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Achievements of ITEP astrophysicists

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Contents

Abstract. **Astrophysical research at the Institute for Theoretical and Experimental Physics (ITEP) is examined historically over a period of more than 30 years. The primary focus is on the supernova problem, starting with how it was approached in the classical pioneering work of Imshennik and Nadyozhin and ending with present-day models of these most powerful star explosions in the Universe. The paper also reviews work in other areas of astrophysics, including chemical nucleosynthesis, the cosmological use of type-IIn supernovae and dark matter models. The paper was written as a contribution to the 70th anniversary of ITEP.**

Keywords: history of physics, astrophysics, supernovae

1. Introduction

The Laboratory of Plasma Physics and Astrophysics was organized at the Alikhanov Institute of Theoretical and Experimental Physics (ITEP) more than 30 years ago. The research field of the laboratory is extremely broad: from stellar evolutionary problems to cosmology. However, the construction of theoretical models of supernova explosions and their appearances (for both core-collapse and thermonuclear supernovae) has been one of the most important fields. Therefore, it seems appropriate to briefly introduce supernovae before reporting on the laboratory achievements.

Supernovae are generally recognized to be the end products of the evolution of massive stars. During a supernova explosion, its brightness increases by several dozen stellar magnitudes in several days and at the maximum is comparable to the brightness of the entire host galaxy. Supernovae include explosions with energies of 10^{50}–10^{52} erg and the emission power above 10^{41} erg s^{-1}. Depending on the stellar mass, a supernova explosion, which results from the dynamical evolution of the stellar core, ends with either total disruption of the star or gravitation collapse of the core.

According to the theory of stellar evolution, in stars with masses of $(4-9)\,M_\odot$ (where $M_\odot$ is the solar mass) carbon–oxygen cores form, which turn into white dwarfs after the outer stellar envelope is lost. If a white dwarf is a component of a binary system, the matter from the secondary companion can fall onto the white dwarf to increase its mass to the Chandrasekhar limit (around $1.44M_\odot$), and a thermonuclear explosion occurs that destroys the whole star. This process explains explosions of type-Ia supernovae. The evolution of stars with masses of $(9-100)\,M_\odot$ ends with the formation of a nondegenerate iron core with subsequent gravitational collapse into a neutron star or a black hole, leading to ejection of the outer layers of the star.

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Supernovae are nonstationary objects. They are accompanied by the formation of rapidly expanding gas shells, called supernova remnants. In addition, undoubtedly, stellar remnants (neutron stars or black holes) remain in some cases. The problem of supernova explosions is closely related to various astrophysical fields; the dynamics of the interstellar medium, formation of the galactic wind, synthesis of heavy elements, evolution of stars, formation of neutron stars and black holes, origin of cosmic rays, nature of gamma-ray bursts, evolution of the stellar population in galaxies, etc. The paramount importance of these problems explains the key role of supernovae in modern astrophysics and ITEP astrophysicists' focus on this research.

2. Foundation of hydrodynamic theory of supernova explosions

In 1964–1971, the founder of our laboratory, Imshennik, in collaboration with Nadyozhin (see review [1] and the references therein) formulated the basics of a radiation–hydrodynamic theory of supernova explosions. This for the first time enabled the temporal and spectral properties of the electromagnetic emission from supernova explosions registered in astronomical observations (light curves) to be calculated self-consistently. This theory also enabled determining the hydrodynamic parameters of the ejected supernova shells, including the total energy of the explosion and the matter velocity distribution. A physical mechanism was proposed to explain the observed prolonged period of constant supernova brightness related to the formation of the cooling recombination wave, which is similar to what is observed during the cooling of an atomic explosion fireball in Earth's atmosphere. Similar calculations carried out in other countries appeared only 7–10 years later. The predictions of the theory have been confirmed by many astronomical observations of supernovae in other galaxies.

Figure 1 shows a typical supernova light curve. The flat part of the light curves with approximately constant luminosity (SN IIP light curves) is exactly due to the recombination cooling wave predicted by the ITEP astrophysicists. Long 'tails' on the light curves are due to radioactive cobalt decay. Also shown are the light curves of the famous SN 1987A that exploded on February 23, 1987 in the Large Magellanic Cloud — a dwarf satellite galaxy to our Milky Way — and the light curve of a thermonuclear type-Ia SN.

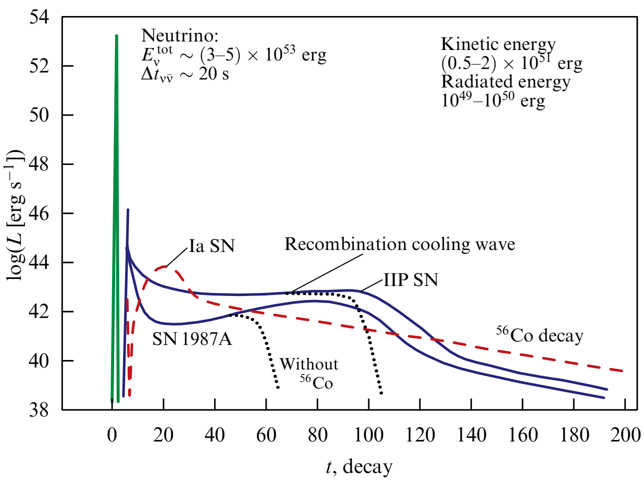

Figure 1. (Color online.) Supernova light curves. Blue and red curves show the photon luminosity of different supernovae (types Ia, IIP, and the famous SN 1987A). The short neutrino pulse is shown in green.

3. Nadyozhin–Chevalier self-similar solution

After supernova explosions with an energy of 10^{51} erg, specific 'bubbles' are formed in the interstellar medium, so-called gaseous supernova remnants. Plasma in the remnants is heated to high temperatures to powerfully shine in X-rays. To describe the gas dynamics in the remnants, the famous self-consistent Sedov solution for strong explosions is often used. This solution describes a single strong shock by ignoring the mass of the remnant. A point-like energy injection into the interstellar medium is assumed, which leads to the formation of a single shock.

However, in fact, the ejected supernova remnant mass can be not small, and the Sedov solution is inapplicable in this case, which is confirmed by calculations and observations of young supernova remnants (with an age of less than several thousand years) (Fig. 2).

This problem was solved in 1980 at ITEP by Nadyozhin (ITEP preprint No. 1, 1980, Ref. [2]), who found a new self-similar solution for supernova remnants with both front and reverse shocks and the contact discontinuity separating them taken into account, as shown in Fig. 2. This solution is extremely important for the theory of supernovae and stellar explosions; it became a working tool of mathematical astrophysics and in particular is used in the SUPREMNA (Supernova Remnants) code elaborated at ITEP jointly with colleagues from the Sternberg Astronomical Institute, Lomonosov Moscow State University (SAI MSU) and from Stockholm University.

