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Supernovae and Properties of Matter in the Densest and Most Rarefied States

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Abstract—An overview of the relationship between the astrophysics of supernovae and fundamental physics is given. It is shown how astronomical observations of supernovae are used to determine the parameters of matter in the most rarefied states ("dark energy"); it is also revealed that the mechanism of supernovae explosion is related to the properties of matter in the densest states. The distinction between thermonuclear and collapsing supernovae is explained. Some problems that arise in the theory of powerful cosmic explositions— supernovae and gamma-ray bursts—and which require new physics for solving them are indicated. © *2005 Pleiades Publishing, Inc.*

1. INTRODUCTION

Still being an upperclassman in secondary school, I eagerly awaited the appearance of each successive issue of the "Feynman Lectures on Physics," translated into Russian by a group of physicists, including Yu.A. Simonov. In one of his lectures, R. Feynman said approximately the following. If asked to choose one clause that would explain the maximum number of phenomena in nature, he would say, "Matter consists of atoms." I recall that I was deeply impressed by these words. Since the main subjects of my scientific activities are associated with modern astrophysics, I have been dealing primarily with processes that are explained by the properties of atoms and ions in various states. Modern theoretical physics focuses primarily on more fundamental things—the properties of fields, strings, or some other geometric objects, on the basis of which theorists try to explain the entire micro- and macrocosm. (Yet, it cannot be stated that all of the theoretical problems—especially those that are needed for applications, in atomic physics, for example—have already been solved.)

Astrophysics is flourishing at the present time. Since the end of the twentieth century, astrophysics and classical observational astronomy have provided ever more data that can crucially affect the development of the most fundamental branches of physics. In particular, it has become clear to date that about 95% of the mean density of the observed Universe does not consist of ordinary matter—that is, of atoms. In this review article, I will consider but a small numbers of facts concerning the impact of astronomy on physics—specifically, supernovae, which are exploding objects, will be the focus of attention here.

At the beginning of the article, it is explained how parameters of cosmological models can be determined with the aid of a constant-power source of light, so-called cosmological standard candle. Further, it is shown that some subtle points in employing supernovae as cosmological standard candles are often treated incorrectly by physicists. For example, Dolgov writes, in his very useful review article [1], that type Ia supernovae are cosmological standard candles. But in fact, these supernovae are not standard candles! Nevertheless, the acceleration of the expansion of the Universe was discovered with the aid of precisely those objects.

There is no doubt that a thermonuclear explosion is the mechanism underlying the explosion of type Ia supernovae. This mechanism leads to a complete disruption of a star. Supernovae of other types stem from the collapse of the core of a star. In contrast to thermonuclear supernovae, there are many more unclear points here in the explosion mechanism. The concluding part of this brief review article is devoted mostly to collapsing supernovae.

2. REDSHIFT IN COSMOLOGY

In 1929, E. Hubble, who worked at a new 2.4-m telescope of the Mount Wilson Observatory near Los Angeles, was able to estimate the distance to galaxies for the first time. By plotting the redshifts z of the spectral lines of those galaxies against the estimated distances d, he constructed a graph that, later on, was

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called the Hubble diagram. Fitting a straight line to these data, he obtained the dependence

$$z = \frac{\lambda - \lambda_{\text{lab}}}{\lambda_{\text{lab}}} = \frac{H_0 d}{c},$$

which is presently referred to as the Hubble law. Here, λ is the observed value of the wavelength for some structure in the spectrum of a specific object, while λ_{lab} is the laboratory value for the same structure. The value of the Hubble constant H_0 was overestimated by Hubble himself by almost an order of magnitude in relation to present-day data [about 70 km/(s Mpc)], but the very fact of the growth of the redshift with distance was established correctly. This fact is referred to as the recession of masses of luminous matter (galaxies and their clusters), in which case z is interpreted as a manifestation of the Doppler effect ($z = v/c$ at $v \ll c$ and $v = H_0 d$). I will try to show that, although it is legitimate to interpret unambiguously the Hubble law as a manifestation of the expansion of the observed Universe, the treatment of the redshift as the Doppler effect at large cosmological distances leads to logical difficulties and is, strictly speaking, unacceptable (sometimes, the cosmological redshift is associated in the literature with the Doppler effect by definition [1]).

Theoretically, the expansion of the Universe was discovered by Friedmann [2, 3] long before Hubble's studies. (De Sitter [4] derived his solutions still earlier, but his treatment of these solutions was purely formal; only the studies of Friedmann [2, 3] established the physics pattern of a nonstationary universe—that is, they created the framework within which modern physical cosmology develops.) Friedmann's line of reasoning can be traced in the following way.

A two-dimensional sphere specified by the metric $d\ell^2 = a^2(d\theta^2 + \sin^2\theta d\varphi^2)$ is curved, but, since it is the surface of the ball $x^2 + y^2 + z^2 = a^2$, the sphere is obviously isotropic and uniform, in just the same way as a two-dimensional (2D) plane, whose metric can be represented in the form $d\ell^2 = a^2(d\theta^2 + \theta^2 d\varphi^2)$, where the polar radius is denoted by θ instead of conventional r.

If we now take a flat three-dimensional (3D) space and replace its metric

$$d\ell^2 = da^2 + a^2(d\theta^2 + \sin^2\theta d\varphi^2)$$

by

$$d\ell^2 = a^2[d\chi^2 + \sin^2\chi^2(d\theta^2 + \sin^2\theta d\varphi^2)], \tag{1}$$

then, by analogy with a 2D sphere, we obtain an isotropic and uniform 3D space in the form of the surface of the 4D ball,

$$w^2 + x^2 + y^2 + z^2 = a^2,$$

where a is the radius of curvature of the 3D space. Writing $ds^2 = c^2dt^2 - d\ell^2$ for four-dimensional space-time, we will arrive at the metric of the world in the form discovered by Friedmann and used in the cosmological section of the textbook by Landau and Lifshitz [5]. A somewhat different form is obtained upon the substitution $\sin\chi = r$, in which case $d\chi^2 = dr^2/(1 - r^2)$; as a result, the interval can be written in the form

$$ds^2 = c^2dt^2 - a^2(t) \times \left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta d\varphi^2)\right].$$

(We note that, here, r is a dimensionless quantity!) This is the Friedmann metric in the Robertson—Walker form. At $k = 1$, we have a closed Friedmann universe (where the curvature of 3D space is positive), while, at $k = 0$, there arises a 4D world with a flat 3D space. In the latter case, the quantity $a(t)$ loses the meaning of the radius of curvature; therefore, it would be better to refer to it as a scale factor for all of the versions. It can easily be verified that the case of $k = -1$ corresponds to yet another world, that where 3D space is of negative curvature, featuring Lobachevski geometry [3]. It is obtained from the case of $k = +1$ by means of the substitution $\sin\chi \to \sinh\chi$. In all of these cases, the point $r = 0$ can be chosen arbitrarily in a uniform space, in just the same way as a pole on a uniform 2D sphere. We assume that galaxies are points associated with fixed values of r, θ, and φ (comoving coordinates) and that the scale factor $a(t)$ determines the expansion of the Universe. According to present-day data, it is better, strictly speaking, to take the centers of mass of galaxy clusters (rather than galaxies) for "fixed" points, since galaxies can move within clusters at peculiar velocities of about 1000 km/s.

