **Si** | $2.8 \times 10^9$ | $3.2 \times 10^7$ | 30 hours |
| Shell **Si** | $3.4 \times 10^9$ | $3.2 \times 10^8$ | 5.5 hours |
| *Core collapse* | $1.6 \times 10^9$ | $1.6 \times 10^9$ | 0.1…0.5 sec |

The late phases of nuclear burning are quite complicated and still not perfectly understood. Soon after ignition of an off-central silicon burning the core composed of iron-group nuclei loses its stability and starts to collapse. A short explanation is that the core mass exceeds the Chandrasekhar limit. The full expression of the Chandrasekhar mass is [13]:

$$M_{\rm Ch} \;=\; 1.44\, M_{\odot}\, (2\, Y_e)^2 \left[1+\left(\frac{S_e}{\pi Y_e}\right)^2\right] \left[1-\frac{3}{5}\left(\frac{12}{11}\right)^{1/3} \alpha\, \bar{Z}^{2/3}+\frac{p_{\rm rad}}{p_{\rm mat}}\right]. \tag{1}$$

It is a function of the electron fraction $Y_e$, the entropy per baryon $S_e$, the nuclear composition expressed through an average nuclear charge $\bar{Z}$, and the ratio of radiation and matter pressure $p_{\rm rad}/p_{\rm mat}$; $\alpha \simeq 1/137$ is the fine structure constant. For $Y_e = 0.5$, $S_e = 0$ and $p_{\rm rad} = 0$ we obtain the famous result $M_{\rm Ch} = 1.44\, M_{\odot}$. The mass of the stellar "Fe" core is in the range of 1.2–2 $M_{\odot}$. A number of processes are important in the last day before the collapse. The electron capture by iron and nickel isotopes decreases the electron fraction in processes such as *e.g.*:

$$^{55}{\rm Fe} + e^- \longrightarrow ^{56}{\rm Mn} + \nu_e\,.$$

Neutrinos carry away the energy from the core decreasing its entropy. The silicon burning Si $\rightarrow$ Fe stops in the core and begins in a surrounding shell. The most important reason of the collapse onset is the decrease of entropy. Usually the Chandrasekhar mass limit is not really exceeded because of a huge external pressure not included in $M_{\rm Ch}$. The instant when the core starts to collapse is deduced from the evolutionary code results. When the speed of contracting matter exceeds some in advance prescribed value, the evolutionary track is finished. This moment is believed to be close to the real stability loss and to start of actual collapse of the core.

Once started, the collapse is fast, close to a free fall. In the numerical simulations the collapse lasts 100–500 milliseconds, depending on the initial conditions and on the input physics. During the first phase the collapse is homologous — the velocity is proportional to the radius. The sound speed decreases with the radius, and at a sufficiently high distance from the center it falls below the matter speed. This place is called the sonic point. Time when the central density reaches its maximum defines the core bounce. At this time the infalling matter is stopped by the pressure component due to nuclear forces which starts to grow very rapidly. In milliseconds the velocity goes to zero and simultaneously the density grows by a few orders of magnitude [14]. Strong sound waves start to propagate outside. As a result of non-linear hydrodynamical effects and the supersonic speed of matter discontinuity forms in velocity, density, pressure and entropy — the sound wave becomes the shock wave.

It was accepted for a long time that the sketched above process is a main part of the real explosion mechanism and is able to provide at least a few foe[2] of energy. The shock was believed to traverse the entire star and reach the surface to produce a spectacular supernova type II (or Ib/c) event. This scenario is known as a prompt explosion. Unfortunately, more detailed calculations with improved physical ingredients, such as a realistic Equation Of State (EOS), general relativity corrections, sophisticated progenitor models and a complete set of nuclear reactions included in new gas-dynamical algorithms, have shown the failure of this idea. The shock wave gets stuck in the Fe core as a result of the energy loss chiefly due to heavy nuclei dissociation ($\sim 8.7\,\mathrm{MeV/nucleon} \simeq 1.7\mathrm{foe}/0.1M_\odot$) and — when shock moves out of the neutrino trapping sphere — the neutrino emission. Although it is still possible to produce a successful prompt shock under extreme assumptions on the equation of state or other part of included physics, nowadays neutrino processes are believed to play a major role in core-collapse supernova explosions, so let us look at them.

As we pointed out already, beyond the nuclear matter density, the EOS stiffens very rapidly. Simultaneously matter initially composed of nuclei and electrons, transforms into a nucleon–electron gas and finally becomes an almost pure neutron matter. Other phases of dense matter, such as *e.g.* the kaon-condensed nuclear matter or the quark-gluon plasma can possibly form, but usually are not considered in the standard supernova scenario. Almost every electron-proton pair is transformed into neutron and neutrino. Initially neutrinos escape freely. But as a result of neutrino cross-sections growth with temperature and density, neutrinos become trapped. It means that the diffusion time is bigger than the dynamical time-scale. The gravitational energy released in the collapse is "frozen" as the energy of the lepton Fermi sea. The inner part of the star which is not blown off, after the core bounce and shock transition becomes a ProtoNeutron Star (PNS). The edge of the neutrino-trapped zone is referred to as the neutrinosphere, with analogy to a photosphere of normal stars. Definition of the neutrinosphere is somewhat ambiguous as different neutrino flavors have different and diffused neutrinospheres. Harder neutrinos escape further out than do the soft ones, because of the cross-section dependence on the neutrino energy. The most important fact is the location of the neutrinosphere between the shock and the neutrino-rich protoneutron star. The trapped neutrinos diffuse out of the protoneutron star in time of the order of one second, and simultaneously the protoneutron star contracts from an initial radius of about 60 km to final radius of 20 km, like a Kelvin–Helmholtz star [15]. Neutrinos carry away about 100 foe of energy, *i.e.* $\sim$99% of the total energy released in the