4. Foundation of the theory of neutrino heat conductivity

The huge energy released during a supernova explosion is mainly carried away by neutrinos. Describing neutrino propagation through the collapsing stellar layers is a very complicated problem. The theory of neutrino heat conductivity in supernovae, developed by Imshennik and Nadyozhin in the 1970s–1980s at ITEP, enabled effective calculations of neutrino fluxes in the case of large optical depths. Based on this theory, expected supernova neutrino spectra and light curves were calculated. Contrarily to estimates in the foreign literature of that time, the ITEP astrophysicists showed that the duration of the neutrino signal from a supernova should be around 10–20 s (and not 1–3 s, as was assumed previously). The respective energies of electron neutrinos and antineutrinos were calculated to be 8 and 12 MeV.

Figure 3 presents the calculated parameters of the neutrino outburst from a supernova explosion [3]. The neutrino light curve includes an extremely short (a few tens of milliseconds) peak (shown in red) of nonthermal neutrinos from non-equilibrium neutronization of matter during the collapse and a much longer relatively flat part corresponding to the thermal stage (shown in blue). At the nonthermal stage, predominantly electron neutrinos are emitted, while at the thermal stage all neutrino and antineutrino species are emitted in approximately equal proportions. The black curve shows the total energy emitted in neutrinos as a function of time.

In 1987, underground neutrino observatories in different countries for the first time detected the neutrino signal from

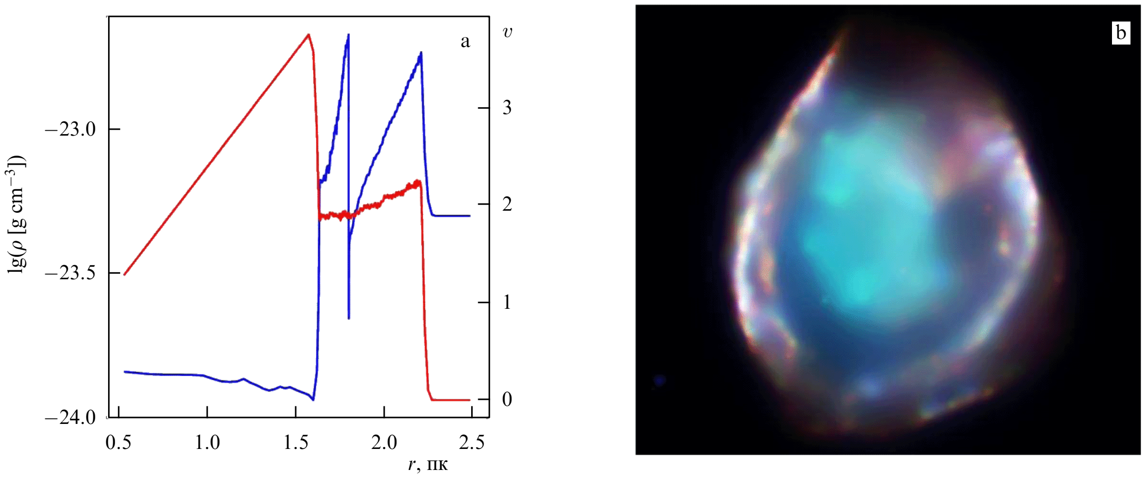

Figure 2. (Color online). (a) Calculations by E I Sorokina (ITEP) for a spherically symmetric young supernova remnant (density — blue curve, velocity — red curve). Forward and reverse shock fronts, as well as the density jump at the contact discontinuity (where the ejecta collides with the interstellar medium) are clearly seen. (b) X-ray image of young supernova remnant DEMP71 obtained by the Chandra X-ray telescope. These structures are also seen here.

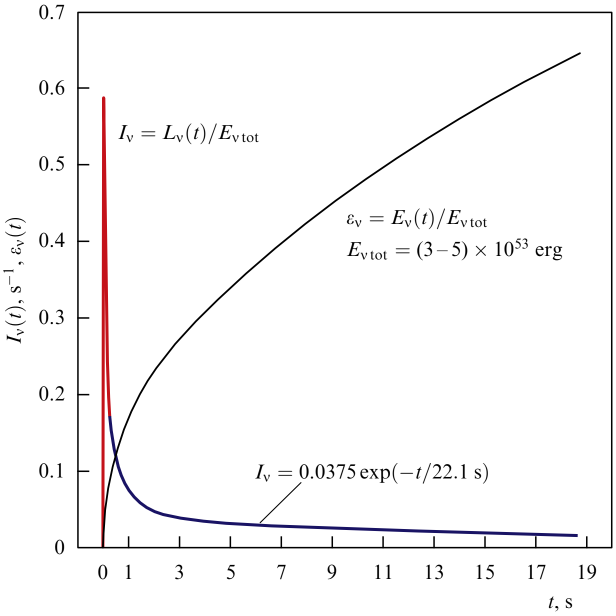

Figure 3. (Color online.) Total energy emitted in neutrinos (the black curve) and the neutrino light curve from a supernova explosion (red and blue curves, respectively).

the nearest supernova 1987A in the Large Magellanic Cloud. The spectral and temporal characteristics of this signal turned out to be close to those predicted in 1978 by the ITEP astrophysicists.

5. Development of the theory of stellar nucleosynthesis

Nuclear astrophysics studies two very important processes: energy generation and the formation of new elements. At ITEP, world-class research on the r-process (r from rapid) has been carried out. This is the process of the formation of elements beyond the iron peak due to neutrons in explosive processes with a high concentration of free neutrons. Such conditions can be realized either in shells ejected during core-collapse supernovae or during coalescences of compact binary neutron stars or neutron-star and black-hole systems. The coalescence of such objects results in the ejection of a fraction of superdense strongly neutronized matter into the surrounding interstellar medium. Cooling and the decreasing density in such matter provide ideal conditions for the synthesis of all elements beyond the iron peak by a chain of consecutive multiple neutron captures and beta-decays that ultimately lead to increasing the atomic number of newly formed nuclei.

In 1996, Blinnikov and Panov [4] formulated a kinetic model of nucleosynthesis that includes all pair reactions with neutrons, protons, alpha-particles, and beta-decays, reactions of electron neutrino captures by nuclei, and a number of special reactions like the 3-alpha reaction and burning reactions of carbon, oxygen, silicon, as well as the fission of nuclei. The development of this model enabled the unification of three stages of the r-process modeling (nuclear statistical equilibrium, alpha-process, and r-process) into one model of rapid nucleosynthesis, which resulted in several pioneering results. For the first time, the weak r-process was shown to be possible due to neutron generation by a neutrino source [5, 6].