Friedmann did much more than just a number of coordinate transformations. He showed (taking into account the possibility that the cosmological Λ term in nonzero) that all versions of the metrics that he considered can provide exact solutions to the Einstein equations for a reasonable choice of equation of state for matter. It is only necessary to determine the behavior of the scale factor $a(t)$ for a nonstationary world with allowance for this equation of state.

From the Einstein equations (see, for example, [5]) or directly from the Hilbert variational principle (see [6]), one can easily obtain

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\text{N}}}{3c^2}\mathcal{E} - \frac{kc^2}{a^2}, \tag{2}$$

where $\dot{a} \equiv da/dt$, G_{N} is the Newtonian gravitational constant and $\mathcal{E}$ is the density of all forms of energy. This relation is referred to as the Friedmann equation.

The physical meaning of this equation can be understood by using prerelativistic physics. If we introduce the mass M within the radius $R = a$,

$$\frac{4\pi\mathcal{E}a^3}{3c^2} = M,$$

the result obtained from the Friedmann equation is identical to that in the Newtonian case under the condition that the whole energy density is due to nonrelativistic baryons—that is, to matter of pressure $P = 0$.

Assuming that the mean matter density ρ is uniform at large scales ($R > 10$ Mpc in the present-day Universe), we find that the mass within the radius R is $M = 4\pi\rho R^3/3$, and Newton's laws lead to the energy-conservation law

$$\frac{u^2}{2} - \frac{G_{\mathrm{N}}M}{R} = -\mathrm{const},$$

which holds as long as $u \equiv \dot{R} \ll c$, so that

$$\frac{(\dot{R})^2}{2} - \frac{4\pi G_{\mathrm{N}}\rho R^2}{3} = -\mathrm{const}.$$

This relation is equivalent to the Friedman equation (2), and this is good, since, on small scales, the world (spacetime) is flat, so that the general theory of relativity must reduce to nonrelativistic mechanics according to the correspondence principle.

But in fact, matter in the Universe is likely to involve, in addition to baryons, dark matter, which is cold in all probability—that is, nonrelativistic. Moreover, the results of observations require introducing a new substance, which was referred to, not quite appropriately, as dark energy (DE). This may be either a constant nonzero vacuum energy density or a new field [1]. In order to explain observations, it is only necessary that an equation of state of the form $P = w\mathcal{E}_{\mathrm{DE}}$ be valid, with the coefficient w being negative (in the first approximation, it is close to -1)—that is, in contrast to ordinary gases, which have a positive pressure, this substance must be in a state of tension, as stretched elastic rubber (but stretched isotropically—that is, uniformly in all directions of 3D space!).

In the Friedman equation (2), one can immediately take into account a nonzero vacuum energy density (dark energy) by assuming that the energy density $\mathcal{E}$ involves two components, $\mathcal{E} = \mathcal{E}_m + \mathcal{E}_{\mathrm{DE}}$, where the first component is the energy density of matter, while the second component is the vacuum (dark) energy density.

In the simplest form, the inclusion of a constant vacuum energy density is equivalent to supplementing the Einstein equations with a cosmological constant Λ. The vacuum energy behaves as an ideal liquid whose density is given by

$$\mathcal{E}_{\mathrm{vac}} = \frac{c^4\Lambda}{8\pi G_{\mathrm{N}}}.$$

We arrive at $P = -\mathcal{E}_{\mathrm{vac}}$, provided that the thermodynamic identity $d(\mathcal{E}_{\mathrm{vac}}/\rho) - Pd\rho/\rho^2 = 0$, where ρ is the baryon-number density, holds. Thus, we have $w = -1$. Below, we will not distinguish between $\mathcal{E}_{\mathrm{vac}}$ and $\mathcal{E}_{\mathrm{DE}}$, but, in general, $w \neq -1$ for the case of dark energy. Since the matter energy density and the radiation energy density both decrease as the Universe expands, the vacuum energy, if any, may appear to be dominant in the dynamics of expansion.

The velocity of expansion is measured by the Hubble parameter

$$H = \frac{\dot{a}}{a}.$$

The value of the Hubble parameter in the present era is referred to as the Hubble constant H_0 (it is constant in space rather than in time in uniform models featuring a synchronized time t [7]). Since $H_0 = (\dot{a}/a)_{\mathrm{now}}$, we can see that the constant k in the Friedmann equation is positive or negative, depending on the ratio

$$\Omega \equiv \frac{\mathcal{E}}{\rho_c c^2}, \quad \text{where} \quad \rho_c \equiv \frac{3H_0^2}{8\pi G_{\mathrm{N}}}.$$

If $\Omega > 1$, then $k = 1$. At $\Omega = 1$, 3D space is flat: $k = 0$; for $\Omega < 1$, we have $k = -1$.

For matter (that is, for ordinary and dark matter taken together), we will write $\Omega_m \equiv \mathcal{E}_m/\rho_c c^2$. For the vacuum or dark energy, we introduce the notation $\Omega_\Lambda \equiv \mathcal{E}_{\mathrm{DE}}/\rho_c c^2$.

Astronomers also introduce the dimensionless deceleration parameter

$$q = -\frac{a\ddot{a}}{\dot{a}^2},$$

which measures the rate at which the velocity of expansion changes. For historical reasons, this parameter was defined with a minus sign, since it was believed that deceleration was natural, but, according to present-day data, $q < 0$; that is, $\ddot{a} > 0$, and the expansion of the Universe is accelerated.

