

# GRAVITATIONAL COLLAPSE OF STARS AND THE METHODS OF ITS OBSERVATIONS

V.G. Kryvdyk

Faculty of Physics, Taras Shevchenko National University of Kyiv,  
Kyiv, Ukraine, *kryvdyk@gmail.com*

**ABSTRACT.** It is present a review of the models of the later stages of stellar evolution and the mechanisms of the generation of neutrinos, charged particles and electromagnetic radiation during the gravitational collapse of stars. The conclusion was made that the most likely method for the registration of the gravitational collapse of stars is the registration of the nonthermal electromagnetic radiation generating in the magnetospheres of stars during theirs gravitational collapse.

**Key words:** stellar evolution, radiation during collapse of stars, observation of stellar collapse, magnetospheres of collapsing stars

## 1. Models of stellar evolution

The evolutionary track of the star depends on its mass, chemical composition, magnetic field, as well as the presence or absence of the close neighboring stars. The evolution of single star significantly differs from the evolution of a star in the close binary system because in these systems of mass exchange is possible between components of the system. First, we consider the evolution of a single star. Theoretical study show that during the stellar evolution in core will be gradual burnout more and more heavy elements ( $He^4, C^{12}, O^{16}, Ne^{20}, Si^{32}$ ). Depending on its mass, the star can evolve into one of the three objects such as the white dwarf, neutron star or black hole (Zeldovich and Novikov, 1977; Shapiro and Teukolsky, 1985; Arnett, 1979; Baiotti et al., 2008; Baumgarte and Shapiro, 2003; Bisnovatyi-Kogan, 2002; Ghezzi, 2005; Limongi and Chieffi, 2003; Liu et al., 2007; Shapiro, 2003; Shibata et al., 2006; Smartt, 2009; Stephens et al., 2007; Stephens et al., 2008).

White dwarfs formed because of the evolution of stars with initial masses  $M < M_{\odot}$ . (Zeldovich and Novikov, 1977; Shapiro and Teukolsky, 1985; Iben and Tutukov, 1985; Wickramasinghe et al, 2009). These objects have radius  $R = 0.1R_{\odot}$ , masses  $M < 1.3M_{\odot}$  and average density  $\rho \approx 10^7 g/m^{-3}$ , the internal pres-

sure which is supported by the degenerate electron gas (here  $M_{\odot}$  and  $R_{\odot}$  is the mass and radius of Sun). Magnetic field of the white dwarf reaches a magnitude  $B \sim 10^8 Gs$ . Calculations also show that the temperature inside the white dwarfs not exceeding the value  $T \approx 8 \cdot 10^8 K$ , by which begins burnout more heavy than carbon elements. Depending on the initial chemical composition of the cores, the massive white dwarfs may consist mostly with CO or ON. The formation of white dwarfs may be accompanied the ejection of a part stellar mass, which will be observed in the form of planetary nebulae.

By the evolution of more massive stars ( $M > 8M_{\odot}$ ) on the final stages can be realized one with the following two scenarios. The first scenario realized when inside stars will burnout carbon  $C^{12} + C^{12} \rightarrow Mg^{24}$ . The later evolution can be in three ways 1) a bubbling inside the nucleus and its compression 2) the explosion and scattering of core, 3) a quick nuclear burnout, in which the future evolution of the stars in the currently is not evaluate. The second scenario will realized when the star loses mass, and by means of the pulsating processes star go to white dwarf. The even more massive stars ( $8 < M/M_{\odot} < 25$ ) formed neutron stars or black holes (Cherepashchuk, 2003; Shapiro and Teukolsky, 1985; Baiotti et al., 2005; Baumgarte and Shapiro, 2003; Ghezzi, 2005; Limongi and Chieffi, 2003; Liu et al., 2007; Noble and Chop-tuik, 2008; Onken et al., 2004; Shapiro, 2003; Shibata, 2003; Shibata et al., 2006; Stephens et al., 2008). In cores these stars to go the gradual burnout elements ( $He^4, C^{12}, O^{16}, Ne^{20}, Si^{32}$ ). This process continues  $10^7$  years and ends with the formation of the objects, the central core that consist mainly with nucleus Fe (nuclei with maximum energy on nucleon). Almost all calculations, regardless of the details, give similar results, indicating that the massive stars at the final stages of their evolution formed core with mass  $M \approx 1.5M_{\odot}$  pressure which is supported by the degenerate neutron gas. This phenomenon is explain that due to a large temperature gradient in the core arise convectional flows, which will knead core and the tem-

perature in it become even (Arnett,1979). While the core becomes more-or-less homogeneous chemical composition. After the burnout of the silicon core the star approach to the stage of dynamic instability that leads to a gravitational collapse. It is associated with two physical processes: 1) the photodissociation of iron nuclei ( $Fe + \gamma \rightarrow 13\alpha + 4n$ ) and the neutronization of core due to of the electrons capture by protons of kernels ( $e^- + (Z, A) \rightarrow (Z-1, A) + \nu_e$ ;  $e^- + p \rightarrow \nu_e + n$ ). Because of these processes the pressure in core fall, leading to his collapse. So begins the gravitational collapse. Calculations show that on some stages collapse go homologous, i.e. its speed varies almost linearly with radius, and the instantaneous density profiles in different moments of time are similar in form, although the density grow (Goldreich and Weber, 1980). The collapse go very quickly and continues as long as the density in the heart core reaches the magnitude  $\rho_n \approx 2.8 \cdot 10^{14} g/m^3$ . If the density in sometimes exceeds this value, the pressure in the core is growing so much that the collapse come to a stop. Inner part of core "bounces" from the Center, while its outer part continues to fall on the center. As a result, a shock wave arises, which spreads out. A characteristic energy of this shock wave is several times greater than  $10^{51} Erg$ . Coming out, it can change the direction of movement of a substance to the opposite, and the part of stellar matter can come off from star. We will observe this phenomenon how supernova explosion. Because of the supernovae explosion will formed neutron star, which can observed as pulsars. Neutron stars are objects with very small radius (10-20 km) and extremely strong magnetic fields ( $10^{12} - 10^{14} Gs$ ). The core of neutron stars consists with of the degenerate neutron, which support the pressure in core. Is it always going to the stars explosion? The answer is ambiguous and is the subject of research. It all depends on whether the energy losses by the shock wave (radiation, neutrinos and the atomic nuclei dissipation) are compensated the kinetic energy inflow of the falling matter and diffusion neutrino up front shock wave (Shapiro and Teukolsky, 1985). Some authors (Henriksen et al., 1979), based on detailed hydrodynamic calculations collapse, conclude about small efficiency of shock wave in supernova explosion. Therefore, the question of whether all the stars evolve from throwing much of their mass is not clean. If a star with mass  $M > 10M_{\odot}$  evolves without exploding and discharge of the mass, on the final stage of evolution such a star forms a black hole. Even more massive stars (with  $(25 - 30) < M/M_{\odot} < 150$ ) collapsed to black holes.