At ITEP, it was shown for the first time that one of the main formation mechanisms of the observed heavy element abundance in the r-process nucleosynthesis is the neutron-induced fission of nuclei, which hampers the synthesis of superheavy nuclei and returns the nuclear fission products to the nucleosynthesis chain as seed nuclei [7]. It was shown that the cadmium, platinum, and rare-earth element peaks are well reproduced by the ITEP model and correspond to observations. Moreover, studies of the r-process revealed that in the domain of intensive neutron-induced, delayed, and spontaneous fission, there is a probability of the process branching into two chains, in the weaker of which part of the fission-survived nuclei can form superheavy elements (SHEs). However, the amount of SHEs is at least 10 orders of magnitude below the amount of uranium formed, and the lifetime of the most long-lived SHEs lasts from several days to several years; they are unstable with respect to alpha-decay and spontaneous fission [8]. The region of the most long-lived

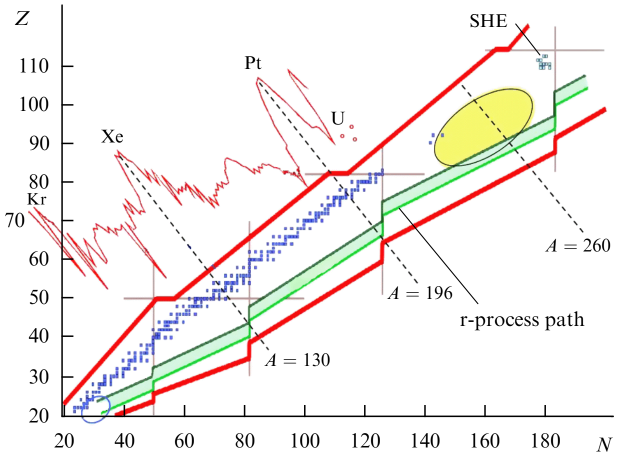

Figure 4. (Color online.) Production of heavy and superheavy elements in strongly neutronized matter ejected during coalescence of superdense stellar remnants in close binary systems (neutron star + neutron star or neutron star + black hole). The thick solid lines mark the proton and neutron stability boundaries. The ellipses show the regions of seed ($A \sim 50-60$) and fission ($A \sim 240-290$) nuclei. The horizontal and vertical segments determine the location of nuclei with completed shells ($Z, N = 50, 82, 114, 126, 184$).

SHEs remains unreachable by the r-process due to the presence of intermediate very short-lived nuclei subjected to spontaneous fission.

The r-process nucleosynthesis occurs in less than one second and involves a great number of short-lived nuclei, whose characteristics should be known. To predict the unknown characteristics of atomic nuclei in the r-process calculations, a method based on the theory of a finite Fermi system was elaborated, which enabled calculating the characteristics of several thousand nuclei, including the beta-decay time and the probability of emission of delayed neutrons and delayed fission [9]. Figure 4 shows the region of heavy-element nucleosynthesis and heavy-nuclei abundance in the r-process (in arbitrary units).

6. Foundation of the theory of neutrino nucleosynthesis

As seen from Section 5, not all features of the observed chemical elemental abundance in nature can be explained by standard nucleosynthesis. In 1978, Nadyozhin and Domogatsky opened a new direction in the theory of the origin of chemical elements: neutrino nucleosynthesis [10]. The main idea of this mechanism is the production of chemical elements in the envelope of a dying giant star by the intensive neutrino flux from its collapsing core. The nuclei produced in such a way are ejected during a supernova explosion to enrich the interstellar medium. This hypothesis explained peculiarities observed in the abundance of some isotopes of light elements (lithium, beryllium, boron, etc.), as well as of heavy elements (bypassed isotopes and isotopes from the 'weak component' of the r-process). Figure 5a presents the observed elemental abundance. The neutrino nucleosynthesis mechanism is schematically shown in Fig. 5b.

7. Binary neutron star coalescence and explosion of the low-mass component of a binary system

Cosmic gamma-ray bursts, which remain an astrophysical enigma, have an energy in the range from several tens of keV to several MeV (sometimes greater). The bursts last from some fractions of a second to several minutes, and sometimes hours. In the 1980s, the distance to the gamma-ray burst sources was not clear at all. They could reside both at cosmological distances and near the Sun. At that time, important work on the nature of gamma-ray bursts was carried out at ITEP [12], which for the first time suggested the possibility of powerful explosions during binary neutron star coalescences. It was predicted that not only powerful gravitational wave emission (as had been suggested for coalescing neutron star and black hole binaries) but also a gamma-ray burst should be produced in this process. Because the explosion energy should be of the same order as that of a supernova, such a burst should be noticeable from long distances.

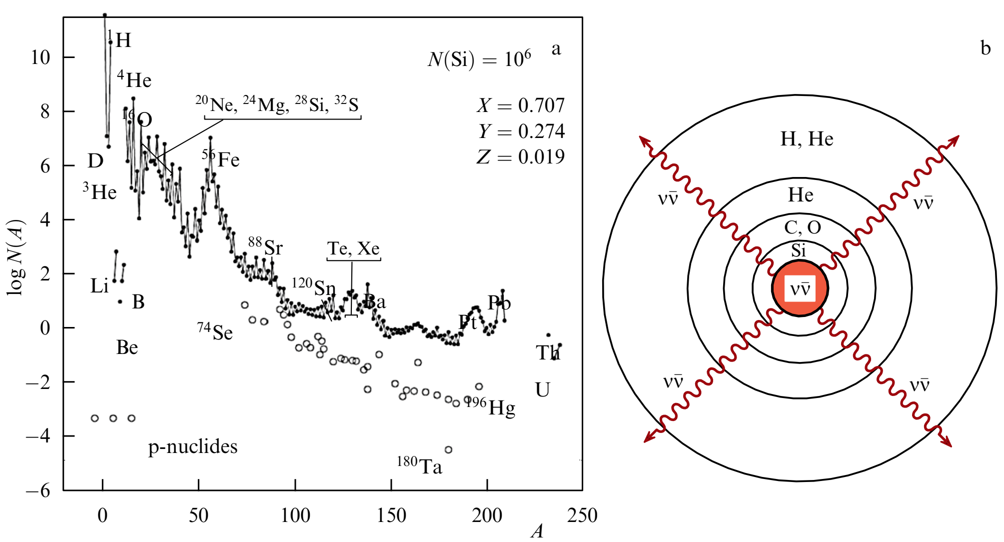

Figure 5. (a) Observed chemical elemental abundance [11]: the relative proportion of a given element as a function of the mass number (the silicon abundance is assumed to be 10^6). Values X, Y, and Z mark the mass fractions of hydrogen, helium, and all other elements. (b) Illustration of neutrino nucleosynthesis: schematic view of the outer layers of a star illuminated by a central neutrino flux during a supernova explosion.

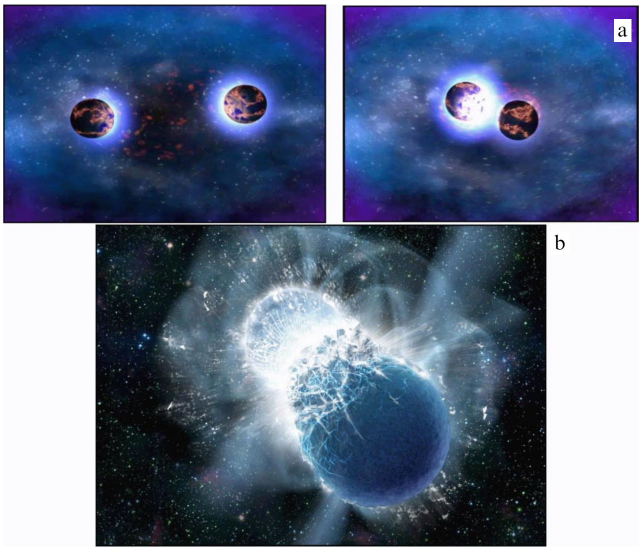

Figure 6. (a) Pair of neutron stars spiraling in due to the loss of angular momentum by gravitational waves. (b) The less massive component of the binary system explodes.