It can be shown that the photon frequency satisfies the relation

$$\omega a(t) = \mathrm{const}. \quad (3)$$

The simplest way to derive this relation is to go over to the conformal time η specified by the equation $d\eta = cdt/a(t)$ (see, for example, [5]).

The metric $ds^2 = c^2dt^2 - a(t)^2d\ell^2$ is nonstatic, but, written in terms of the time coordinate η, it assumes the form $ds^2 = a(\eta)^2(d\eta^2 - d\ell^2)$. The spatial part $d\ell^2$ is independent of η, so that zero geodesic lines are $ds = 0$—that is, light rays in the coordinates η and ℓ are identical for different initial instants η_e of the emission of light signals, and all intervals $\Delta\eta$ between the signals are constant. This means that, if the interval of the physical time between the instants of emission of two light signals at one point is Δt_e, then the interval between the instants of reception, Δt_r, varies in proportion to a, since $dt \propto a(t)d\eta$, whence we obtain Eq. (3).

A photon emitted with a frequency ω_1 will be observed with a lower frequency ω_0 if the scale factor grows:

$$\frac{\omega_0}{\omega_1} = \frac{a_1}{a_0}.$$

In cosmology, the subscript "0" is always reserved for the modern era, so that a_1 is an earlier (and smaller) value of the scale factor than a_0. The redshift measured by astronomers is then given by

$$z = \frac{\lambda_0 - \lambda_1}{\lambda_1} = \frac{a_0}{a_1} - 1.$$

It should be emphasized that this redshift does not reduce to the conventional Doppler effect, although relation (3) can sometimes be deduced, under some assumptions, from the Doppler effect for close observers. The relative velocity of close observers (occurring at a small distance of $c\delta t$) is $v = Hc\delta t = \dot{a}c\delta t/a = c\delta a/a$. According to the Doppler effect, we then have

$$\frac{\delta\omega}{\omega} = -\frac{v}{c} = -\frac{\delta a}{a},$$

whence we obtain Eq. (3) upon integration. This derivation is given by Zeldovich and Novikov in [8], but the following comments are in order here: first, this derivation does not work in all of the cases where the above derivation in terms of the conformal time η from [5] is valid; second, it is hazardous to apply the Doppler interpretation of the cosmological redshift z at large distances. This issue was discussed in detail by Harrison [7, 9], predominantly from the philosophical point of view. I will give more physical arguments.

Let us consider the closed Friedmann universe ($k = +1$), and let t_0 correspond to the instant of largest expansion: $\dot{a}(t_0) = 0$. Suppose that an observer who measures redshifts has the coordinate $r = 0$. In the first order in r, neighboring objects are immobile; however, the velocity of recession of objects at a distance $c\delta t = a(t_0)r$ is nonzero in the second order, and calculations reveal that the Doppler redshift is $z_{\rm Dop} = r^2$. At the same time, the correct result according to Eq. (3) is $z = r^2/2$. This distinction is explained trivially by the difference in the expressions for the velocity $\delta v = \ddot{x}\delta t$ and the coordinate $\delta x = \ddot{x}(\delta t)^2/2$. The correct answer arises only upon supplementing the Doppler effect with the Einstein effect of violet shift, $z_{\rm Ein} = \delta\phi/c^2 = -r^2/2$ (here, $\delta\phi$ is the change of the gravitational potential between the objects). We then have $z = z_{\rm Dop} + z_{\rm Ein} = r^2/2$, in which case the derivation of the cosmological redshift according to [8] is inapplicable, this being indicated there. In the general case of a variable density, the Einstein shift effect cannot be singled out in a pure form, so that the equations of photon propagation must be solved directly [10].

Despite a strong temptation to attribute the cosmological redshift to the relative motion of an observer and an emitter, this is possible at large distances only in a flat world. In a curved space, this can be done only at the instant when an observer and an emitter occur at the same point, moving relative to each other. The problem is that, in a curved spacetime one cannot transport a vector (the velocity of a far object here) to the observation point: the result of a parallel transportation depends on the path along which this is done. By way of illustration, we take an arbitrary vector at the emission time t_1 at the point r_1 and transport it parallelly toward an observer at t_0 at the point r_0. In doing this, we fix the angular coordinates θ and φ and compare two possible "natural" paths of the transportation of this vector:

(i) that which first goes from r_1 to r_0 at constant $t = t_1$ and then from $t = t_1$ to t_0 at constant $r = r_0$;

(ii) that which first goes from t_1 to t_0 at constant $r = r_1$ and then from r_1 to r_0 at constant $t = t_0$.

It is clear that the results will be different for the different paths in a curved spacetime, the difference being proportional to the area within the contour formed by these two paths (that is, it increases with increasing difference of t_1 and t_0 and with increasing difference of r_1 and r_0). It should be emphasized that a nonempty 4D world is curved even if $k = 0$ and 3D space is flat! Therefore, the interpretation of the redshift in terms of the Doppler effect loses physical meaning at cosmological distances, since the concept of a relative velocity becomes meaningless. (Davis and Lineweaver [11] discussed the inapplicability of the formulas of the special theory of relativity in what is concerned with the Doppler effect in cosmology, but they did not even touch upon a greater danger—the fact that the concept of a relative velocity loses physical meaning.) It is safe to say that, owing to the relation $\omega a(t) = \text{const}$, the redshift is a geometric effect of the expansion of the Universe, but it is illegitimate to associate the change in the photon frequency with the relative velocity of the objects being considered.

3. PHOTOMETRIC DISTANCE

The redshift can be measured: if we know the laboratory wavelengths of various spectral lines in the spectra of distant objects, we can say how their wavelengths changed from the emission instant t_1 to the observation instant t_0. From here and from (3), we know the ratio of the scale factors at these two instants:

$$\frac{a(t_0)}{a(t_1)} = 1 + z.$$

How can we measure distances?

We can introduce a formal definition of a proper distance:

$$d(t) = a(t)r; \tag{4}$$

it would be measured (at $k = 0$) at the coordinate-time instant t by a set of observers with rigid rulers between the points having the radial coordinates 0 and r [10, 12]. (Recall that r is dimensionless!)

The definition of a comoving distance, $d_c = a(t)\chi$, where χ is the Friedmann radial coordinate introduced in Eq. (1) (see, for example, [13]), is of importance in theoretical cosmology.