[2] foe — fifty-one-erg — $10^{51}$ erg.

collapse. The neutrino flux vanishes in tens of seconds. This picture was in general confirmed by the detection of neutrinos during the SN1987A event and now this is the best established part of core-collapse supernova theory. In spite of very small neutrino cross-sections about 1% of the energy is transferred to the hot radiation bubble between the nascent neutron star and the shock in hundred milliseconds. It causes the shock wave revival. Later, the explosion is similar to that of a prompt mechanism. This scenario is called a delayed or neutrino-driven supernova mechanism. Currently it is a subject of very active studies. The neutrino transport and convection appear to be the most important processes of this scenario [16].

The shock produced in the engine of supernova by prompt or delayed mechanism traverses the entire star ionizing the gas, igniting nuclear reactions and triggering convection [17, 18]. The shock wave may reflect at the shell boundaries. The onion-like structure of different nuclei layers is destroyed. Intensively mixed matter from the center may move close to the surface. In a few hours the shock reaches the surface. The photosphere begins to expand and we can see the enormous growth of brightness. A supernova appears on the sky. During the first few weeks the light curve is dominated by the recombination of ionized atoms. Later, the light curve mimics the decay curve of beta-radioactive $^{56}$Ni. The subsequent decay of $^{56}$Co with $T_{1/2} = 77$ days is the energy source for supernova during the next months.

## 4. Rotation in supernova theory

A major deficiency of the sketched above supernova theory is suppression of rotation of the presupernova star. From the observational point of view there is growing evidence that rotation can play an important role in the explosion. Below we discuss some relevant data. However, before we attempt to assess whether the inclusion of rotation is necessary to explain the observed properties, we address the following important questions:

- are massive stars rapid rotators?
- do cores of massive star rotate?
- what is the shape of the rotating core?
- what is caused by the angular momentum conservation during collapse?

### *4.1. The simplest rotating star*

Let us consider the behavior of a rigidly rotating body which is incompressible and homogeneous and bound by the Newtonian gravity. This is very simple and idealized model of a rotating star, closer to the liquid drop model of the atomic nucleus [19] except of the surface tension, which is negligible for astrophysical objects and huge for atomic nuclei.[3] It illustrates, however, basic features of the rotation's influence on properties of real objects.

The most important parameter, which determines physics of rotating and gravitating bodies, is the ratio of rotational to gravitational energy, $E_{\rm rot}/E_{\rm grav}$ (here $E_{\rm grav}$ is the absolute value of the gravitational energy). In case of zero angular momentum the body is of spherical shape. Any rotation leads to a spheroidal shape, as shown by Maclaurin in 1742. But when $E_{\rm rot}/E_{\rm grav}$ exceeds the value of 0.1375 two solutions of the problem exist (Jacobi, 1834). The first solution is the Maclaurin spheroid, and the second one is a triaxial ellipsoid. The latter solution is the ground state corresponding to the minimum of the sum of rotational and gravitational energy. Transition from the Maclaurin spheroid to the Jacobi ellipsoid requires some dissipation mechanism, because of difference in the total macroscopic energy. Maclaurin spheroids beyond $E_{\rm rot}/E_{\rm grav} = 0.1375$ are secularly unstable with respect to dissipative processes, such as, *e.g.* viscosity.

When the rotational frequency of the body increases, for example in effect of shrinking, two cases are possible. If the dissipative time-scale is short compared to the dynamical time-scale, the body evolves through a sequence of Jacobi ellipsoids. For $E_{\rm rot}/E_{\rm grav}$ approaching the critical value of 0.16 the barrier separating Jacobi ellipsoids from unstable configurations, called Poincaré pears, disappears and the Jacobi ellipsoids dynamically fission. If dissipative processes are negligible the body evolves along a sequence of Maclaurin spheroids, which are dynamically stable up to $E_{\rm rot}/E_{\rm grav} = 0.2738$. Beyond this limit no stable configuration exists and the body has to get rid of the angular momentum or to breakup.

Surprisingly, inclusion of a differential rotation and a compressible equation of state (and also general relativity corrections) results in minor changes of the secular and dynamical instability limits of $E_{\rm rot}/E_{\rm grav}$ which are important for supernova theory. Recent publications report the possibility of significant decrease of those limits, for a toroidal density stratification. The secular instability limit of the ratio $E_{\rm rot}/E_{\rm grav}$ becomes 0.038 [20], for transitions leading to bar-like configurations. The dynamical instability limit is found to be $E_{\rm rot}/E_{\rm grav} = 0.14$ [21].