The main idea of this mechanism is as follows: neutron stars in a close binary spiral in due to unavoidable energy and angular momentum loss by gravitational waves. At a certain moment, the star with the smaller mass (which has a larger radius according to the mass–radius relation for neutron stars) starts mass transfer onto the more massive component. Thus, the mass of the low-mass companion of the pair decreases and that of the high-mass companion increases. Remarkably, there is a minimum possible mass for equilibrium neutron stars, because at too small a mass, and hence density, the Fermi momentum of electrons becomes too low and neutrons can decay. In fact, of course, it is not free neutrons but neutron-rich nuclei that decay, in which beta-decay occurs very rapidly, in a few fractions of a millisecond, and the process bears an explosive character. Thus, by reaching the minimum mass, the neutron star explodes. Some stages of this process are schematically shown in Fig. 6.

These ideas were developed in a subsequent paper [13] (1990), jointly with Imshennik and Nadyozhin. Later, in 1992, Imshennik used the idea of this scenario in his original mechanism of supernova explosions [14]. Paper [12] also became known abroad, in spite of the lack of contacts with western colleagues at that time. For example, it was further developed by Colpi et al. [15] (account for neutrino emission). This scenario was fully used by Eichler et al. in 1989 in the famous paper published in *Nature* [16] (unfortunately, without reference to the paper by Blinnikov et al. [12] of 1984, but with reference to [15]).

Only in 1998, using observations by the BeppoSax satellite, was it established that gamma-ray bursts occur in remote galaxies and not in the vicinity of the Solar System. The scenario of gamma-ray bursts in binary neutron star coalescences, developed at ITEP, became widely recognized for short gamma-ray bursts (shorter than 2 s).

8. Rotational mechanism of core-collapse supernovae

The evolution of sufficiently massive stars ($M \geqslant 10 M_{\odot}$) in the main sequence ends with the collapse of the iron stellar core. However, the first numerical models showed that the 'standard' theoretical one-dimensional spherically symmetric scheme cannot explain the huge explosion following the core collapse with a kinetic energy of the ejected shell of the order of 10^{51} erg. The shock formed due to reflection of the accreting matter flow from the central proto-neutron star rapidly spends energy on dissociation of nuclei in the stellar envelope behind the front and decays without ejecting the envelope. During almost half a century of intensive work by many astrophysical groups on the construction of a theoretically self-consistent model of core-collapse supernova explosions, several possible scenarios were proposed taking different supplementary factors into account. Nevertheless, so far there has been no complete and universal solution of this problem. Moreover, observations of the most studied SN, 1987A in the Large Magellanic Cloud, have introduced additional difficulties related to the registration of two neutrino signals separated by a long time interval (4.7 h).

In 1992, Imshennik proposed a rotational mechanism of core-collapse supernovae. The effects of rotation, which is unavoidable in all stars, play the key role in this mechanism. The theoretical model is based on a large number of studies carried out at different times by collaborators at the astrophysical laboratory of ITEP, especially [12–14, 17].

The main ideas of this mechanism can be illustrated with the example of the famous SN 1987A supernova (Fig. 7). As was mentioned above, it is assumed that by the time of the loss of stability, the iron core of the pre-supernova has a

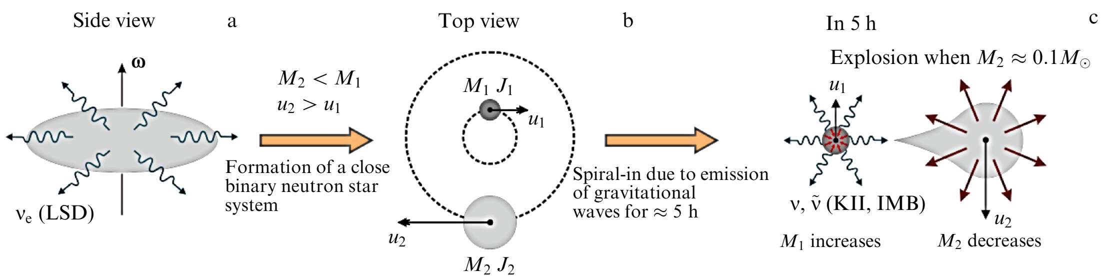

Figure 7. Rotational mechanism of core-collapse supernova explosion. (a) During the collapse, the total energy of rotation $E_{\rm rot}$ increases the dynamical stability limit $E_{\rm rot}/|E_{\rm g}| > 0.27$ ($E_{\rm g}$ is the gravitational binding energy of the proto-neutron star). (b) The components of a binary neutron star system spiral in due to the loss of orbital energy and angular momentum by gravitational waves. (c) The less massive neutron star first fills its Roche lobe. Rapid mass exchange between the binary components occurs and ends with the explosion of the low-mass neutron star when it reaches the minimum possible mass. Detectors that registered neutrino signals from SN 1987A: LSD — Liquid Scintillator Detector, KII — Kamiokande II, IMB — Irvine–Michigan–Brookhaven.

substantial rotation. Due to the conservation of specific angular momentum, a strongly differentially rotating configuration is formed during the core collapse [18], with a high ratio of the total rotational energy to the gravitational binding energy $\tau = E_{\rm rot}/|E_{\rm g}|$ ($\tau \sim 0.42$ from calculations in [19]). The critical value of the parameter τ for dynamical instability to arise (in the analytic theory for Maclaurin spheroids) is ~ 0.27. Most important in this mechanism is the hypothesis of the formation of a double neutron star system from the development of dynamical instability in the initially spherically symmetric configuration with subsequent fission (fragmentation) into separate parts. Here, a substantial part of the initial angular momentum of the core transforms into the orbital angular momentum of the binary system. As in the 'standard' model, the collapse of the rotating pre-supernova core is accompanied by powerful neutrino emission (although with notably different characteristics [21]), which can be identified with the signal detected by the LSD neutrino detector under Mont Blanc at the universal time $t_{\rm UT} = 2$ h 52 min (February 23, 1987) [20].