We cannot measure directly the "distances" d and d_c to far objects in the expanding Universe with the aid of rules or radio detection and ranging. Instead, various definitions are introduced in cosmography that depend on those measurements that can actually be performed (for example, the angular distance determined by measuring the transverse angular size of a standard ruler). Details are nicely explained by Weinberg [12]. I also follow the text of Carroll [14], but I would like to emphasize that it is not easy to find, in standard textbooks, a complete derivation of a formula that would relate distances to cosmological parameters. Therefore, I give such a derivation in the present article.

The so-called photometric distance

$$d_L = \left(\frac{L}{4\pi S}\right)^{1/2},$$

where L is the absolute luminosity (light power) of a source and S is the flux measured by an observer (energy arriving within a unit time per unit area of the receiver), is the most valuable for us. This definition corresponds to the statement that, in flat space, the flux at distance d from the source is $S = L/(4\pi d^2)$. In the Friedmann universe, however, it would be incorrect to substitute here naively $d = a_0 r$ from (4), where a_0 is the scale factor at the instant when photons were observed at the comoving coordinate r measured from the source.

The point is that the flux decreases because of two effects: individual photons undergo a phase shift by the factor $(1 + z)$, and the frequency of photon arrival also decreases by the factor $(1 + z)$. Therefore, we have

$$S = \frac{L}{4\pi a_0^2 r^2 (1+z)^2}$$

or

$$d_L = a_0 r(1 + z) = d(t_0)(1 + z). \tag{5}$$

The photometric distance d_L is a quantity accessible to measurement if we have at our disposal an astrophysical source whose absolute luminosity L is known (cosmological standard candle). But r is not observable, so that it is necessary to get rid of it. On the zero geodesic line where $d\theta = d\varphi = 0$, we have

$$0 = ds^2 = c^2 dt^2 - \frac{a^2}{1 - kr_1^2} dr_1^2$$

or

$$\int\limits_{t_1}^{t_0} \frac{c\,dt}{a(t)} = \int\limits_0^r \frac{dr_1}{(1 - kr_1^2)^{1/2}}.$$

We now make the transformations

$$\int\limits_{t_1}^{t_0} \frac{dt}{a(t)} = \int\limits_{a_1}^{a_0} \frac{dt}{da}\frac{da}{a} = -\int\limits_{a_0/a_1}^{1} \frac{a}{a_0}\frac{dt}{da} d\left(\frac{a_0}{a}\right)$$

$$= \int\limits_{1}^{a_0/a_1} \frac{a}{a_0}\frac{dt}{da} d\left(\frac{a_0}{a}\right),$$

whence we obtain

$$a_0 \int\limits_0^r \frac{dr_1}{(1 - kr_1^2)^{1/2}} = c\int\limits_1^{z+1} \frac{d(z_1+1)}{H} = c\int\limits_0^z \frac{dz_1}{H},$$

so that everything has reduced to observables like $1/H$ (equal $a/\dot{a}$), z (with the aid of the relation $a_0/a_1 = z + 1$), and so on. In this way, we can get rid of r in the expression for d_L by expressing r in terms of the elementary integral $\int_0^r (1 - kr_1^2)^{-1/2} dr_1$ and $\int_0^z dz_1/H$.

In order to do this, we make use of the Friedman equation, taking simultaneously into account the possibility of a nonzero vacuum energy.

We write the Friedmann equation (2) in the form

$$H^2 = \frac{8\pi G_N \mathcal{E}}{3c^2} - \frac{kc^2}{a^2},$$

which is equivalent to

$$H^2 = H_0^2[\Omega_m (1+z)^3 + \Omega_\Lambda + (1 - \Omega_m - \Omega_\Lambda)(1+z)^2],$$

where $\Omega_m = \mathcal{E}_m/\rho_c c^2$ and $\Omega_\Lambda = \mathcal{E}_{\rm DE}/\rho_c c^2$ are the parameters that were introduced above to characterize, respectively, the density of nonrelativistic matter [its density $\mathcal{E}_m$ varies in proportion to $(1+z)^3$ in accordance with the variation of the comoving volume] and the vacuum-energy density (this density is constant in the simplest case of the Λ term). Substituting H into the expression $\int_0^z dz_1/H$ and expressing r in terms of $\int_0^r (1-kr_1^2)^{-1/2} dr_1$ only for the case of $k=-1$ (the cases of other k values are obtained automatically by means of an analytic continuation), we arrive at the required formula for the photometric distance:

$$d_L = \frac{c}{H_0}(1+z)\frac{1}{\sqrt{\Omega_k}}\sinh\left\{\sqrt{\Omega_k}\int\limits_0^z \left[\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2\right]^{-1/2} dz\right\}.$$

Here, $\Omega_k \equiv 1 - \Omega_m - \Omega_\Lambda$; for $\Omega_k < 0$, the hyperbolic sine (sinh) goes over to the trigonometric sine (sin), while $\sqrt{\Omega_k}$ goes over to $\sqrt{|\Omega_k|}$. For $\Omega_k \to 0$, the limit can easily be evaluated, sinh disappearing from the expression for d_L, where there only remains the integral $\int_0^z [\ldots]^{-1/2} dz$.

The dependence $d_L(z)$ can now be expressed in terms of cosmological parameters. We can see from Eq. (5) that d_L is very simply related both to d from Eq. (4) and to the Friedmann radial coordinate χ from Eq. (1).

For some important particular cases, we can write simple analytic expressions for the proper distance $d = d(z)$, which, according to Eq. (5), differs from d_L only by the factor $(1+z)$. By way of example, we indicate that, for the vacuum-dominated de Sitter universe ($\Omega_\Lambda = 1$, $\Omega_m = 0$), the result is

$$H_0 d = cz.$$

For an empty universe ($\Omega_\Lambda = 0, \Omega_m = 0$), we have

$$H_0 d = \frac{c}{2}\left[(1+z) - \frac{1}{1+z}\right].$$

In the case of a flat (parabolic) Friedmann universe ($\Omega_\Lambda = 0$), $\Omega_m = 1$:

$$H_0 d = 2c\left(1 - \frac{1}{\sqrt{1+z}}\right).$$

In all of the above cases, these formulas reduce to the Hubble law $H_0 d = cz$ at small z, but they differ significantly at large value of the redshift z.

Intermediate values of $\Omega_\Lambda \approx 0.7$ and $\Omega_m \approx 0.3$ correspond to the modern standard model of the Universe ("concordance model"). These values were first obtained from observations of distant supernovae. We will now proceed to consider these extremely interesting objects.