So far, we have considered the evolution model of the isolated, single stars. A somewhat different path evolving stars in close binary systems with the accretion of matter in compact objects (white dwarfs or neutron stars). In such systems the mass compact objects can significantly increase during a short time, and their

evolution will be greatly different from the evolution of single objects of the same class (Baiotti et al, 2008). For example, the mass of white dwarfs in binary systems can increase as a result of accretion, and they can collapse to neutron stars (so-called induced collapse). (Cheng et al., 2009; Dermer and Atoyan, 2006; Dessart et al., 2007; Kiuchi et al., 2009; Nomoto and Kondo,1992; Nomoto and Kondo,1991; Van Paradijs J. et al., 1997; Wickramasinghe et al., 2009; Woosley and Baron, 1992; Woosley S.E. et al., 1992). Binary systems with massive stars ( $M \geq (8-10)M_{\odot}$ ) on the final stages of their thermonuclear evolution will be formed neutron star or black holes. In Fig. 1 shows an evolutionary scenario of the formation neutron stars and black holes in close binary systems with massive stars (Postnov and Yungelson, 2006).

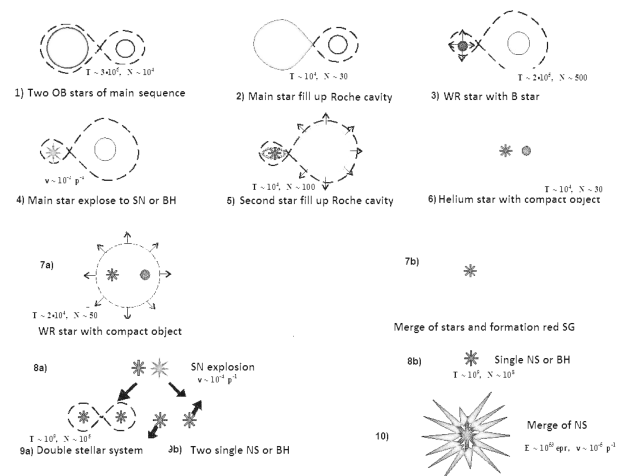


Figure 1: An evolutionary scenario of the formation neutron stars and black holes in close binary systems with massive stars (Postnov and Yungelson, 2006)

We consider in more detail the stages of evolution of stars in close binary systems.

Stages 1-2. In the initial stages two massive OB star's main sequence do not interact and are inside their cavities Roche. Due to centrifugal forces, a more massive star fills the Roche shell. Duration of this stage of evolution for the massive stars in the main sequence is a few million years. The number of stars in the Galaxy that can evolve this way, there are about 10 thousand. Stages 2-3. After hydrogen burnout in the kernel of double-star system, the more massive stars coming off from the main sequence and it rapidly expand. When the radius approaches to cavities Roche, its mass will transfer to the second, less massive star, which is still in the main sequence. Mass transfer from the more massive star is going to as long as the majority of hydrogen the stars transfer to the less massive star, in consequence of more massive stars can rest only helium core. This core has be observed as Wolf-Rayet

stars with mass  $(7-8)M_{\odot}$  and the intense stellar wind. The second double-star system has been observed as Be star main sequence with fast rotation. Duration of this evolution stage is about  $10^4$  years.

Stages 4-5. Wolf-Rayet stars evolve quite quickly (about  $2 \cdot 10^4$  years) due to the strong stellar wind, and at the end of their thermonuclear evolution they explode as supernovas Ib (or Ic) with the formation of the neutron star or black hole. If during the supernova explosion will be eject more than half of the original mass of the double system, then the double system can destroy, and after OB evolve as separate. If the double system is not destroyed during by supernova explosion, then the double system will consist with a young neutron star and Be star with rapid rotation. It is assumed that in this way formed the majority of double systems, observed as double Be x-ray systems. Duration of this stage collapse is determined by the duration of the burning of hydrogen in Be star and is approximately  $10^4$  years.

Stage 6. After that comes the so-called stage of evolution in the mutual shell, when Be star loses mass as a result of a powerful stellar wind, filling his matter of all the double system, exposing the helium core and the forming Wolf-Rayet stars. The system consists with two compact objects- neutron stars and Wolf-Rayet star, on which to occur the accretion of matter shell.

Stages 7-10. Further, the dual system can evolve according to two scenarios: a) or b). Scenario a). If in consequence of the mass accretion the Wolf-Rayet star core rise to quantities, sufficient for the collapse and explosion of the star as a supernova Ib, then the dual system will consist with two relativistic objects (neutron stars or black holes). Neutron star can also collapsed to black holes, if its mass will increase because of the accretion to a mass of Chandrasekhara. Thus formed the system of two relativistic stars. Because of the merger of stars, which will be accompanied the intense gravity and electromagnetic radiation, can form a black hole (scenario 7a-10). Second scenario b) for the evolution of the double system will be realized when Wolf-Rayet star not exploding as the supernovae, and merge of the components of the dual system is in the earlier stages of evolution. As a result of this merger arise red supergiant with core in form a neutron star or black hole (objects Torn-Zitkova). When the supergiant lost its shell due to accretion, on the site of a double system is formed a single neutron star or black star.