During the collapse of the stellar core the ratio $E_{\rm rot}/E_{\rm grav}$ grows significantly, by a factor of a few tens. Given the insensitivity of the instability limits with respect to details of rotation and to the compressibility of matter, the values listed above seem to be sufficiently accurate to allow us to assess the possibility of triaxial deformations and the core breakup in SN events.

[3] In a ball of water the gravitational energy exceeds the surface tension energy if radius is bigger than 10 m.

### 4.2. Rotation of supernovae progenitors

Are supernova progenitors rapid rotators? The answer is well known to astronomers [22]. Single stars which are supposed to be supernova progenitors begin their lives as O and B main sequence stars with initial masses $M > 8M_{\odot}$. The surface velocity is very high for these stars. It can be determined observationally with some uncertainty due to an unknown angle between the rotation axis and the observer direction. The velocity may be close ($\sim$70%) to Keplerian velocity at the surface radius. But, except of the Sun[4], it is impossible to determine rotation inside the star. To address the problem one must resort to stellar modeling.

In the last few years new detailed evolutionary calculations of rotating stars have been carried out [24]. The results are in good agreement with observed surface properties. One can thus treat predictions with regard to the internal structure with some confidence. Contrary to previous opinions, numerical results show that cores of stars rotate fast with velocity not significantly dependent on the initial conditions. Nevertheless, one should mention that the calculations described above neglect magnetic fields which may transport angular momentum and slow down the core.

Typically, according to [24] Fe cores have radii of about 2000 km, masses of $1.5M_{\odot}$ and rotate differentially with periods of the order of 10 seconds. Outer convective shells surrounding cores rotate rigidly, and the rotational frequency drops at shell boundaries discontinuously. The ratio $E_{\rm rot}/E_{\rm grav}$ reaches, near the center, the maximum values up to 0.04. It was assumed in calculations of [24] that it is safe to neglect the possibility of non-axisymmetric core deformations because $E_{\rm rot}/E_{\rm grav} = 0.04$ is only $\sim$30% of the Maclaurin spheroid secular instability limit. Results cited in the previous subsection [20] suggest the secular instability for toroidal "fizzler"[5] configurations at 0.038 and the possibility of "triaxial" cores during the last phases of the stellar evolution seems not to be excluded if the core is far from a spheroidal shape. In spite of the rapid core rotation almost all angular momentum is located in distant massive shells, but $E_{\rm rot}/E_{\rm grav}$ is very small there, as indicated in Table III.

---

[4] Helioseismology allows us to see the interior of the Sun. Other stars are in the range of observational abilities too; see *e.g.* [23].

[5] This is a transient object between those stabilized by the degenerate electron gas pressure (*e.g.* "Fe" cores and white dwarfs) and neutron stars. Its existence and dynamical stability are the results of extremely strong centrifugal force, but "fizzlers" are secularly unstable.

TABLE III

Parameters of rotation of inner shells of a typical presupernova star from [24].

| **Part of star** | **Angular velocity** | $E_{rot}/E_{grav}$ | **Angular momentum** |
|---|---|---|---|
| **"Fe" core** | $10 \ldots 0.01$ rad/s | $0.04 \ldots 0.01$ | $2 \cdot 10^{49}$ erg · s |
| **"CO" shell** | $10^{-2}$ rad/s | $10^{-2}$ | $10^{50}$ erg · s |
| **He shell** | $10^{-4}$ rad/s | $10^{-3}$ | $10^{50}$ erg · s |
| **H shell** | $10^{-10}$ rad/s | $10^{-6}$ | $10^{51}$ erg · s |

### *4.3. The shape of rotating star*

Calculations presented above are based on the assumption that the density stratification is not far from spheroidal and the rotation is close to "shellular", *i.e.* the angular frequency is constant on a family of spheroidal surfaces. The set of stellar structure equations is modified due to rotation but this method preserves the conventional description of the stellar structure in terms of a one-dimensional mass coordinate, with constant mass surfaces being non-spherical [24]. In this approach some processes, such as the transport of angular momentum, the mixing of stellar matter and nuclear reactions are well described. However, the real two-dimensional structure is treated only approximately.

Such an approach is especially unsatisfactory when we attempt to analyze the collapse of the core because the star model *is not in full mechanical equilibrium.* The situation is analogous to starting the simulations of the rotating core collapse from the initial configuration which is that of a non-rotating core endowed with some amount of rotation. This case has been analyzed in [25], where it was shown that some of the models without initial equilibrium evolve in a significantly different way, compared to initially hydro-stationary models. In this way only rough estimates of the basic quantities, such as *e.g.* the density at the core bounce, can be obtained. The analysis has been performed in the axisymmetric case with the cylindrical rotation and the barotropic EOS. One may expect a similar result for an arbitrary rotation law of the initial model.