4. SUPERNOVAE OF VARIOUS TYPES

Supernovae (Supernova = SN, Supernovae = SNe) are explosive bursts of stars whose luminosity (that is, radiation power) is $L \sim 10^{10} L_\odot$ or higher for a few weeks. Here, $L_\odot \approx 4 \times 10^{33}$ erg/s is the luminosity of the Sun—that is, one supernova develops, within some time interval, the same light power as a mean galaxy consisting of billions of stars. It is this power that makes it possible to use supernovae in cosmography. A larger part of the star mass is disintegrated and ejected. Supernovae are among the strongest explosions in the Universe: the ejected kinetic energy is $E \sim 10^{51}$ erg.

The energy of an explosion is estimated as follows. From the widths of spectral lines, it can be found that the speed in the atmosphere is $v \sim 10^4$ km/s or higher. On the basis of a simulation of the light curves—that is, the dependences $L(t)$—the mass $M_{\rm ej}$ is estimated at about $1 M_\odot$ to a few tens of $M_\odot$.

From here, one obtains estimates for the kinetic energy of supernova ejection for all types of supernova outbursts [the Ia, Ib/c, and II types are introduced in accordance with the special features of respective spectra (for details, see below)]: on average, $E \sim 10^{51}$ erg $\equiv$ 1FOE [10 raised to the power of 51 or Fifty-One Ergs (FOE)], although there occur deviations of an order of magnitude above and below this value. Within a few ten thousand years, this energy dissipates in the circumstellar medium, heating it and generating x rays and cosmic rays—that is, it generates a gaseous remnant of a supernova.

The aforementioned ejecta enrich the medium in heavy elements. Shock waves gather the circumstellar medium into dense clouds, and this leads to the formation of young stars. The history of investigations devoted to supernovae is outlined in the monograph of Shklovsky [15] and in the review articles [16, 17].

Owing to the use of state-of-the-art astrophysical methods, a vast body of observational data on supernovae has been obtained over all ranges of electromagnetic radiation—from the radio-wave to the x-ray range. Also, the first nonelectromagnetic signals—neutrinos from the SN 1987A—have been recorded. Despite all this, the mechanisms of supernova explosions have yet to be clarified conclusively. In recent years, there have appeared indications that some cosmic gamma-ray bursts are related to supernovae. Possibly, the origin of gamma-ray bursts is also related to the origin of supernova explosions.

Cosmic gamma-ray bursts are irregular pulses of photons whose energies range between about 0.1 and 1 MeV or take even higher values, the pulse duration being a few tenths of a second to a few minutes. The exposure corresponding to the weakest of such pulses is $S \sim 10^{-7}$ erg/cm^2 $\sim$1 photon/cm^2, but many of them are much stronger. Gamma-ray bursts are surveyed in [18, 19]. However, any surveys are always behind the latest advances in the vigorously developing science that explores powerful explosions in the Universe, this especially concerning the most recent discoveries in the realms of gamma-ray bursts.

Theory proposes various explanations for the origin of the supernova energy and seeks mechanisms underlying supernova explosions. In thermonuclear scenarios, an explosion begins because of the development of a thermal instability in the degenerate stellar core upon the ignition a carbon–oxygen mixture (helium in some scenarios).

The gravitational collapse of a star into a neutron star or a black hole—this seems a more efficient mechanism of a star explosion—was described long ago. Theoretically, the energy released in this case may be an order of magnitude higher than the thermonuclear energy—specifically, it must be about 10% of the star-core mass. For a core of mass $1M_\odot$, this energy is about 10^{53} erg; for a more massive core, it is naturally still higher. But in the case of supernova explosions, the bulk of energy is carried away by the neutrino flux. In gamma-ray bursts, gamma-ray photons alone carry up to about 10^{54} erg! This value is obtained from the observed flux S by the formula $E_{\text{gamma-ray burst}} = 4\pi S d_L^2$, where d_L is the photometric distance to the gamma-ray burst under study. It is of course clear that, in this formula, the flux S must be multiplied by some small solid angle rather than by 4π. The energy will then be lower, but it is necessary to reveal concurrently the reasons behind the release of energy in the form of a narrow beam or jet within this small angle. Possibly, the asymmetry of explosions is related to some phenomena in supernovae.

The traditional astronomical classification partitions supernovae into two classes: type-I (SN I, whose spectrum does not contain hydrogen lines in the vicinity of the maximum light) and type-II (SN II, whose spectrum features hydrogen lines there) supernovae. Later, this classification was refined. The first class was divided into subclasses: SN Ia and SN Ib/c. The spectra of SN Ib/c in the vicinity of the maximum light do not exhibit a silicon line, which is pronounced in SN Ia. The spectra of SN Ia and SN Ib/c show the most glaring distinctions within a late era, $t \gtrsim 250$ days after the explosion, where the spectra of SN Ia are formed largely by the lines of ionized iron, while the spectra of SN Ib/c are dominated by an extremely powerful emission from oxygen. Nonthermal radiation from SN Ib/c was discovered, and these objects are likely to be correlated with the regions of active star formation. In all probability, these supernovae explode through the collapse of cores of massive stars (in just the same way as SN II), whereas SN Ia are thermonuclear explosions of white dwarfs in binary systems that have lost hydrogen by the instant of the explosion (no neutron stars or black holes arise in this case). Thus, the classical astronomical classification of supernovae does not take fully into account the special features of the mechanism governing the explosion, which occurs in the interior of the star—it is more adequate to the structure of the outer layers of a supernova.

The SN II phenomenon can arise at the end of the lifetime of a single massive star that preserved hydrogen in its envelope. The outbursts of SN Ib/c can occur in the collapse of the core of a single massive star that lost hydrogen. If the SN Ic subtype can actually be distinguished from SN Ib, this means that SN Ic massive presupernovae lost not only hydrogen but also helium. In SN Ia, approximately half the ejected mass is due to elements of the iron peak, while, in SN Ib/c, the bulk of these elements went into the collapse. Therefore, SN Ib/c ejection is dominated by elements like oxygen, whereby the distinction between the spectra of supernovae belonging to different types is explained.

The affiliation of a star with a binary system plays a crucial role in the evolution of type Ia presupernovae. Binarity effects seem responsible for the properties of some peculiar type II supernovae as well. The possibility of a gamma-ray burst in a binary system leads to interesting effects—this is one of the possible models for the afterglow of a gamma-ray burst [20]. Moreover, the idea that gamma-ray bursts can be generated at cosmological distances in the merger of a neutron-star binary was put forth long ago [21].