Stars with the low mass in the compact binary systems evolve in different way (Abdikamalov et al, 2009; Baiotti et al., 2008). If the initial system consists with the two stars of the main sequence, the mass of which does not exceed  $(2-2,5)M_{\odot}$ , then by the evolution of a more massive star fills the entire shell Roche, and a helium white dwarf will form. The stars with mass

$M > (2-2,5)M_{\odot}$  form the system with CO white dwarf. As a result of the accretion, mass of white dwarf can grow to the value, when it can collapsed and explode as a supernova (Fedorova et al., 2004; Hachisu and Kato, 2001; Han and Podsiadlowski, 2006; Han and Podsiadlowski, 2004; Lesaffre et al., 2006; Li and Heuvel, 1997; Yungelson and Livio, 1998). Thus, on the final stages of the stellar evolution in a binary stars system will form the various configurations of close binary systems, such as systems with white dwarf, neutron stars and black holes. These objects have a small size, a large density and the nonstationary strong magnetic fields. By such conditions, charged particles will accelerate, and they will generate of the electromagnetic radiation. Therefore, such systems are sources of the powerful electromagnetic radiation and cosmic rays.

## 2. Generation of high-energy particles in the magnetosphere of collapsing stars

In this section, we consider the mechanisms of the generation of high-energy particles in magnetosphere of collapsing stars. First in the magnetosphere will accelerate the initial protons and electrons due to the interaction with the magnetic field. These particles will lose its energy on the ionization and radiation. Interacting between themselves and the fields, these particles in later on will be generated secondary particles, such as electrons, protons, neutrons, mesons, neutrinos, antineutrinos and gamma photons. Because of these multiple interactions will be generated particles with which to consist the magnetosphere of collapsing star on the later stages of collapse. There are many the mechanisms of the particles generation during of stellar collapse (Leng, 1984; Bahcall and Wolf, 1965; Braaten and Segel, 1993; Bruenn, 1985; Canuto et al., 1970; Chiu, 1961; Chiu and Morrison, 1960; Chiu and Stabler, 1961; Dicus, 1972; Friman and Maxwell, 1979; Hansen, 1968; Itoh et al., 1989; Koers and Wijers, 2005; Lattimer et. al., 1991; Munakata et al., 1985; Qian and Woosley, 1996; Ratkovic S. et al., 2003; Reynoso et al., 2006; Yakovlev et al., 2001).

In author articles (Kryvdyk, 2014a; Kryvdyk, 2014b) was considered possible mechanisms of generation of high-energy particles and the nonthermal electromagnetic radiation in a magnetosphere of collapsing star, namely:

1. The formation of pi-mesons, mu-mesons, electrons, neutrinos and positrons by nuclear interactions in a magnetosphere of collapsing star.
2. The formation of electron-positron pair by interaction of gamma rays with nuclear.
3. The formation of electron-positron pair by a collision of charged particles.
4. The formation of electron-positron pair by a colli-

sion the two photons.

5. The formation of mu-mesons pairs by interaction of gamma rays with nuclear.
6. The formation of electron impact by a collision of charged particles.
7. The formation of neutrino in the magnetosphere of collapsing stars.

Because of these processes in the magnetosphere of collapsing star will generate neutrinos, photons, neutrons and charged particles, which, by interacting with the magnetospheric magnetic field, will in turn generate the nonthermal electromagnetic radiation.

### 3. Electromagnetic radiation of stars on the final stages of their evolution

In the previous sections, we have reviewed models of the evolution of the various types stars and the generation of particles and photons in their magnetospheres during the gravitational collapse. As you can see, stars undergo several stages of evolution, depending on their mass, chemical composition and the presence or absence of a close companion. One of these stages is the gravitational collapse of star, which begins when star loses its energy reserves and begin compress under their gravitational field. Depending on the mass of the core, star can collapse to one with the three objects, such as the white dwarf, neutron star or black hole. As follows from the theoretical calculations, during the gravitational collapse of stars the gravitational and electromagnetic radiation will generate. (Kryvdyk, 1998; Kryvdyk, 2008; Kryvdyk, 2009; Kryvdyk, 2010; Chau, and Zhang, 1992; Gunningam et al., 1978; Gunningam et al., 1979; Gunningam et al., 1980; Hanami, 1997; Henricson et al., 1979; MacFadyen and Woosley, 1999; Mitsuda et al., 2005; Moncrief, 1980; Morley and Schmidt, 2002; Paranjape and Padmanabhan, 2009; Ruffini et al., 2005a; Ruffini et al., 2005b; Ruffini et al., 2007; Ruffini et al., 2003; Shibata and Taniguchi, 2006; Uzdensky, 2007), (Kryvdyk, 2014a; Kryvdyk, 2014b; Anchordoqui, 2009; Becker and Biermann, 2009; Blinnikov et al., 1988; Dutta et al., 2000a; Dutta et al., 2000b; Lu and Qian, 2007; Nakazato et al., 2007; Ryazhskaya, 2006; Vigorito et al., 2008; Yu et al., 2008).

The gravitational radiation, theoretically predictable by the collapse of stars, currently not registered. As regards the registration of electromagnetic radiation, the numerical calculations indicate that the collapsing star can be sources of the short giant x-ray and gamma-ray bursts observed on space-based telescopes. The only one case of the registration of neutrino was detected from supernovae SN 1978A (Alekseev et al., 1987; Davydkin et al., 1987; Bionta et al., 1987; Hirata et al., 1987).