An important conclusion from the above considerations is that the exact density distribution and the velocity field inside the presupernova star in the full hydro-stationary equilibrium are required as an input for the analysis of the collapse of the core and its later evolution. To find the exact density distribution, in particular the shape of the stellar surface and the iso-density contours inside the star, one has to solve the equations of hydrostatic, or more explicitly hydro-stationary, equilibrium, taking into account the non-zero velocity field. This has been achieved in very simplified stellar models only. For the equation of state $p = p(\rho)$, including polytropes, the rotation was assumed to be cylindrical with angular velocity being a function of the radial variable in cylindrical coordinates only [26]. Under these conditions one can derive an analytic first-order approximation to the resulting integral equation for the axisymmetric density distribution:

$$\rho_1(r,z) = f^{-1}\left[\, f(\rho_0) - \Phi_{\rm c}(r) + \langle \Phi_{\rm c}\rangle\right], \qquad (2)$$

where $\rho$ is the density as a function of cylindrical coordinates $(r, \phi, z)$, and $\langle \Phi_{\rm c}\rangle$ is the centrifugal potential $\Phi_{\rm c}$ corresponding to the angular frequency distribution inside the star $\Omega(r)$,

$$\Phi_{\rm c}(r) = \int\limits_0^r \tilde{r}\,\Omega(\tilde{r})^2 d\tilde{r}, \qquad (3)$$

averaged over the volume $V_0$ of a non-rotating star with the density $\rho_0(r)$ and the radius $R_0$:

$$\langle \Phi_{\rm c}\rangle = \left(\frac{4}{3}\pi {R_0}^3\right)^{-1} \int\limits_{V_0} \Phi_{\rm c}(r)\, dV. \qquad (4)$$

In Eq. (2) $f(\rho)$ is the enthalpy[6] of the barotropic gas with an EOS $p = p(\rho)$:

$$f(\rho) = \int \frac{1}{\rho}\, dp\,. \qquad (5)$$

From Eq. (2) (or using any numerical method of Ref. [26, 27]) we can see (Fig. 2) that the shape of the stellar core is far from spherical or spheroidal one. In case of the rapid differential rotation the density distribution is toroidal with an off-center maximum. This "disk-like" shape (Fig. 2) is sometimes referred to as a "concave-hamburger". A common feature of realistic density calculations is a cusp at the star surface in the polar region. It is a result of the strong centrifugal force near the rotation axis which is balanced by a rather weak gravity far from the center.

[6] The density in Eq. (2) is the inverse function $f^{-1}$: $f(f^{-1}(\zeta)) = f^{-1}(f(\zeta)) = \zeta$.

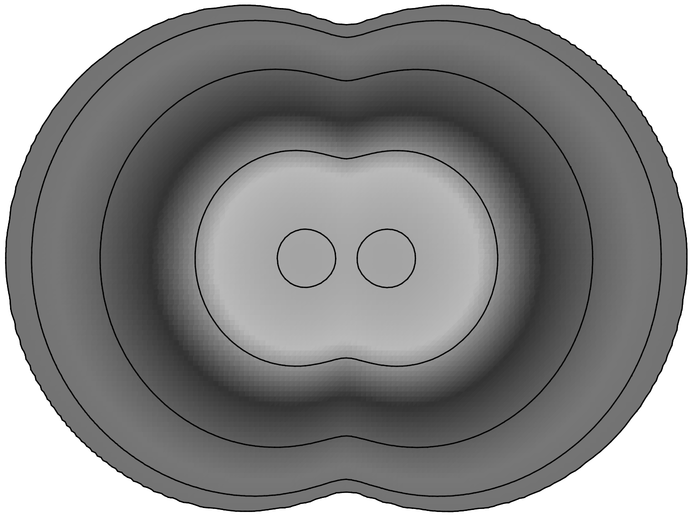

Fig. 2. An example of the iso-density contours for n=3/2 ($p = K\rho^{5/3}$ EOS) polytropic model with a cylindrical distribution of the angular frequency, $\Omega(r) = \Omega_0/(1 + r/A)$, concentrated near the rotation axis ($A = 0.1\,R_0$, where $R_0$ is the equatorial radius) calculated using Eq. (2). The off-center density maximum, the flattened shape, the toroidal density distribution in the central region and the "cusp" in the polar region are common features of rapidly and differentially rotating polytropes.

Using the equilibrium approach we can obtain highly deformed and very flattened structures, but we cannot forget that if they exceed stability limits their structure will be destroyed. Less constrained rotation, different from cylindrical and rigid one, results in a much more complicated problem because a physically consistent treatment requires accounting for the temperature-dependent equation of state and the meridional circulation in a star. It could be important to include the "shellular rotation" and the external pressure. The conclusion is that the current status of the stellar structure models with rotation does not allow us to predict firmly the initial state of the collapsing core in the supernova theory. A non-axisymmetric and ring-like shape of the core is a very intriguing possibility as it may be partially responsible for violent processes during the last phases of the presupernova evolution and for the onset of the core collapse. The growing evidence of both axisymmetric and non-axisymmetric supernova explosions indicates a significant amount of rotation of the presupernova core but details are still unclear. It seems thus quite possible that at least some of the supernova progenitor cores can be properly described within a framework of the sketched above picture.

### 4.4. Rotating core collapse

We mentioned already that the ratio $E_{\rm rot}/E_{\rm grav}$ grows as a result of the core contraction. This happens during subsequent nuclear burning phases and collapse. When the star exhausts a given nuclear fuel (H, He, C/O, Si) the core contracts until the next nuclear reactions ignite. After contraction the size of the core is smaller but the ratio $E_{\rm rot}/E_{\rm grav}$ is bigger. During last phases of nuclear burning it may reach values as high as 0.04 [24].