5. TYPE Ia SUPERNOVAE: STANDARDIZATION OF A CANDLE

Owing to a number of factors, type Ia supernovae (SN Ia) are convenient for measuring distances and for determining the geometry of the Universe. First, these are very bright objects, so that we can obtain rich information about them even if they explode in very distant galaxies characterized by large redshifts z. Second, the spectra of SN Ia and the shapes of their light curves seem to suggest, at first glance, that they form quite a uniform class. Formerly, it was assumed that they are cosmological standard candles in the sense that the maxima of the absolute luminosity are identical for different SN Ia.

However, this is not so! A closer inspection of SN Ia revealed distinctions within this class of objects.

Long ago, Pskovskiĭ showed [22] that the flux maxima in the SN I spectra are not identical, and his colleagues revealed clear-cut distinctions even within the subclass of thermonuclear SN Ia [23].

Pskovskiĭ [22] also found the interplay between the maximum luminosity of SN Ia and the rate of the subsequent weakening of flux. The flux of more powerful bursts decreases more slowly than the flux of their less powerful counterparts. Later on, this dependence was vigorously studied by many astronomers interested in SN Ia—especially meticulous studies on the subject were performed by Phillips and his colleagues [24, 25] on the basis of observations of close supernovae characterized by moderately small z.

When astronomers discover a supernova characterized by a large redshift z, they determine the rate of the decrease in its flux after the maximum; only after the application of the Pskovskiĭ–Phillips dependence, which provides the only way to perform the "standardization of a candle", can one estimate the luminosity of the supernova and, hence, the photometric distance d_L to it. However, the Pskovskiĭ–Phillips dependence is of a correlation rather than a functional character; therefore, each individual measurement may involve large errors.

An unexpected result was obtained in the studies of two groups [26, 27]: from observational data on distant supernovae, it follows quite reliably that $\Omega_\Lambda > 0$; that is, the expansion of the Universe accelerates.

A vast body of observational data has been accumulated since then. The table presents the cosmological parameters obtained in one of the recent studies [28] on SN Ia. The authors of [28] show that the observed distribution of $d_L(z)$ can be explained only by assuming a nonzero vacuum energy or a rather artificial systematic effect: the emergence of dust in a recent era.

It should be noted that, in all of the studies devoted to high-z supernovae, use was made of relations of the Pskovskiĭ–Phillips type (*maximum luminosity–rate of the decrease in flux* relation), which were obtained from an analysis of close objects. But even for close SN Ia, deviations from such dependences for individual objects cannot be explained by the errors of the observations exclusively.

From the theoretical point of view, the flux decreases more slowly with increasing maximum luminosity because both these quantities are controlled primarily by the amount of ^{56}Ni formed in the explosion. The maximum of the luminosity of SN Ia is determined by the amount of ^{56}Ni since the light curve is formed predominantly by the contribution of its radioactive decay. On the other hand, a large amount of nickel is expected to increase the nontransparency of matter greatly. The diffusion of radiation through a stellar medium takes a longer time, and the light curve becomes more gently sloping. However, the decrease on the light curve depends not only on the amount of nickel but also on its distribution (and on the distribution of other heavy elements as well) within the expanding star and on the velocity of the expansion of matter. In turn, this distribution and this velocity depend on how burning propagated through the star.

Values of χ^2 in comparing data on 157 SN Ia with various models

Model	χ^2
$\Omega_m = 0.27, \Omega_\Lambda = 0.73$	171
$\Omega_m = 1.00, \Omega_\Lambda = 0.00$	497
$\Omega_m = 0.00, \Omega_\Lambda = 0.00$	196
Gray dust (at $\Omega_m = 1.00, \Omega_\Lambda = 0.00$)	293
Recent dust (at $\Omega_m = 1.00, \Omega_\Lambda = 0.00$)	168
Weakening in proportion to z (at $\Omega_m = 1.00, \Omega_\Lambda = 0.00$)	241

The theory of burning in supernovae has actively developed since the studies of Arnett [29], Ivanova *et al.* [30], and Nomoto *et al.* [31], but many problems in it have yet to be solved (see, for example, [32, 33]).

A great number of models have been proposed to describe the explosion of SN Ia characterized by various masses, various regimes of burning (detonation, deflagration, and various combinations of these mechanisms), various energies of the explosion, and various velocities of matter expansion. In these theoretical models, chemical elements originate from burning in markedly different proportions, their distributions over the star also being different. This leads to different theoretical light curves. By comparing the resulting light curves with their observed counterparts, one can find out which explosion models are more realistic.

By considering the possibility of employing SN Ia in cosmology, it was concluded in [34] that, at the present time, the statistics of distant supernovae are insufficient for drawing definitive conclusions on the geometry of the Universe. Terrestrial experiments revealed that the regime of burning in an explosion cannot always be predicted in advance. For supernovae, the situation is similar: it is quite feasible that the distinction between initial conditions only changes the probabilities of various scenarios of burning, but that this does not pinpoint a specific scenario. Since the regime of burning affects strongly the shape of the light curve, the rate of the decrease cannot be reliably predicted if only initial conditions are known. The probability of one value of the rate of the decrease in flux or another—recall that this quantity plays a significant role in determining cosmological parameters—can be established only upon collecting sufficiently vast observational statistics of SN I*a* at various values of z.

Upon an increase in statistics, it would be possible to reveal subtler effects—in particular, to answer the question of whether the dark-energy density is constant and to establish the relevant equation of state. For example, there are even presently attempts [35] at extracting, from observations of SN I*a*, the z dependence of the coefficient w in the equation $P = w\mathcal{E}_{\rm DE}$. These attempts are as yet premature, since they take no account of the fact that the properties of supernovae themselves or the regimes of burning in them and their light curves can evolve with the age of the Universe. Moreover, there are also problems in the very procedure for extracting the dependence $w = w(z)$ from observations (see, for example, the article of Jonsson *et al.* [36], who criticize the results reported in [35]). In addition, it should be noted that no significant evolution of dark energy can be revealed [37] by combining data on supernovae with data on cosmic microwave background radiation and x-ray radiation from galaxy clusters.

6. CORE-COLLAPSE SUPERNOVAE

Let us now briefly touch upon the as-yet-unresolved problem of explaining the explosion in the core collapse and indicate what may be here in common with the problem of gamma-ray bursts.

At the end of the lifetime of massive stars, a core collapse must develop upon the depletion of the nuclear fuel.