In articles (Gunningam et al., 1978; Gunningam et

al., 1979; Gunningam et al., 1980; Moncrief, 1980), based on the numerical calculation of wave equations, was obtained spectra and energy for gravitational and electromagnetic radiation, generating during the relativistic collapse of stars with magnetic fields. As follows from these calculations, the radiation does not depend on the dynamics of collapse inside star. The dipole radiation from the collapsing uniform spheroid with a constant rotation was calculated in work (Henricson et al., 1979). It is shown, that during the collapse of the object with a mass of  $1.4M_{\odot}$ , the initial density of  $10^8 g/cm^{-3}$  and a magnetic field  $10^8 Gs$  to black hole energy dipole radiation is about  $2.4 \cdot 10^{40} Erg/sec$ . However, the frequency of this radiation 1 kHz is very low, and it can not be registered by means of modern telescopes. In paper (Ruffert and Janka, 1999) was calculated the formation of the accretional torus by merge of the two neutron stars, as a results of a compact remnant with mass  $3M_{\odot}$  formed, which then collapses into a black hole. The authors find that after a merge of neutron stars will form torus, and the neutrino was radiate with the total energy  $10^{53} Erg/sec$ . The contribution of radiation energy from the annihilation of neutrino-antineutrino in torus is  $(3 - 5)10^{50} Erg/sec$  with the duration radiation  $0.02 - 0.1 sec$ . It is show that neutrino-antineutrino annihilation by the accretion on black hole, which is formed after a merger of two neutron stars, could provide enough energy for low short periodical gamma-ray flares. In paper (MacFadyen et al., 2001) was investigated the evolution of helium stars with a mass  $M > M_{\odot}$ , in which by the collapse of an iron core are not formed enough of a powerful shock wave that can come out, but instead forms a black hole. The author's investigated the formation of the accretion disk and strong relativistic jets in polar regions. When these jets comes out through the surface of the star, the relativistic flows may experience. These flows have energy about  $10^{51} Erg/sec$ . By this the gamma-ray bursts with a duration less than a few seconds can generated. The generation of electromagnetic pulse during the stellar gravitational collapse was calculated in the article (Morley and Schmidt, 2002) as for star with the average magnitude core, in which to take place hydrodynamical rebound, and for star with massive core, which collapses to black hole. The authors show, that the two types of stars should exist, separating by the maximum permissible masses, those that collapse as a single star (with minimal dynamic mass) and those that collapse in binary systems and where possible accretion masses (with static mass of neutron stars). In article was calculated the energy of electromagnetic radiation for stellar objects with the rebound in core, which form a stable neutron star, and massive stellar objects that collapse directly into a black hole. The maximum of this radiation falls on very low frequency (wavelength is about 2 km). Such low frequency radiation will be absorbed in Earth at-

mosphere, and it not can be observed on radio telescopes. Evolution of the electromagnetic field of magnetic stars, which collapse to black holes, was resolved in the general theory of gravity in the article (Baumgarte and Shapiro, 2003). Author assumed that during collapse the mass of star has infinite conductivity and the magnetic field is dipolar. Evolution of the magnetic and electric fields was determined analytically for the matter inside the stars and numerically for external vacuum. Research has shown that during the collapse of the longitudinal magnetic field will transform into transverse electromagnetic waves. Part of the electromagnetic radiation is captured by black hole, and the rest is propagated outside on the large distance. Theoretical research with the purpose to explain gamma-ray bursts was analyzed in the works (Ruffini et al., 2005a; Ruffini et al., 2005b; Ruffini et al., 2007). Authors made conclusions that: (1) only the basic structure of gamma-ray burst is the unchanging characteristic for gamma-ray bursts and their afterglow; (2) the long periodical gamma-ray bursts are just the peaks of afterglow, and their variations can be explained because of the interstellar medium heterogeneity; (3) short bursts can be identified as the typical gamma-ray bursts, therefore the key information of the relativistic effects and the vacuum polarization is encoded in their spectrum and in the intensity variations with time. These gamma-ray bursts radiate because of processes of the vacuum polarization in dyosphere of black holes with the formation of optically thin electron-positron plasma, which is self-acceleration. Theoretical prediction of the electromagnetic radiation signal by the gravitational collapse of star core to black hole was examined in the paper (Ruffini et al., 2003). Final phase of gravitational collapse was investigated, which lead to the formation of black holes with the under critical electromagnetic field and the formation of the outgoing pulse initially fine  $e + e$  photon plasma. This impulse reaches the transparency for the Lorenz factor 102 – 104. The authors find the clear signs of the formation of the electromagnetic signal during the gravitational collapse. The collapse of neutron stars to black holes in binary systems for the explainion of short gamma-ray busts are considered in the paper (Dermer and Atoyan, 2006). It is found, that the accretion of matter with mass  $(0.1 - 1)M_{\odot}$  through Roche cavity on the neutron star from its companion or as a result of the merger of neutron stars with a white dwarf in a double system with a small mass will be sufficient to exceed the critical mass of neutron stars, and cause it to collapse to black holes, which causes the generation of short gamma-ray flashes. A two-dimensional axial-symmetric magnetohydrodynamical model of star collapse with a mass of  $40M_{\odot}$  was calculated in work (Fujimoto et al., 2006) for the explanation of collapse as a source of gamma-ray bursts. Author studied the formation of the accretionary disc arousing black

holes and the formation of jets near it. In the works (Uzdensky and MacFadyen, 2006; Uzdensky and MacFadyen, 2007) was proposed a magnetic mechanism for the collimating explosion of massive stars, which concerns the long periodical gamma-ray and x-ray bursts and asymmetric collapse the supernovae core. In this model the core of massive stars, that revolve, collapse to collapsar with black hole with the accretionary disk or millisecond magnetar. The collapse of gipermassive neutron stars as the source of short gamma-ray bursts was considered in the article (Shibata M. et al., 2005). These stars form after the merge of neutron star in double system. The authors find that gipermassive neutron star undergoes a "delayed" collapse to black holes with the rotation because of the transfer of angular moment due to magnetic braking and magneto-rotational instability. As a result, a black hole arise, surrounded a massive hot torus with collimated magnetic field. Torus fall on black hole with the quasi-constant speed  $10M_{\odot}/s$ . Lifetime this torus is 10 Ms. The temperature in torus reaches  $10^{12}K$ , which leads to the intense neutrino-antineutrino generation. This scenario of collapse is attractive for an explanation of the generation low-period giant gamma-ray bursts and accompanying their gravitational waves and neutrinos. In work (Dessart et al, 2007) made the two dimensional magnetohydrodynamical modeling for the accretion-induced collapse of a white dwarf with a mass  $1.92M_{\odot}$  with rapid rotation. Authors identified the role of MHD process after the formation of the proton-neutron star with the milisecond period, and they found that the magnetic tension could lead to a powerful blast with a energy in several Bethe and mass injection  $0.1M_{\odot}$ . Core will rotate after the rebound, and the energy of rotation that is extracted from core, turns into magnetic energy, which generates a strong magnetic collimated wind.