The basic parameters of the newly formed close binary system of neutron stars are its total mass and the mass ratio of the components, which, due to a large uncertainty in this process, can be considered free parameters of the model. Remarkably, the evolution of such a binary system is determined solely by a powerful gravitational wave emission: the bigger the difference between the component masses is, the longer the process. The neutron stars approach each other due to the energy and angular momentum loss by gravitational waves. The orbits of the components become virtually circular, even if the initial orbital eccentricity was appreciable [22]. Ultimately, the low-mass component of the binary system (because of the inverse mass–radius relation for neutron stars) first fills its Roche lobe. The subsequent quite short stage of the evolution of the binary system is accompanied by a nonstationary mass exchange between the components from the low-mass to high-mass star [12, 13]. When the lighter component of the binary system reaches the minimum possible mass for neutron stars, $\sim 0.1 M_{\odot}$, it is explosively destroyed in the orbit. As a result of a chain of nuclear reactions, iron-group nuclei are produced with a total energy release of ~ 4.7 MeV per nucleon [12] and the total explosion energy $\sim 10^{51}$ erg. During the mass exchange, the more massive proto-neutron star loses the excessive angular momentum to undergo a secondary collapse. This is accompanied by a neutrino outburst registered by several neutrino detectors at the time $t_{\rm UT} = 7$ h 36 min on February 3, 1987. Its characteristics should apparently be close to the properties of the neutrino signal in the 'standard' collapse model [20].

Separate stages of the evolution of a close binary system are accompanied by a powerful emission of gravitational waves with specific features, which can be used to identify this core-collapse supernova mechanism in future gravitational wave experiments. In addition, the proposed scenario has a number of undisputable advantages. The rotational mechanism offers a theoretical interpretation of two subsequent neutrino signals from SN 1987A separated by about 5 h [20]. The destruction of the low-mass neutron star moving with a high orbital velocity explains the supernova explosion with the required energy and significant asymmetry, which is observed in the remnant of SN 1987A. High proper motion velocities observed in young pulsars naturally arise in this scenario due to a high orbital velocity of the massive neutron star at the moment of destruction of its light companion.

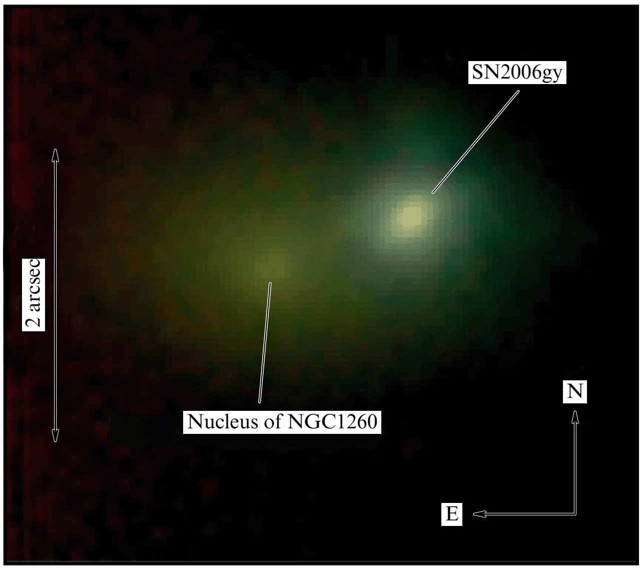

Figure 8. Supernova SN32006gy and the nucleus of the galaxy NGC 1260.

9. Electron–positron pair instability supernovae

In 2006, in the galaxy NGC 1260, astronomers discovered one of the most powerful supernovae, SN2006gy, which at that time had a record high peak luminosity (since then, more powerful supernovae have been discovered). Figure 8 suggests that the radiation flux from SN2006gy exceeds that of the host galaxy, which contains several billion stars. This supernova was an order of magnitude brighter than the powerful thermonuclear type-Ia SN explosions, which are used in cosmology, and two orders of magnitude brighter than ordinary type-II SN, which also show hydrogen lines in their spectra. However, SN2006gy demonstrates peculiar spectral line profiles: in addition to lines with wide profiles (due to the high expansion velocity of matter), there are narrow spectral lines, which classify it as a type-IIn (n for narrow) supernova.

The extreme luminosity of SN2006gy has been challenging for astrophysicists. Several explanations have been suggested, but the most successful turned out to be the idea put forward by Nadyozhin and Grasberg [23] for another type-IIn supernova. According to this model, the huge luminosity is explained by a shock running across the shell produced by a weak explosion that occurred several years or months before the main strong explosion.

In 2007, *Nature* published a paper by Woosley, Blinnikov, and Heger [24], who calculated the evolution of a massive star (with an initial mass of $110 M_{\odot}$) that ejected mass in powerful pulsations. These pulsations are due to the electron–positron pair instability in the stellar interiors (pulsational pair-instability supernova). Thus, by the time of explosion, the star should be surrounded by an extended envelope made of the previously ejected matter. A supernova explosion inside such a shell generates a shock running across the shell, in full agreement with earlier idea by Nadyozhin. Calculations of the light curve from such a supernova carried out by the radiation hydrocode STELLA (Static Eddington-factor Low-velocity Limit Approximation) developed at ITEP demonstrated good agreement with observations (Fig. 9).

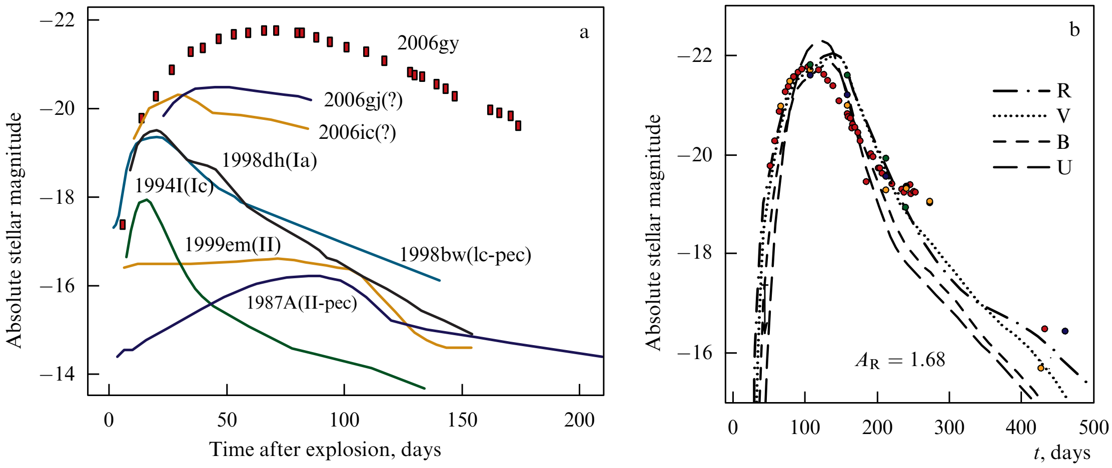

Figure 9. Light curve of SN 2006gy in comparison with light curves of other supernovae (in particular, of the famous SN 1987 A). (b) Observational data (circles) compared to model results (curves; shown is the luminosity in different spectral ranges). Difference in one stellar magnitude corresponds to a luminosity difference by about 2.5 times.

10. Type-IIP supernovae

Type-IIP supernovae are the most abundant among hydrogen-rich supernovae. They show insignificant spectroscopic variance and have a very broad range of photometrical properties, with their luminosities ranging from very low to very high, and their light curves varying from typical plateau-like to a specific dome-like form. An important fact that hydrogen ionization and excitation in atmospheres of type-IIP SN are nonstationary was established by Utrobin from ITEP [25].