To imagine what may happen in the collapsing and rotating core let's look at the behavior of a homogeneous and rigidly rotating sphere of a decreasing radius. In this case:

$$\frac{E_{\rm rot}}{E_{\rm grav}}(R) = \frac{E_{\rm rot}^{(0)}}{E_{\rm grav}^{(0)}}\,\frac{R_0}{R}\,, \tag{6}$$

where quantities with indices "0" are just before the beginning of shrinking. From Eq. (6) we can see that the ratio $E_{\rm rot}/E_{\rm grav}$ grows as $\sim R^{-1}$. From this simple consideration one can infer the existence of the critical radius for which every stability limit will be exceeded. This implies impossibility of too big a shrinking even for a moderately fast rotating body. The process of shrinking will be stopped by the body breakup or another catastrophe.

During the collapse of the core its radius, $R$, is decreasing very fast. As we mentioned, in calculations of [24] the iron cores with $E_{\rm rot}/E_{\rm grav} = 0.01\ldots0.04$ and with the initial radii $R_0 \approx 2000\,$km are found. The final radius is $R \approx 10\,$km — a typical value of the neutron star radius. Actually, just after the collapse the radius of a newborn protoneutron star is $R \approx 60\,$km, and after about one second it shrinks to $\approx 20\,$km. Finally, after tens of seconds the radius sets at $R \approx 10\,$km as a result of deleptonization. The dynamical instability limit of 0.27 for Maclaurin spheroid is exceeded if the Fe core radius shrinks to $80\ldots300\,$km, respectively, for the initial ratio $E_{\rm rot}/E_{\rm grav} = 0.01\ldots0.04$. This indicates the possibility of a violent hydrodynamical instability. Because the shock front is born at approximately the same radius and at the same time, only very detailed dynamical simulations can give the actual behavior of the collapsing core.

Recently, results of full three-dimensional simulations with no symmetry of the collapsing core assumed have been published [28]. In this paper a simplified equation of state and initial models of [25] were used. This work focused on the gravitational radiation emission from the core. The core gets rid of the extra angular momentum in the form of the spiral arms or a small "satellite" as can be seen (see footnote 7 for WWW address) in the results of Rampp [28]. Possible future detections of gravitational waves correlated with SN explosions by the next generation detectors (LISA, LIGO) would be an ultimate proof of the strongly asymmetric processes in the supernova engine.

Detailed numerical calculations of the supernova explosion with inclusion of the neutrino processes have been reported in [29, 30] for an axisymmetric case with the equatorial symmetry assumed. However, the obtained results are rather ambiguous (see next section).

## 5. Rotation and extended classification scheme

In previous sections we have discussed some problems encountered when one attempts to include rotation in the core-collapse supernova theory. A question thus arises is such an extension of the theory necessary from the observational point of view? The answer is definitively affirmative. Presently available astronomical data relevant to the supernova phenomenon suggest strong non-sphericity of the explosion. The most important pieces of evidence include velocities of pulsars sometimes correlated with an apparent deformation of remnants and the asymmetry of explosion deduced from the measured polarization. Also, some events appear to be superluminous under assumption of the spherical symmetry. Finally, the very recent identification of the supernova component in the light curve of GRB011121 provides a compelling argument in favor of the core rotation as discussed below.

Let us explain how the core rotation can account for the those features of the data that cannot be understood in the standard supernova scenario.

Pulsars have much higher velocities than the average velocity of stars in the disk of the Galaxy. The highest observed speed exceeds 2300 km/s [31]. The observed pulsar speed [32] is generally a sum of two components:

- a "kick" imparted to the nascent neutron star during the supernova explosion
- an inherited velocity due to progenitor revolution in a binary system — when SN occurs in a binary (what happens quite often, probably most SN are in binaries).

If the explosion disrupts a binary system we can see a runaway pulsar. The existence of binary pulsars tells us that some of the systems survive two SN events. This also generally requires some momentum transfer to reduce the orbital velocity because of dramatic mass loss during the explosion. The velocity component due to the pulsar's birth in a binary system can be subtracted statistically from the distribution of pulsar velocities. We then obtain the distribution of kick velocities directly related to the SN explosion (Fig. 3). These velocities are still large enough to challenge the results of spherically symmetric supernova models. Proposed explanations of such large kicks include [34]:

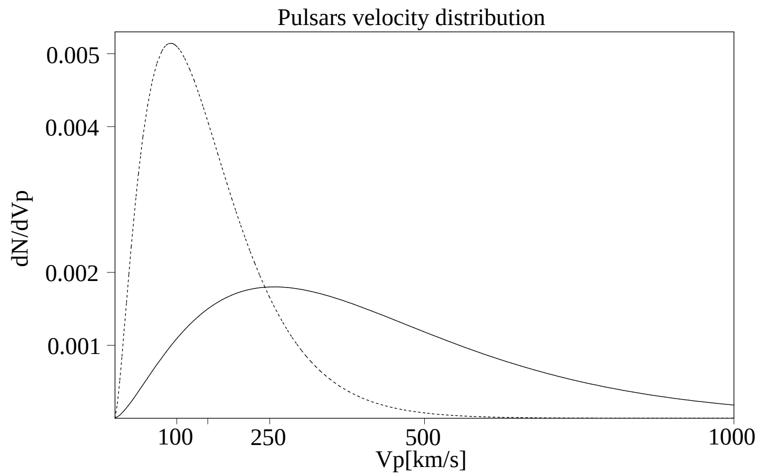


Fig. 3. Distributions of pulsar velocities. The solid line corresponds to the observed velocities and the dashed line to natal velocities obtained by subtracting binary effects. Both solid and dashed curves are described by a $\chi^2$-like distribution, $f(v_p) = a\, v_p^{3/2}\, \exp(-v_p/b)$, adopted from [32] with $a = 1.96 \times 10^{-6}$ , $b = 514/3$ and $a = 2.7 \times 10^{-5}$ , $b = 60$, respectively.

- hydrodynamically driven kicks (fluctuations in *a non-rotating core collapse*)
- asymmetric neutrino emission
- electromagnetic post-natal "rocket effect".

All these models disregard any dynamically significant rotation. As a kinematical effect, the rotation adds some stochastic component to such processes as the convective motion or the neutrino emission.

Although kicks in rapidly rotating supernova models which lead to non-axisymmetric deformations have not been studied systematically, the asymmetric disruption of a rapidly rotating core can be seen in some calculations. Results presented in [28] show how a non-zero component of the velocity perpendicular to the rotation axis arises in simulations of a formation of PNS[7].

It is in principle possible to distinguish between kicks produced with a different amount of rotation if the relative orientation of the spin and the direction of motion is known. When the rotation is slow with respect to the kick mechanism there is no correlation between the rotation axis and the kick direction. When the rotation is dynamically unimportant but faster than the

[7] `http://www.mpa-garching.mpg.de/~wfk/MOVIES/`

kick mechanism, the angular averaging effect leads to the parallel orientation. For very fast rotation, leading to the asymmetric disruption of the core, we expect the rotation axis to be perpendicular to the momentum. In all three cases the relative orientation of the current velocity vector and the rotation axis can be found. The analysis of the binary neutron star system B1913+16 [33] gives the result that the angle between the kick direction and the orbital plane is less than $5°$–$10°$. If the orbital momentum and the spin were aligned before the explosion, as it was assumed in the cited article, we would get an almost perpendicular orientation of the kick and the PNS rotation axis. The study of Vela and Crab pulsars [34] based on observed jets shows an apparent alignment on the sky of the velocity and the rotation axis.

Statistical analysis of other 28 pulsars shows no correlation between their motion and rotation [35]. Uncertainty of these results is due to difficulties in the analysis itself, simplifying assumptions and poor quality of the data. We only note that perpendicularity of the rotation axis to the kick direction, favored by the asymmetrical disruption of a rapidly rotating core in the SN explosion, is not disproved from the observational point of view.

We also note that the fast rotation of pulsars is a strong evidence in favor of a huge angular momentum of the central part of exploding star. Rotation of the neutron star is the immediate consequence of the presupernova core rotation. There is no need to invoke any other mechanism, such as *e.g.* an off-center kick, to account for fast rotation of pulsars, in contrast to stellar models with very slow rotation of the presupernova core.

### *5.1. GRB–SN connection*

Next argument in favor of strong rotation in supernovae comes from observations of superluminous events like SN1998bw — well known from its controversial coincidence with the gamma ray-burst GRB980425. Spectral analysis classified it as type Ic, but the absolute magnitude was close to that of type Ia [36, 37]. A spherically symmetric modeling has given an enormous explosion energy of 20–50 foe, the ejected mass in the range 12–15 $M_{\odot}$ and the radioactive nickel amount as big as $0.5$–$0.8 M_{\odot}$ [38]. Listed values are considered impossible in the standard supernova scenario. That is why these events are often called hypernovae[8]. As it has been shown in [39] observed results could be well understood if the prolate asymmetry of the expansion, with the axis ratio 2:1, is assumed. We note, that the prolate expansion velocity produces oblate iso-density contours. This requires the standard explosion energy of 2 foe if observed $60°$ above the plane of symmetry. The ejected mass and the $^{56}$Ni amount are $2 M_{\odot}$ and $0.2 M_{\odot}$, respectively —

[8] This in not a hypernova in the sense of the theoretical GRB models, but the possibility of a real connection between the two is not excluded and is a topic of current research.

typical values for a luminous core-collapse supernova. Polarization of light, which is more directly related to the asymmetry of expansion, is often present during hypernova events, again indicating a non-spherical explosion. Analysis of this sort, based on the rescaling of a spherical model tells us nothing about physical processes responsible for the asymmetry, but the rotation of the collapsing core is one of the most probable reasons.