As you can see, for the all models of the collapse of stars is common the generation of the electromagnetic radiation pulse and the formation of relativistic jets. There are many models of the relativistic jets formation by the stellar collapse (Aloy et al., 2000; Beskin et al., 2008; Blandford and Payne 1982; Bucciantini et al., 2008; Couch et al., 2009; Fendt, 2009; Kato et al., 2004; Koide et al., 1998; Komissarov and Barkov, 2007; Kryvdyk, 2008; Kryvdyk, 2010; MacFadyen et al., 2001; Matsakos et al., 2008; Meliani et al., 2006; Mizuno, et al., 2004; Ono et al., 2009; Takiwaki et al., 2009; Uzdensky and MacFadyen, 2007; Zhang et al., 2003).

Blandford and Znajek (1977) considered the model in which the relativistic particles acceleration and jets formation going on at great distances from the black hole in a magnetized accretionary disk of a rotating black hole. Model formation of relativistic jets in the accretion plasma disk, surrounding black hole, was considered in work (Koide et al.,1998). Jets arise by the in-

jection plasma with disk, bordering upon to the black hole. These jets are the two-level structure, which consists with the fast gas jets inside arising as a result of the pressure gradient, and the slow jets in other parts of the disk, that are associated with the poloidal magnetic field of disk. The jets are formed as a result of the strong increase of pressure and the shock wave formation in the disk through the fast accretion streams.

The formation of relativistic jets during the evolution of helium stars with mass  $M > 10M_{\odot}$ , where the collapse of the iron core does not generate strong shock waves that can come out, and instead formed black hole, is considered in work (MacFadyen and Woosley, 1999). In this model relativistic jets are formed as result of the accretion in the polar regions and go outside. In article (MacFadyen et al., 2001) were analyzed MHD processes and the formation of supernova stars and high-energy transient during the collapse of massive stars with rotation. Relativistic jets in this model arise by mass accretion from the disk. The total relativistic 2.5- dimensional MHD model of the gravitational collapse of a massive magnetized star with the rotation is calculate in article (Mizuno et al., 2004). Simulation results show that during collapse formed a disk structures and the jets generated, wich formed during the rebound the shock wave from the core. These jets are accelerated by means of the magnetic pressure and centrifugal force.

#### 4. Electromagnetic radiation from magnetospheres of collapsing stars

In view of the observations of the most interesting is the high-frequency radiation, which generate in a magnetosphere of collapsing star and it little is absorbed in the areas of their generation and in interstellar medium. Such radiation can reach the Earth and can be registered with modern telescopes in various ranges of electromagnetic radiation.

In author articles (Kryvdyk, 1998; Kryvdyk, 1999; Kryvdyk, 2009; Kryvdyk, 2010, Kryvdyk, 2014a; Kryvdyk, 2014b) was studied in detail the processes of charged particles acceleration in a magnetosphere of collapsing star, and the nonthermal radiation from these particles in a magnetic field was calculated. In these articles were calculated the synchrotron radiation flows from charged particles in a external magnetic field collapsing stars, that grows during the collapse and accelerate these particles by means of the betatron mechanism. Author considered the physical conditions and the charged particles dynamics in the magnetosphere, and the Stokes parameters calculated that characterize the radiation of these particles in the magnetosphere. It is shown that in a magnetosphere of collapsing star will be generated charged particles (protons, electrons, positrons, pi-mesons), neutrons and neutrinos. Neu-

trons and neutrinos do not interact with the magnetic fields, therefore they will be free to go with the magnetosphere, bringing a significant portion of energy. As a result, the star will cool.

Charged particles (protons, electrons and positrons), moving in the variable magnetic field, will generate a powerful impulse of the nonthermal electromagnetic radiation in a wide range of frequencies, from gamma to radio frequencies. In Table 1 are give the numerical calculations of the electromagnetic radiation flow in the magnetosphere of collapsing stars, generating by mowing of charged particles with a power spectrum in magnetic fields. In Table 2 gives the value of the flow of radiation at different frequencies for  $R_* = 1000$  and  $I_{\nu_0} = 10^{-25} W/m^2 Gz$ . The value  $\nu/\nu_0 = 1$  is chosen for frequency  $\nu_0 = 10^{10} Gz$ . As follows from calculation, the radiation flow reaches the largest values at low frequencies and decrease with a frequency by law  $I_{\nu P} \sim \nu^{(1-\gamma)/2}$ . For a power particles spectrum with  $\gamma \approx 2.5$  the radiation flow depend from frequency as  $I_{\nu P} \sim \nu^{-0.7}$ . This is a typical frequency dependence for the cosmic nonthermal electromagnetic radiation of particles in the strong magnetic fields. As you can see, during the stellar collapse will generated a powerful radiation flow that can be registered by using the gamma and x-ray satellites (Kryvdyk, 2010). Such observations are extremely important, because so far we do not have the astrophysical observations, which would really confirm such the stage of evolution of stars as their gravitational collapse. Figure 2 shows the ratio between the flow of radiation  $I_{\nu P}$  at some point collapse of star with radius R and the initial electromagnetic radiation flow  $I_{\nu P0}$  stars from the original  $R_0$ . It is evident that the radiation flow increases during the collapse in the hundreds of millions of times in comparison with the original flow.

#### 5. Conclusion

If from a theoretical point of view the stage of gravitational collapse (compression) for more than half a century been extremely detailed, then from the observational point of view we still not have the direct astrophysical data that would confirm this stage of the evolution of stars. Indeed, white dwarfs and neutron stars we observe how objects that were formed after the gravitational collapse, i.e. after compression. A supernova stars observed because of the collapse of the core of a star when it is already compress to nuclear density. Therefore these events are events after the fact, i.e. that occurred as a result of compression, and they are not the direct observational evidence of gravitational compression.