Hydrodynamic modeling carried out at ITEP in a wide range of parameters and comparison with observed light curves and expansion velocities of a supernova shell enabled determining the main parameters of the supernova: the presupernova radius, the ejected mass, the explosion energy, and the mass of radioactive ^{56}Ni. It was confirmed that progenitors of normal type-IIP objects are red supergiants, while peculiar supernovae 1987A and 2000cb with dome-like light curves result from blue supergiants. The diversity of observed type-IIP SN is due to a very broad range of their main parameters. The increase in luminosity at the main plateau stage by almost two orders of magnitude and in the total mass of radioactive ^{56}Ni in the range $(0.006-0.4)\,M_\odot$ in the very bright supernova 2009kf compared to the very faint supernova 2003Z is equivalent to variation of the explosion energy in the range $2.5\times10^{50}-2.2\times10^{52}$ erg and the envelope mass in the range $(14-28)\,M_\odot$.

We note that SN 2009kf is the first type-IIP supernova with a very high explosion energy of 2.2×10^{52} erg, which suggests the formation of a black hole and not a neutron star from the gravitational collapse. The mass of the ejected shell, together with the mass of the neutron star and the mass ejected by the stellar wind, enables estimating the main-sequence stellar mass. Interactions of the ejected shell with the stellar wind and circumstellar matter were studied using H-alpha, Na I, and Ca II lines [26, 27]. The explosion energy and radioactive ^{56}Ni mass are shown as a function of the main-sequence stellar mass in Fig. 10. These dependences compellingly demonstrate the most important result that both the explosion energy and the radioactive ^{56}Ni mass increase with the main-sequence stellar mass.

Astrophysicists from ITEP first proposed that the disagreement between H-alpha and H-beta lines in early spectra of SN 2008in can be explained by assuming clumped outer layers of the ejecta [28, 29]. The problem, which arose only after high-quality spectra taken during the first month after the explosion had become available, is that these lines cannot be described by a spherical model with a smooth density distribution. Utrobin showed that the problem can be solved by assuming a clumped structure of the outer layers of the shell. The inhomogeneity of the outer layers of the presupernova was taken into account in hydrodynamic modeling of type-IIP SN 2012A [30]. This study showed that taking the inhomogeneous outer layers of the presupernova into account leads to an appreciable increase in the velocity (up to 30%). This very important result may decrease the presuper-

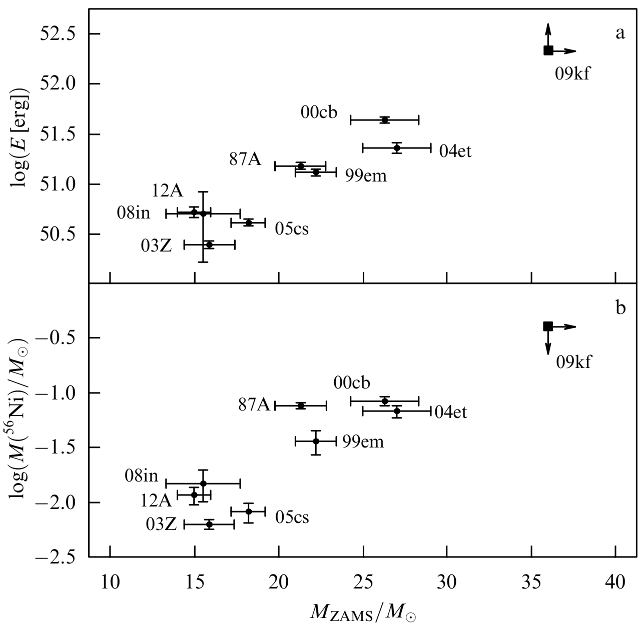

Figure 10. (a) Supernova explosion energy and (b) mass of synthesized ^{56}Ni as a function of the main-sequence star mass.

nova masses obtained from the hydrodynamic modeling of type-IIP supernovae.

An analysis of the central density of oxygen in the shells of nine type-IIP supernovae at the nebular stage inferred from the doublet [O I] 6300, 6364 A showed that the number density of oxygen 300 d after the explosion lies in the narrow range $(1.3-3.3)\times10^9$ cm^{-3}. We stress that this result is independent of the distance to the supernovae, extinction, and other model assumptions. The analysis of the obtained density distribution suggests that the energy of a type-IIP supernova increases with the stellar mass (see Fig. 10) [31].

The best-studied type-IIP supernova is SN 1987A. Its investigation at ITEP greatly developed radiation hydrodynamic methods and supernova atmosphere modeling. The nonstationary character of ionization and excitation of hydrogen without assuming local thermodynamic equilibrium in type-IIP supernova atmospheres allowed explaining intense hydrogen lines whose origin had been mysterious for a long time. The effect of the degree of mixing of ^{56}Ni on the bolometric light curve suggested that a moderate mixing of ^{56}Ni in the velocity range 2500–3000 km s^{-1} could explain the observed light curve of SN 1987A. At the same time, numerical simulation of the H-alpha profile at the so-called Bochum stage revealed the main result: a high-velocity clump of ^{56}Ni with a mass of about $0.001M_\odot$ moves in the far hemisphere with an absolute velocity of 4700 km s^{-1} [32, 33].

The detection of type-IIP supernovae that demonstrate a gradual spectral transformation from type II to type Ib significantly complemented the physical picture of core-collapse supernovae. The first object of this class was SN 1993J, which was used as the prototype of a new subclass of type IIP supernovae. The bolometric and visual light curves of this supernova and the evolution of helium in its optical spectrum are in good agreement with the hydrodynamic model elaborated at ITEP, according to which the mass of ejecta is $2.4M_\odot$, including $0.1M_\odot$ of hydrogen, and the energy of the explosion is 1.6×10^{51} erg [34, 35]. The hydrodynamic models and synthetic spectra compellingly demonstrated that nonthermal processes dominate after the second maximum (after about 30 d) and play a crucial role in both the observed smooth luminosity decrease after the maximum and the gradual emerging of helium lines in the optical spectrum of SN 1993J (in the time interval from 24 to 30 d). The supernova explosion in this case occurred in a red supergiant with a mass of about $4M_\odot$ due to gravitational collapse of the stellar core, and it is very likely that the presupernova was in a close binary system. This assumption was later reliably confirmed.

11. New method of cosmological distance measurements using type-IIn supernovae

In recent decades, progress in observational astronomy has enabled probing of the high-redshift Universe. Not only have very remote galaxies with the redshift $z = 7.7$ (13 bln light years) been found, but also simultaneous surveys covering large sky areas have been conducted. Broad-angle sky surveys (Sloan Digital Sky Survey (SDSS), Palomar Transient Factory (PTF), Catalina Real-Time Transient Survey (CRTS), etc.) enabled the detection of transient objects almost immediately after their appearance, which led to an explosive increase in the number of discovered supernovae. Presently, several thousand supernovae are being discovered yearly, while 10 years ago only several hundred were studied over the whole history of observations.