As far back as the 1930s, Baade and Zwicky [38] put forth the idea that there is a relationship between supernovae outbursts and the formation of neutron stars; however, the quantitative theory of the explosion mechanism in the collapse is still far from completion. From a simple estimate of the gravitational energy $\mathcal{E}_g = -G_{\rm N}\int mdm/r \sim -G_{\rm N}M^2/R$, it follows that an energy of about $|\mathcal{E}_g| \sim 10^{53}$ erg is released in the formation of a neutron star of mass $M \approx 1M_\odot$ and radius $R \approx 10^6$ cm. However, this energy is released predominantly in the form of neutrinos rather than in the form of cosmic rays or photons, as was hypothesized by Baade and Zwicky. It is not easy to estimate the energy that is transferred to the envelope around the emerging neutron star and which is responsible for a supernova outburst. Even detailed computer calculations yield contradictory results because of uncertainties in the equation of state for superdense matter, in the rates of weak-interaction reactions, and in the fundamental properties of the neutrinos (for example, their oscillations), as well as because of difficulties in describing neutrino transport and because of the emergence of convection.

If, in the main sequence, a star had a mass in the range $8M_\odot \lesssim M \lesssim 20M_\odot$, then, at the end of its evolution, there arises a partly degenerate core of mass close to the Chandrasekhar limit. At the same time, the density becomes so high (10^9–10^{10} g/cm^3) that, owing to a large chemical potential (Fermi energy) of electrons, the neutronization reactions

$$e^- + (A, Z) \to (A, Z-1) + \nu_e \qquad (6)$$

begin to proceed actively even at zero temperature. As a matter of fact, the temperature at these stages reaches of few tens of kiloelectronvolts, this enhancing electron-capture reactions. Since electrons are relativistic at such densities, the adiabatic exponent is close to the critical value of 4/3. With increasing density, the number of electrons per baryon, Y_e, decreases, and the pressure begins, at some instant, growing more slowly than in proportion to $\rho^{4/3}$; this means that the gravitational force grows faster than the pressure force, with the result that a catastrophic compression (collapse) develops [16]. At the initial mass of a star in the region $M > 20M_\odot$, the mass and temperature are substantially higher, and a collapse begins owing to the photon-induced splitting of nuclei. At a still higher mass, $M \gtrsim 60M_\odot$, the production of e^+e^- pairs begins contributing to the reduction of the elasticity of matter and to the loss of stability. It should be borne in mind that the above mass values are very rough because the modern theory takes very roughly into account a number of important phenomena, including a continuous loss of star mass, the rotation of stars, and the fact that they form binary systems.

As the collapse reaches the dynamical stage, the central regions of the star are compressed, within a hydrodynamic time of $t_{\rm hyd} \sim (G_{\rm N}\rho)^{-1/2}$, which is a few tenths of a second, to nuclear-matter densities. Within so short a time, photon diffusion and the electron thermal conductivity are unable to remove heat efficiently; therefore, temperature grows almost adiabatically at first. The majority of the nucleons remain bound in nuclei up to densities at which nuclei begin touching one another. Only at such densities does the elasticity of matter increase sharply, and there can occur the termination of the collapse if the mass does not exceed some limit. The reverse motion (bounce) of matter generates a shock wave at a distance of about 50 km from the center, and this shock wave heats matter strongly. There then appear many free nucleons (because of the disintegration of nuclei). As a result, processes like

$$e^- + p \to n + \nu_e, \quad (7)$$

$$e^+ + n \to p + \bar{\nu}_e, \quad (8)$$

and the annihilation of electron–positron pairs into neutrionos,

$$e^- + e^+ \to \nu + \bar{\nu} \quad (9)$$

(this is one the most important processes at later stages of the evolution of massive stars), come into play.

An order of magnitude estimate of weak-interaction cross sections is $\sigma \sim \widetilde{G}_{\mathrm{F}}^2 E^2$, where E is the characteristic energy of a given process and $\widetilde{G}_{\mathrm{F}} = G_{\mathrm{F}}/(\hbar c)^3$, with G_{F} being the Fermi constant. If one measures the particle energy in megaelectronvolts, it is convenient to write $\widetilde{G}_{\mathrm{F}}^2 = 5.3 \times 10^{-44}\ \mathrm{cm}^2/\mathrm{MeV}^2$. At temperatures of a few tens of MeV, which are attained in the case of collapse, an estimate of the cross section shows that neutrinos are vigorously produced, and it seems that they can readily transfer energy to the envelope. In the formation of a neutron star, neutrinos carry away more than 10^{53} erg—that is, about 10% of the mass of the Sun! If one percent of this energy were captured by the envelope of a star, the problem of the core-collapse mechanism of supernova explosion would be solved.

From the estimate of σ, it can be seen that, at densities above a value of about 10^{12} g/cm^3, the neutrino mean free path is indeed short—it may become five to six orders of magnitude smaller than the dimensions of a hot neutron star. In deep layers, the mean free path is determined primarily by the reactions that are inverse to the processes in (7) and (8). In the vicinity of the neutrinosphere and above it, coherent neutrino scattering on surviving nuclei is more important. Because of short mean free paths, neutrinos diffuse slowly, lose energy, and cannot eject its envelope.

For heating and ejecting outer layers of a collapsing stellar core, the process

$$\nu + \bar{\nu} \to e^- + e^+ \to \gamma,$$

which is inverse to that in (9), may also be of importance. Neutrino–antineutrino pairs of all neutrino flavors must be copiously produced in the collapse. The detailed neutrino spectra were first calculated by Nadyozhin [39]. Unfortunately, the neutrinos are overly soft for this process to be of importance for supernovae. But if hard neutrinos escape into a vacuum, it can produce many photons there! In fact, the process $\nu\bar{\nu} \to e^- + e^+$ was proposed by Berezinskii and Prilutskii [40] for explaining gamma-ray bursts before the commencement of its applications in the physics of supernovae.

7. ASYMMETRY OF THE EXPLOSION

Since spherically symmetric model calculations of collapsing presupernovae have not yet provided a successful pattern of explosions, it is necessary to seek mechanisms that do not feature symmetry. These mechanisms may be operative in gamma-ray bursts as well. If they produce a radiation flux into a solid angle Ω, the requirements on the energy of gamma-ray bursts are relaxed by the factor $\Omega/(4\pi)$. Observations have given many indications that supernova explosions are asymmetric:

(i) Radiation from collapsing supernovae is polarized to a considerable extent. The degree of this polarization grows with decreasing mass of the hydrogen envelope, reaching a maximum for SN Ib/c, which are deprived of hydrogen. A spectacular example is provided by a record polarization of the type Ic SN 1997X (in all probability, such supernovae are deprived of not only the hydrogen but also the helium envelope, and this means that the ejected mass must be especially small and that the asymmetry of the explosion must be the most pronounced in such objects).