In order to confirm the existence of a gravitational collapse with the help of astrophysical observations, we must register the signals in the short period of time,

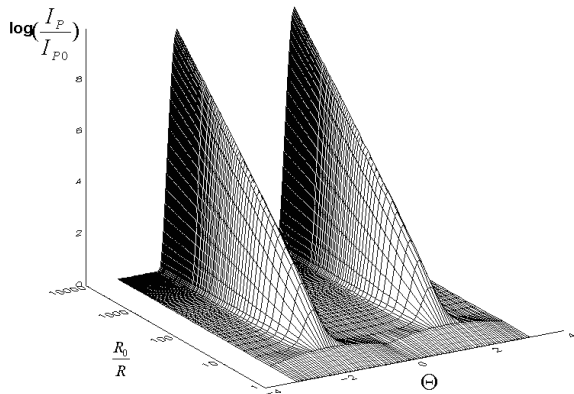


Figure 2: Pulses of nonthermal radiation from the magnetosphere of collapsing star with a power distribution of particles. Here  $I_{P0}$  is a initial radiation flow (when radius star is  $R_0$ ),  $I_P$  is the radiation flow in a particular moment of collapse (when the radius of the star decreases to value  $R$ ). (Kryvdyk, 2010)

Table 1: Flows radiation  $I_{\nu P}(W/m^2 Hz)$  for different  $R_* = R/R_0$  and various index  $\gamma$  of a particles power spectrum  $N(E) \sim E^{-\gamma}$  (Kryvdyk V, 1999)

$\gamma$	2.4	2.6	2.8
$R_*$	$I_{\nu P}$		
100	$2.57 \cdot 10^{-22}$	$2.14 \cdot 10^{-20}$	$1.81 \cdot 10^{-20}$
200	$1.37 \cdot 10^{-21}$	$1.65 \cdot 10^{-20}$	$2.00 \cdot 10^{-19}$
300	$3.72 \cdot 10^{-21}$	$5.52 \cdot 10^{-20}$	$8.31 \cdot 10^{-19}$
400	$7.57 \cdot 10^{-21}$	$1.31 \cdot 10^{-20}$	$2.29 \cdot 10^{-18}$
500	$1.32 \cdot 10^{-20}$	$2.56 \cdot 10^{-20}$	$5.05 \cdot 10^{-18}$
600	$2.08 \cdot 10^{-20}$	$4.45 \cdot 10^{-19}$	$9.66 \cdot 10^{-18}$
700	$3.05 \cdot 10^{-20}$	$7.09 \cdot 10^{-19}$	$1.67 \cdot 10^{-17}$
800	$4.27 \cdot 10^{-20}$	$1.06 \cdot 10^{-18}$	$2.69 \cdot 10^{-17}$
900	$5.74 \cdot 10^{-20}$	$1.52 \cdot 10^{-18}$	$4.09 \cdot 10^{-17}$
1000	$7.48 \cdot 10^{-20}$	$2.10 \cdot 10^{-18}$	$5.96 \cdot 10^{-17}$

when the star compress by its own gravitational field. These signals can be: 1) gravitational waves that will generate by collapse; 2) neutrino; 3) electromagnetic radiation that will generate by collapse. Registration of gravitational waves today is quite problematic issue, because this method of observation of gravitational collapse is the question of the future. Registration of neutrinos flow from space with sufficient space and time accuracy is also a problem in the future. Therefore the most likely and reliable method of the observation of the stars on the stage of its gravitational compression gives us the observation of electromagnetic radiation, that is generated during its gravitational collapse.

As we can see from Fig.1 and Table 1 and Table 2, during the collapse in the magnetosphere of collapsing stars a powerful pulses the nonthermal electromag-

Table 2: Values  $I_{\nu P}$  for different frequency  $\nu/\nu_0$  and different index  $\gamma$  for a particles with a power spectrum  $N(E) \sim E^{-\gamma}$ . Here  $\nu_0 = 10^{10} Gz$ . (Kryvdyk, 1999).

$\gamma$	2.4	2.6	2.8
$\log(\nu/\nu_0)$	$I_{\nu P}$		
-4	$4.72 \cdot 10^{-20}$	$3.32 \cdot 10^{-20}$	$2.37 \cdot 10^{-20}$
-2	$1.88 \cdot 10^{-20}$	$8.35 \cdot 10^{-20}$	$3.76 \cdot 10^{-20}$
0	$7.48 \cdot 10^{-20}$	$2.10 \cdot 10^{-20}$	$5.96 \cdot 10^{-20}$
2	$2.98 \cdot 10^{-20}$	$5.27 \cdot 10^{-20}$	$9.45 \cdot 10^{-20}$
4	$1.19 \cdot 10^{-20}$	$1.32 \cdot 10^{-20}$	$1.50 \cdot 10^{-20}$
6	$4.72 \cdot 10^{-20}$	$3.32 \cdot 10^{-20}$	$2.37 \cdot 10^{-20}$
8	$1.88 \cdot 10^{-20}$	$8.35 \cdot 10^{-20}$	$3.76 \cdot 10^{-20}$
10	$7.48 \cdot 10^{-20}$	$2.10 \cdot 10^{-20}$	$5.96 \cdot 10^{-20}$
12	$2.98 \cdot 10^{-20}$	$5.27 \cdot 10^{-20}$	$9.45 \cdot 10^{-20}$
14	$1.19 \cdot 10^{-20}$	$1.32 \cdot 10^{-20}$	$1.50 \cdot 10^{-20}$

netic radiation will generate with amplitudes, enough to register on the gamma-ray and x-ray space telescopes, as well as ground-based radiotelescope. Such impulses to be found primarily among the single radio, gamma and x-ray bursts of an unknown nature, which are not associated with the regular astrophysical objects. Such bursts will register only once and not repeated. They can be observed as well as precursor of supernova stars, when the supernova precursor star compressed, and then explode as a supernova. If collapsing star not explodes as supernova and form a black hole, then we will observe the damping impulse, which disappears when the radius of the star becomes less than the Schwarzschild radius.

Thus, the existence of gravitational compression (collapse) stars still not confirmed by direct astrophysical observations. Therefore, an extremely important task in astrophysics is the development of the astrophysical observation, which direct confirm the stage of gravitational compression. Without this, the gravitational collapse will be the only subject of theoretical research, not confirmed astrophysical observations.