The large bulk of observational data on supernovae enabled detailed studies of the rare type-IIn supernovae, which were classified as a separate group only in 1990 [36]. These supernovae exhibit extremely narrow spectral hydrogen lines; hence the letter n in their designation. Astronomers discovered a rich variety of photometric and spectroscopic properties of type-IIn supernovae. Some of them shine very powerfully and reach the peak luminosity $M_{\rm R} = -21$ in the absolute stellar magnitude (for example, the famous SN 2006gy [37]). The ability of type-IIn supernovae to glow so brightly led to their classification as superluminous supernovae (SLSNs). These objects have been actively studied at ITEP and other scientific centers.

At the astrophysical laboratory of ITEP, such supernovae had been studied long before they were identified as a separate subclass. In 1986, Grasberg and Nadyozhin [23] showed that the observed spectrum of SN 1983K with narrow lines can be explained by an explosion inside a shell ejected 1–2 months prior to the burst. Later, more complex and detailed models describing the observational data well were constructed at the ITEP astrophysical laboratory. Presently, this mechanism is one of the leading hypotheses to explain the extremely high luminosity of SLSNs.

Based on numerical simulations, Blinnikov, Potashov, and Baklanov suggested and successfully tested a new method [38] for measuring the distance to type-IIn supernovae. The method can be applied to type-IIn supernovae with the highest luminosity, which enables its use for cosmological measurements, which is important from the standpoint of testing cosmological models. This is a direct method of distance determination, which does not require the preliminary calibration using objects with the known distance (measured by other means). Even for remote supernovae, there is no need to rely on the cosmological distance scale, unlike the standard-candle type-Ia supernova method.

The idea of the method stems from earlier work by Baade [39] and Wesselink [40], in which it was applied to pulsating stars — cepheids. We imagine a spherically symmetric star with the photosphere radius $R_{\rm ph}$ at a distance D. If the flux at the photosphere level is $F_{\rm ph}$, the flux measured by the telescope from the star is $F_{\rm obs} = F_{\rm ph}R_{\rm ph}^2/D^2$. Assuming a Planckian flux with the observed color temperature $T_{\rm c}$, $F_{\rm ph} = \pi B_v(T_c)$, it is possible to find either the angular diameter of the star $\theta = R_{\rm ph}/D = \sqrt{F_{\rm obs}/F_{\rm ph}}$ or its variation $\Delta\theta = \theta_2 - \theta_1 = \big(R_{\rm ph}(t_2) - R_{\rm ph}(t_1)\big)/D$. If the photosphere moves with matter, from the known velocity u measured by the Doppler effect for weak spectral lines, it is possible to calculate the photospheric velocity $v_{\rm ph}$. The velocity $v_{\rm ph}$ allows determining the change in the photospheric radius over the time interval $t_2 - t_1$: $\Delta R_{\rm ph} = \int_{t_1}^{t_2} v_{\rm ph}\,{\rm d}t$. Using θ and $\Delta\theta$ with a known $R_{\rm ph}$ or the corresponding change $\Delta R_{\rm ph}$ in a certain time interval, it is easy to find the distance D.

Baade's beautiful idea turned out to be inapplicable to ordinary type-IIP supernovae. The reason is that in type-IIP supernovae, the photosphere is not related to a certain layer of matter but moves relative to it [41]. It is impossible to directly derive the photospheric velocity $v_{\rm ph}$ from observations; it is only possible to measure the velocity of matter at the photosphere level using the Doppler effect and assuming weak spectral line formation close to the photospheric layer. In expanding supernova shells, the photosphere can shrink and u and $v_{\rm ph}$ are oppositely directed. But if $v_{\rm ph}$ is unknown, it is impossible to obtain $\Delta R_{\rm ph}$, which is necessary for determining the distance. Therefore, for type-IIP supernovae, Kirshner and Kwan proposed another method of distance determination called the expanding photosphere method (EPM) [42]. To find the radius, they proposed utilizing the feature of type-IIP supernovae to rapidly, with the characteristic time $t \sim 8$ d, come to the free expansion stage. The matter radius is then related to the velocity by the Hubble relation $R = u(t - t_0)$, where t_0 is the time of explosion.

However, type-IIP SN are unusual supernovae. They are surrounded by heavy matter, and the shock cannot break out into the rarefied interstellar medium for several months and sometimes years. Type-IIn models calculated at the astrophysical laboratory of ITEP demonstrate that the supernova shock in the shell turns into a strong radiative shock. Radiation effectively carries out heat from the contact zone between the shock and the outer layers of the supernova ejecta. Because of this, a thin dense layer is formed in the ejecta, which plays the key role in the new method of supernova distance determination, called the dense shell method (DSM). In the dense layer, a photosphere appears that moves together with it, and therefore Doppler measurements of the velocity of matter u enable the estimation of the photosphere velocity $v_{ph} = u$. This corresponds to Baade's idea for cepheids described above and makes it possible to calculate the distance to the supernova.

To apply the new DSM to determine cosmological distances using type-IIn supernovae, it is necessary to perform the following steps:

— to measure 'narrow' spectral line components to assess the properties (density and velocity) of the circumstellar shell; here, high measurement and model accuracies are not required;

— to measure 'broad' emission line components and to find the velocity u in the photosphere with a maximum possible accuracy. Although the law $u = R/t$ for type-IIn supernovae is inapplicable, the measured velocity u corresponds to the 'true' photospheric velocity v_{ph}, and not only to the matter flow velocity, as in the case of type-IIP supernovae;

— to find the change in radius $\Delta R_{ph} = v_{ph}\Delta t$ by time integration with account for scattering, the limb darkening/brightening effect, etc. The obtained values of the radius must be used iteratively to find the optimal model;

— to determine the distance D by making the variation of the observed flux change consistent with the variation of R_{ph}.

The simplified variant of the method presented above allows fairly good estimations of distances to type-IIn supernovae. To improve the accuracy for significant changes in the color temperature T_c, such a simple approach should be modified. It is necessary to construct a best-fit model of the observed broad-band photometric light curve and velocity v_{ph}, which is controlled by observations of $\Delta R(t)$. Such a model is needed in order to calculate the evolution of R_{ph} and to predict the theoretical flux R_{ph} in detail (Fig. 11).

Astrophysicists from ITEP have successfully used the DSM to find distances to three type-IIn supernovae. The first supernova, SN 2006gy, was chosen because its luminosity at that time exceeded those of all known objects. The galactic extinction to the supernova is known with a large dispersion, and it was assumed to be $A_R = 1.3 \pm 0.25^{\rm m}$. From observations [43, 44], the distance to SN 2206 gy $D \approx 68^{+19}_{-15}$ Mpc has been derived [38]. This value is in good agreement with the known modulus of the distance to the host galaxy, $D = 71$ Mpc [45]. We note that very large errors in the distance determination are related not to the method inaccuracy but to the uncertainty in the galactic extinction.