Very recently, observations of a SN event in the light curve of GRB011121, have been reported [40]. Joint campaign of optical and X-ray observations, also from space, succeeded to firmly establish the presence of a supernova in the GRB011121 place, when the afterglow has declined. The supernova is of type Ic. Collected observations of GRB011121 fit nicely to the collapsar model of MacFadyen and Woosley [41]. In this model, rotation of the progenitor's core plays a crucial role and the rotation axis determines the direction of jets which produce observed gamma rays. Despite the formation of a black hole from the collapsing core, matter rich in $^{56}$Ni is expelled along the rotation axis and its emission forms a typical supernova light curve [41].

### *5.2. Including rotation into the classification scheme*

We feel encouraged by the above analysis to unify the phenomena of supernovae, hypernovae and some GRBs in a two-dimensional classification scheme which will expand that shown in Fig. 1. As a second dimension we include some measure of rotation of the progenitor's core (*e.g.* its angular momentum). We conjecture that classical supernovae correspond to some relatively low amount of angular momentum, which is just enough to produce a neutron star with proper natal momentum. Here we assume that the explosion itself may be treated as a strong argument in favor of a sufficiently high rotation of the presupernova core. The simulations have shown the failure of the idea of explosion by the prompt mechanism. The delayed mechanism improved the situation but it is not clear at all if it really works. Indeed, some of the models still fail to produce SN events in spite of inclusion of the neutrino processes.

When the core angular momentum is bigger one expects that some part of the collapsing core is locked for a while in a sort of "fizzler" and is accreted back onto the inner part. Depending on the falling back mass, a neutron star can form, or further collapse to black hole can proceed. As the fizzlers possess large angular momentum, very fast rotating neutron stars can form, if the accreted mass does not exceed some fraction of the solar mass. In case this mass is much higher, of a couple of solar masses (as in numerical simulations happens for heavier iron cores formed in massive helium stars of say 10 solar masses), a Kerr black hole finally forms. A transient accretion disk feeds the angular momentum to the black hole and cools by emitting strong neutrino flux. One can conjecture, that hypernovae and GRBs are "fireworks" corresponding to such a core collapse. Positions of various phenomena in the two-dimensional classification scheme are shown in Fig. 4.

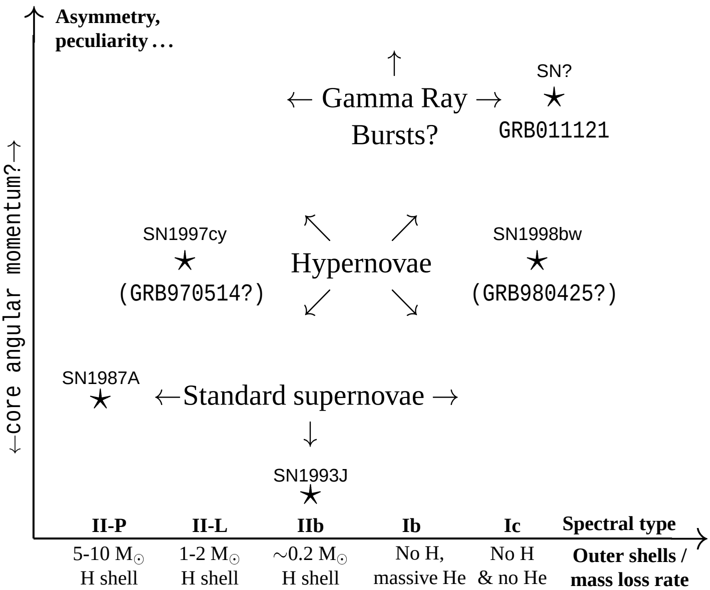


Fig. 4. Two-dimensional classification of supernovae and some GRB events. The vertical axis represents a property which can serve as a measure of the core angular momentum.

### *5.3. Discussion*

If simulations of the rotating supernova fail in the sense that the energy of radiation and ejecta is similar to that obtained in the simulations without rotation which give a sufficient explosion power, we should accept standard scenario. In the opposite situation we have an indirect argument in favor of including the rotation of the Fe core. The reasoning presented above holds provided the results of simulations of such a complex problem as the supernova engine are reliable. One should notice that some serious difficulties are reflected in the published results of simulations with rotation. Yamada and Sato [30] found stronger explosion but recently Fryer and Heger [29] obtained decrease of explosion energy.

Finally we note that the evidence of strong asphericity in supernova explosions is being established now. Besides the arguments mentioned in the previous section, some very suggestive images of supernova remnants are available. One of them is Puppis A with the asymmetry apparently correlated with the movement of a young neutron star [42]. Pictures like this are very suggestive and tell us that pulsar kicks are natal and produced by the supernova engine. A lot of processes may be responsible for this, however rotation is the most common feature of astrophysical objects and it is reasonable to examine its possible effects first. The knowledge relevant to a wide range of problems related to rotation, such as the initial pre-collapse state and the behavior of the contracting core which exceeds the rotation stability limits, is still unsatisfactory. Advances in the supernova rotation research will hopefully lead to a better understanding of many problems of supernova physics, such as the mechanism of pulsar kicks, the GRB-SN connection, the emission of gravitational waves and the formation of Kerr black holes.

The authors are grateful to W.J. Świątecki for critical reading of the manuscript and for claryfing discussions on stability of Jacobi ellipsoids [43].

## REFERENCES

[1] V. Trimble, *Rev. Mod. Phys.* **54**, 1163 (1982).