### References

Abdikamalov E.B. et al.: 2009, *MNRAS*, **392**, 52.  
 Alekseev E.M. et al.: 1987, *Pisma JETP*, **45**, 461.  
 Aloy M.A. et al.: 2000, *Ap. J.L.* **531**, 119.  
 Anchordoqui L.A.: 2009, *MNRAS*, **396**, 1629.  
 Arnett W.D.: 1979, "Sources of gravitational radiation". Ed. Smarr. Cambridge.  
 Bahcall J.N., Wolf R.A.: 1965, *Phys. Rev. B*, **140**, 1452.  
 Baiotti L. et al.: 2008, *Phys. Rev. D*, **78**, id. 084033.  
 Baiotti L. et al.: 2005, *Phys. Rev. D*, **71**, id. 024035.  
 Baumgarte T.W., Shapiro S.L.: 2003, *Ap. J.*, **585**, 930.  
 Becker J.K., Biermann P.L.: 2009, *Astropart. Phys.*, **31**, 138.

- Beskin G. et al.: 2008, *Adv. Space Res.*, **42**, 523.
- Bionta R.M. et al.: 1987, *Phys. Rev. Lett.*, **58**, 1494.
- Bisnovaty-Kogan G.S.: 2002, *Stellar Physics*, Berlin, Springer.
- Blandford R.D., Znajek R.L.: 1977, *MNRAS*, **179**, 433.
- Blandford R.D., Payne D.G.: 1982, *MNRAS*, **199**, 883.
- Blinnikov S.I., Imshennik V.S., Nadyozhin D.K.: 1988, *Astrophys. Space Sci.*, **150**, 273.
- Braaten E., Segel D.: 1993, *Phys. Rev. D*, **48**, 1478.
- Bruenn S.W.: 1985, *Ap. J. Sup. Ser.*, **58**, 771.
- Bucciantini N., et al.: 2008, *MNRAS*, **383**, L25.
- Canuto V., et al.: 1970, *Phys. Rev. D*, **2**, 281.
- Chau, W.Y.; Zhang, J.L.: 1992, *Astrophys. Space Sci.*, **190**, 131.
- Cheng K.S., et al.: 2009, *Journ. Cosmol. Astropart. Phys.*, **9**, 7.
- Cherepashchuk A.M.: 2003, *Physics Uspekchi*, **46**, 335.
- Chiu H.Y.: 1961, *Phys. Rev.*, **123**, 1040.
- Chiu H.Y., Morrison P.: 1960, *Phys. Rev. Lett.*, **5**, 573.
- Chiu H.Y., Stabler R.C.: 1961, *Phys. Rev.*, **122**, 1317.
- Couch S.M., Wheeler J.C., Milosavljevic M.: 2009, *Ap. J.*, **696**, 953.
- Davydkin V.D., et al.: 1987, *Pisma JETP*, **45**, 464.
- Dermer C.D., Atoyan A.: 2006, *Ap. J.*, **643**, L13.
- Dessart L. et al.: 2007, *Ap. J.*, **669**, 585.
- Dicus D.A.: 1972, *Phys. Rev. D*, **6**, 941.
- Dutta G. et al.: 2000a, *Phys. Rev. D*, **61**, id. 013009.
- Dutta G. et al.: 2000b, *Phys. Rev. D*, **62**, id.093014.
- Fedorova A.V., Tutukov A.V., Yungelson L.R.: 2004, *Astron. Lett.*, **30**, 73.
- Fendt C.: 2009, *Ap.J.*, **692**, 346.
- Friman B.L., Maxwell O.V.: 1979, *Ap. J.*, **232**, 541.
- Fujimoto S. et al.: 2006, *Ap. J.*, **644**, 1040.
- Ghezzi C.R.: 2005, *Phys. Rev. D*, **72**, id. 104017.
- Goldreich P., Weber S.: 1980, *Ap. J.*, **238**, 991.
- Gunningam C.T., Price R.H., Moncrief V.: 1978, *Ap. J.*, **224**, 643.
- Gunningam C.T., Price R.H., Moncrief V.: 1979, *Ap. J.*, **230**, 870.
- Gunningam C.T., Price R.H., Moncrief V.: 1980, *Ap. J.*, **236**, 674.
- Hachisu I., Kato M.: 2001, *Ap. J.*, **558**, 323.
- Han Z., Podsiadlowski P.: 2006, *MNRAS*, **368**, 1095.
- Han Z., Podsiadlowski P.: 2004, *MNRAS*, **350**, 1301.
- Hanami. H.: 1997, *Ap. J.*, **491**, 687.
- Hansen C.J. 1968, *Astrophys. Space Science*, **1**, 499.
- Henriksen R.N., Chau W.Y., Chau K.L.: 1979, *Ap. J.*, **227**, 1013.
- Hirata K. et al.: 1987, *Phys. Rev. Lett.*, **58**, 1490.
- Iben Jr.I., Tutukov A.V.: 1985, *Ap. J. Sup. Ser.*, **58**, 661.
- Itoh N. et al.: 1989, *Ap. J.*, **339**, 354.
- Kato Y., Hayashi M.R., Matsumoto R.: 2004, *Ap. J.*, **600**, 338.
- Kiuchi K. et al.: 2009, *Phys. Rev. D*, **80**, id. 064037.
- Koers H.B.J., Wijers R.A.M.J.: 2005, *MNRAS*, **364**, 934.
- Koide S., Shibata K., Kudoh T.: 1998, *Ap. J. L.*, **495**, L63.
- Komissarov S.S., Barkov M.V.: 2007, *MNRAS*, **382**, 1029.
- Kryvdyk V.: 2008, *Adv. Spac. Res.*, **42**, 533.
- Kryvdyk V.: 1998, *Kinematica Fiz. Nebesn. Tel*, **14**, 475.
- Kryvdyk V.: 2010, *Kinem. Phys. Cel. Bodies*, **25**, 277.
- Kryvdyk V.: 1999, *MNRAS*, **309**, 593.
- Kryvdyk V.: 2009, *Kinematica Fiz. Nebesn. Tel*, **25**, 415.
- Kryvdyk V.: 2014a, *Europ. Pys. J. C. S.*, **70**, 56.
- Kryvdyk V.: 2014b, *Odessa Astron. Publ.*, **27/2**, 119.
- Lattimer J.M. et. al.: 1991, *Phys. Rev. Let.*, **66**, 2701.
- Leng K.R.: 1984, *Astrophysical formulae*, Mir, Moscow.
- Lesaffre P. et al.: 2006, *MNRAS*, **368**, 187.
- Li X.-D., van den Heuvel P.J.: 1997, *Astron. Astrophys.*, **322**, L9.
- Limongi M., Chieffi A.: 2003, *Ap. J.*, **592**, 404.
- Liu Y.T., Shapiro S.L., Stephens B.C.: 2007, *Phys. Rev. D*, **76**, id. 084017.
- Lu Y, Qian Y.-Z.: 2007, *Phys. Rev. D*, **76**, id. 103002.
- MacFadyen A.I., Woosley S.E.: 1999, *Ap. J.*, **524**, 262.
- MacFadyen A.I., Woosley S.E., Heger A.: 2001, *Ap. J.*, **550**, 410.
- Matsakos T. et al.: 2008, *Astron. Astrophys.*, **477**, 521.
- Meliani Z.V. et al.: 2006, *Astron. Astrophys.*, **447**, 797.
- Mitsuda E., Yoshino H., Tomimatsu A.: 2005, *Phys. Rev. D*, **71**, id. 084033.
- Mizuno Y., et al.: 2004, *Ap. J.*, **606**, 395.
- Moncrief V.: 1980, *Ap. J.*, **238**, 333.
- Morley P.D., Schmidt I.: 2002, *Astron. Astrophys.*, **384**, 899.
- Munakata H., Kohyama Y., Itoh N., 1985, *Ap. J.*, **296**, 197.
- Nakazato K., Sumiyoshi K., Yamada S.: 2007, *Ap. J.*, **666**, 1140.
- Noble S. C., Choptuik M. W.: 2008, *Phys. Rev. D.*, **78**, id. 064059.
- Nomoto K., Kondo Y.: 1992, *NATO ASI Ser. C.*, **377**, 189.
- Nomoto K., Kondo Y.: 1991, *Ap. J. L.*, **367**, L19.
- Onken C.A. et al.: 2004, *Ap. J.*, **615**, 645.
- Ono M. et al.: 2009, *Progr. Theor. Phys.*, **122**, 755.
- Paranjape A., Padmanabhan T.: 2009, *Phys. Rev. D.*, **80**, id. 044011.
- Postnov K.A. Yungelson L.R.: 2006, *Living Rev. Relativity*, **9**, 1.
- Qian Y.Z., Woosley S.E.: 1996, *Ap. J.*, **471**, 331.