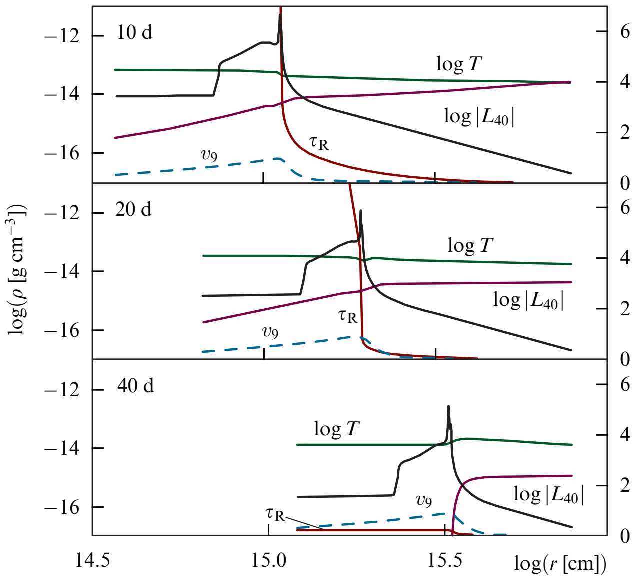

Figure 11. The density ρ (black curve), the optical depth τ_R, the logarithm of temperature T, the logarithm of luminosity L_{40}, and the photospheric velocity v_9 as functions of radius at different time moments. The density is shown on the left ordinate, while all other values are shown on the right.

The second supernova, SN 2009ip, exploded in the galaxy NGC 7259 in a gas- and dust-free region with small interstellar extinction. In addition, this remarkable supernova produced several ejections in 2009, which were observed in detail [46]. The DSM yielded the supernova distance $D = (20.1 \pm 0.8)$ Mpc [47], in perfect agreement with the known modulus of the distance to the host galaxy $D = 20.4$ Mpc.

A simplified variant of the DSM was applied to a third supernova, SN 2010jl [48]. The obtained distance estimate to SN 2010jl is $D = 49$ Mpc, which is in agreement with the known distance to the host galaxy, 50 Mpc. Distances to supernovae SN 2006gy, SN 2009ip, and SN 2010jl determined by the DSM are consistent with the known distances to the host galaxies, which justifies the applicability of the method.

12. Development of models of thermonuclear supernovae

Specialists from the astrophysical laboratory of ITEP jointly with colleagues from SAI MSU, the Max-Planck Institute for Astrophysics in Garching, and the University of California (Blinnikov, Sorokina, Roepke, Woosley et al.), have carried out many cosmologically important calculations of light curves of thermonuclear (type Ia) supernovae (Fig. 12). This is the so-called external problem for supernovae, because calculations of light curves can be done without detailed knowledge of the explosion mechanism itself. Such calculations help clarify properties of the explosion required to reproduce observations. It was established that a sufficient amount of the radioactive isotope ^{56}Ni should be synthesized such that after the electron capture it decays into radioactive ^{56}Co and then into the most stable iron isotope ^{56}Fe. If no radioactive isotopes were produced in the explosion, no photon source would appear after the explosion of the compact degenerate star — a white dwarf. It became clear that the observed expansion velocity of the supernova can be ensured only after the transformation of the slow thermo-

Figure 12. Type-Ia supernova SN 1994D and the host galaxy NGC 4526.

nuclear burning into detonation; however, too early a detonation is prohibited: if the whole star were detonated, the supernova ejecta would entirely consist of iron-peak elements, but in fact lighter elements are observed (silicon, sulfur, etc.). This can occur if initially the burning is slow: the subsonic flame runs across the star, which transforms into detonation after the radius of the star increases by several orders of magnitude.

The detailed mechanism of the transition to detonation is the key (and so far unsolved) problem in the modern theory of thermonuclear supernovae (the internal problem for type-Ia supernovae). Papers by Blinnikov and Khokhlov [50, 51] showed how a spontaneous deflagration front can form in the center of a carbon–oxygen white dwarf (Zeldovich's gradient mechanism), which generates the shock leading to detonation. Presently, this idea remains one of the most feasible mechanisms in the theory of type-Ia supernovae.

Recently, deflagration in thermonuclear supernovae has been studied by the ITEP researcher S I Glazyrin. He developed the multidimensional hydrodynamic code FRONT3D. The flame is subjected to different hydrodynamic instabilities: Rayleigh–Taylor–Landau, Landau–Darrieus, etc., which results in turbulence. All these processes are difficult to model due to a significant (12 orders of magnitude) difference in the flame scale (its width is only 10^{-4} cm) and the size of the star (10^8 cm). This prevents taking all physical processes into account, but nevertheless the combination of numerical simulations with semi-analytic models is promising for the solution of the problem of thermonuclear supernovae in the nearest future.

13. Neutrino magnetic moment and axions

In addition to the studies of stellar explosions and collapses, the astrophysical group at ITEP obtained important results in fundamental physics. In particular, Blinnikov and Dunina-Barkovskaya [52, 53] derived an upper bound on the magnetic moment of the neutrino from the observed distribution of white dwarf temperatures, which is less than 10^{-11} Bohr magnetons, and the coupling of hypothetical axions to electrons, i.e., the axion fine structure constant, which is estimated to be $\alpha_a < 5 \times 10^{-26}$. These results are still cited in the literature, and the limit for axions is included into the list of fundamental constants by the Particle Data Group.

14. Dark matter (mirror matter) models

The fundamental paper by Kobzarev, Okun', and Pomeranchuk [54] on particles of mirror matter was published in 1966, when physicists did not know that dark matter (DM) would soon become one of the main puzzles in cosmology and elementary particle physics [55]. The motivation of the authors of [54] was different: they introduced 'mirror particles' to compensate mirror asymmetry discovered by that time in weak interactions of ordinary particles (even with the particles replaced by antiparticles in the mirror reflection). The authors of [54] did not relate their hypothetical mirror particles to DM, but they came to a very important conclusion: if mirror particles exist, they cannot interact with ordinary particles either via nuclear or via electromagnetic forces. This is exactly what is needed for DM (Fig. 13).

When the DM problem became recognized in world science, Blinnikov and Khlopov [56] made the first proposals on searches for mirror matter and stressed its possible role in cosmology. Later, Blinnikov proposed considering invisible stars made of mirror matter as sources of gravitational microlensing and even of cosmic gamma-ray bursts [57] (with account for oscillations of neutrinos into sterile species). Presently, DM does not appear to be precisely like mirror matter. Nevertheless, this model serves as a source of useful ideas in the search for DM, especially in view of obtaining more stringent upper bounds on DM interaction with matter by underground detectors and the latest discoveries in the dynamics of interacting galaxies, which point to a nonzero self-interaction of DM particles [58, 59]. All

Figure 13. (Color online). Galaxies of one of the binary galaxy clusters are shown in yellow (dots and spots of different shapes), the baryon gas of these clusters is shown in red, and dark matter (as restored from gravitational microlensing) is shown in blue.

these facts comply with the properties of mirror matter predicted at ITEP.

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