[2] K.W. Weiler, R.A. Sramek, *Annu. Rev. Astron. Astrophys.* **26**, 295 (1988).

[3] R. Minkowski, *PASP* **53**, 224 (1941).

[4] L.D. Landau, *Sov. Phys. JETP* **8**, 70 (1958); L.D. Landau, *Sov. Phys. JETP* **3**, 920 (1956); L.D. Landau, *Sov. Phys. JETP* **5**, 101 (1957).

[5] W. Baade, F. Zwicky *Proc. Natl. Acad. Sci. USA* **20**, 254 (1934).

[6] W.A. Fowler, F. Hoyle, *Astrophys. J. Suppl.* **9**, 201 (1964).

[7] F. Hoyle, W.A. Fowler, *Astrophys. J.* **132**, 565 (1960).

[8] M.M. Phillips *Astrophys. J.* **413**, L105 (1993).

[9] B. Leibundgut *Astron. Astrophys. Rev.* **10**, 179 (2000).

[10] E. Cappellaro, M. Turato, *Astrophys. Space Sci. Libr.* **264**, 321 (2000).

[11] A.V. Filippenko, A.J. Barth, T. Matheson, *et al.*, *Astrophys. J. Lett.* **450**, L11 (1995).

[12] A. Chieffi, M. Limongi, O. Straniero, *Astrophys. J.* **502**, 737 (1998).

[13] H.A. Bethe, *Rev. Mod. Phys.* **62**, 511 (1990).

[14] A. Burrows, J. Hayes, B.A. Fryxell, *Astrophys. J.* **450**, 830 (1995).

[15] W. Keil, H.-Th. Janka, E. Müller, *Astrophys. J.* **473**, L111 (1996).

[16] H.-Th. Janka, *Astron. Astrophys.* **368**, 527 (2001).

[17] K. Kifonidis, T. Plewa, H.-Th. Janka, E. Müller, in Procedings of the 10-th Workshop on Nuclear Astrophysics, ed. W. Hillebrandt, E. Müller, held at Rinberg Castle, Tegernsee, Germany, March 20–25, 2000.

[18] K. Kifonidis, T. Plewa, H.-Th. Janka, E. Müller, in Procedings of the 10-th Workshop on Astronomy with Radioactivities, ed. R. Diehl, held at Rinberg Castle, Tegernsee, Germany, 29 Sep–2 Oct, 1999.

[19] S. Cohen, F. Plasil, W.J. Swiatecki, *Ann. Phys.* **82**, 557 (1974).

[20] J.N. Imamura, R.H. Durisen, *Astrophys. J.* **549**, 1062 (2001).

[21] J.N. Centrella, K.C.B. New, L.L. Lowe, J.D. Brown, *Astrophys. J.* **550**, L193 (2001).

[22] I. Fukuda, *PASP* **94**, 271 (April 1982).

[23] F. Carrier *et al.*, *Astron. Astrophys.* **378**, 142 (2001).

[24] A. Heger, N. Langer, S.E. Woosley, *Astrophys. J.* **528**, 36 (2000).

[25] T. Zwerger, E. Müller, *Astron. Astrophys.* **320**, 209 (1997).

[26] Y. Eriguchi, E. Müller, *Astron. Astrophys.* **147**, 161 (1985).

[27] I. Hachisu, *Astrophys. J. Suppl. Ser.* **61**, 479 (1986).

[28] M. Rampp, E. Müller, M. Ruffert, *Astron. Astrophys.* **332**, 969 (1998).

[29] C.L. Fryer, A. Heger, *Astrophys. J.* **541**, 1033 (2000).

[30] S. Yamada, K. Sato, *Astrophys. J.* **450**, 245 (1995).

[31] N.K. Glendening, *Compact Stars*, Springer-Verlag New York Inc. 1997, p. 123.

[32] D. Vanbeveren, C. De Loore, W. Van Rensbergen, *Astron. Astrophys. Rev.* **9**, 63 (1998).

[33] N. Wex, V. Kalogera, M. Kramer, *Astrophys. J.* **528**, 401 (2000).

[34] D. Lai, D.F. Chernoff, J.M. Cordes, *Astrophys. J.* **549**, 1111 (2001).

[35] A.A. Deshpande, R. Ramachandran, V. Radhakrishnan, *Astron. Astrophys.*, **351**, 195 (1999).

[36] S.R. Kulkarni *et al.*, *Nature* **395**, 663 (1998).

[37] T.J. Galama, *Nature* **395**, 670 (1998).

[38] K. Iwamoto *et al.*, *Nature* **395**, 672 (1998).

[39] P. Holfich, J.C. Wheeler, L. Wang, *Astrophys. J.* **521**, 179 (1998).

[40] J.S. Bloom, S.R. Kulkarni, P.A. Price, *et al.*, *Astrophys. J. Lett.* **572**, L45 (2002).

[41] A. MacFadyen, S.E. Woosley, *Astrophys. J.* **524**, 262 (1999).

[42] R. Petre, C.M. Becker, P.F. Winkler *Astrophys. J. Lett.* **465**, L43 (1996).

[43] W.J.Świątecki, Lawrence Berkeley Laboratory report, LBL-3363, 1974.