- Ratkovic S., Dutta S.I., Prakash M.: 2003, *Phys. Rev. D.*, **67**, id. 123002.
- Reynos M.M., Romero G.E., Sampayo O.A.: 2006, *Astron. Astrophys.*, **454**, 11.
- Ruffert M., Janka H.-Th.: 1999, *Astron. Astrophys.*, **344**—, 573.
- Ruffini R. et al.: 2003, *Amer. Inst. Phys. Conf. Proc.*, **668**, 16.
- Ruffini R. et al.: 2005a, *Amer. Inst. Phys. Conf. Proc.*, **782**, 42.
- Ruffini R. et al.: 2007, *Amer. Inst. Phys. Conf. Proc.*, **910**, 55.
- Ruffini R. et al.: 2005b, *Intern. J. Modern Phys. D.*, **14**, 131.
- Ryazhskaya O. G.: 2006, *Physics Uspekhi*, **49**, 1017.
- Shapiro S.L.: 2003, *Astron. Inter. Proc. Conf.*, **686**, 50.
- Shapiro S.L., Teukolsky S.A.: 1985, *Black Holes, a White Dwarfs, and Neutron Stars. Mir, Moscow.*
- Shibata M.: 2003, *Ap. J.*, **595**, 992.
- Shibata M. et al.: 2005, *Phys. Rev. Let.*, **96**, id. 031102.
- Shibata M. et al.: 2006, *Phys. Rev. D*, **74**, id. 104026.
- Shibata M., Taniguchi K.: 2006, *Phys. Rev. D*, **73**, id. 064027.
- Smartt S.J.: 2009, *Ann. Rev. Astron. Astrophys.*, **47**, 63.
- Stephens B.C., et al.: 2007, *Classical and Quantum Gravity*, **24**, 207.
- Stephens B.C., Shapiro S.L., Liu Y.T.: 2008, *Phys. Rev. D.*, **77**, id. 044001.
- Takiwaki T., Kotake K., Sato K.: 2009, *Ap. J.*, **691**, 1360.
- Uzdensky D.A., MacFadyen A.I.: 2006, *Ap. J.*, **647**, 1192.
- Uzdensky D.A., MacFadyen A.I.: 2007, *Ap. J.*, **669**, 546.
- Van Paradijs J. et al.: 1997, *Astron. Astrophys.*, **317**, L9.
- Vigorito C. et al.: 2008, *J. Phys. Conf. Ser.*, **136**, id.042074.
- Wickramasinghe D. T., et al.: 2009, *Journ. Phys. Conf. Ser.*, **172**, 12.
- Woosley S.E., Baron E.: 1992, *Ap. J.*, **391**, 228.
- Woosley S.E., Timmer F.X., Baron E.: 1992, *NATO ASI Ser. C*, **377**, 189.
- Yakovlev D.G., et al.: 2001, *Phys. Rep.*, **354**, 1.
- Yu Y.W., Dai Z.G., Zheng X.P.: 2008, *MNRAS*, **385**, 1461.
- Yungelson L.R., Livio M.: 1998, *Ap. J.*, **497**, 168.
- Zeldovich J.B., Novikov I.D.: 1977, *Theory of gravity and stellar evolution. Nauka, Moscow.*
- Zhang W., Woosley S.E., MacFadyen A.I.: 2003, *Ap. J.*, **586**, 356.