(ii) In many cases (maybe even always), the explosion of a collapsing supernova is followed by the formation of a neutron star (known examples are provided by pulsars in the Crab nebula and in the Vela remnant). Many radio pulsars are observed to have velocities of up to 1000 km/s. A high momentum corresponding to such velocities is possibly associated with an asymmetry of the respective explosion.

(iii) Observations of SN 1987A revealed that

(a) in the course of the explosion, radioactive matter was very fast transferred to outer layers (also, a considerable mixing of ^{56}Ni is required for explaining the SN 1987A light curves);

(b) the infrared lines of oxygen, iron, nickel, and hydrogen exhibit a considerable asymmetry of the profiles;

(c) light was polarized;

(d) photographs from the Hubble cosmic telescope show a manifest asymmetry of ejecta, and the Chandra x-ray observatory recorded jets.

(iv) In the vicinity of the young remnant of the supernova ~1680 Cassiopeia A (Cas A), there are quickly moving lumps of matter rich in oxygen beyond the main envelope of the remnant (maybe, there are also two oppositely directed jets).

Three-dimensional images of the Cas A remnant show that the flocculent distribution of calcium, sulfur, and oxygen is not symmetric in the direction toward an observer. No simple spherical envelopes can be seen. This and other remnants have a systematic velocity of up to 900 km/s with respect to a local circumstellar medium. All of these asymmetries are expected to be associated with asymmetric flows of type Ib/c presupernovae leading to explosions that produce remnants like Cas A—that is, stars of the Wolf–Rayet type.

The latest x-ray observations of Cas A from the Chandra satellite show that ejected lumps rich in iron are farther from the center than layers rich in silicon.

(v) X-ray observations of ROSAT revealed lumps ("bullets") beyond the main envelope of the Vela remnant, radio-wave-emitting shock waves associated with them being indicative of a high speed of ejection of these lumps in a supernove explosion.

7.1. Mechanisms of the Asymmetry of a Collapse

Searches for the mechanism of a supernova explosion in the collapse of the stellar core have been a challenge for the theory for several decades. I would like to indicate three possible ways of an explosion:

(i) explosion under the effect of a neutrino flux,

(ii) magnetorotational mechanism of a supernova outburst (see [41] and § 36 in [42]; see also [43] for the latest results on the subject),

(iii) merger and explosions of neutron stars.

All of these mechanisms involve asymmetry in some degree and have some bearing on the generation of gamma-ray bursts. We will briefly dwell upon the last idea exclusively.

7.2. Exploding Neutron Stars in Binary Systems

For a neutron-star binary (NS + NS), an evolution scenario that leads to the explosion of one of the components and to a possible gamma-ray burst was proposed in [21]. The evolution of such a binary system is determined by gravitational radiation, which leads to the merger of the components. A similar process of the merger of white dwarfs may be one of the possible ways toward the explosion of SN Ia. It is then natural to address the question of how frequently such events may occur in the Milky Way Galaxy. This question was explored in [44], and it was shown there that the frequency of the (NS + NS) mergers of neutron-star binaries, $R_{\rm NS}$, is approximately equal to unity per about 3000 years if there is no recoil in the formation of neutron stars. This frequency falls to unity per about 10 000 years at a recoil velocity of 400 km/s.

The evolution of a neutron-star binary has not yet been calculated in detail. In just the same way as in some models of gamma-ray bursts, there can occur a direct merger involving the formation of a black hole and jets induced by the accretion disk. An alternative possibility was considered in [21]. When the major half-axis a of the orbit of a binary star becomes significantly smaller than its initial value, the less massive component (whose radius is larger) will fill its Roche lobe. This may lead to a significant flow to a massive satellite [21]. A neutron star of mass satisfying the condition $M < M_{\rm cr} \simeq 0.1 M_\odot$ is dynamically unstable. Therefore, the low-mass satellite must explode at some stage. A numerical simulation revealed that the explosion results in an energy release of $E_{\rm kin} \simeq 8.8 \times 10^{50}$ erg ($\sim$4.8 MeV/nucleon). Upon taking into account more accurately physical processes accompanying the explosion, this value becomes somewhat smaller—neutrino carry away a considerable part of the energy.

If, at the center of a quickly rotating collapsing presupernova, a neutron-star binary is formed (owing to the disintegration of the core), this must lead to an asymmetric explosion, which may serve as a trigger for a full-scale supernova explosion and to a strong mixing. This scenario was proposed by Imshennik [45]. It should be noted that, in contrast to what we have in the magnetorotational mechanism [42, 43], the magnetic field does not play a crucial role in the scenario considered in [45]. If the stability of flow is lost prior to reaching the minimum mass, there occurs the merger of neutron stars, in which case the energy is released predominantly in the form of neutrinos. Concurrently, there can occur jet formation [46]. In any case, the explosion is asymmetric.

7.3. Prospects of Verifying the Mechanisms of the Explosion of Collapsing Supernovae and Possible Relation to Gamma-Ray Bursts

Per average galaxy, the outbursts of core-collapse supernovae are severalfold more frequent than the outbursts of thermonuclear supernovae; however, the understanding of the former has not yet reached the level of understanding of the latter. The reasons for this are the following: the physics of matter at densities in excess of the nuclear-matter density is more uncertain, it is necessary to take into account all interactions (including relativistic gravity) at such densities, hydrodynamic flows are multidimensional in a collapse, and so on.

We will briefly indicate the main difficulties for employing the aforementioned promising mechanisms of the explosion of core-collapse supernovae.

(i) An explosion under the effect of neutrino radiation in a collapse requires developing an elaborate formalism that would describe neutrino transport in a three-dimensional convective flow for all neutrino flavors. It is necessary to take into account rotation and magnetic fields; possibly, it is also necessary to allow for the emission of gravitational waves. For an overview of the current state of this sector of supernovae theory, the interested reader is referred to [47], for example.

(ii) At the present time, the magnetorotational mechanism of a supernova outburst [41, 43] is the most successful. Here, the theory takes fully into account rotation and magnetic fields, which form the basis of the mechanism; however, other physics—for example, neutrino transport—has so far been described quite roughly. An insufficiently fast rotation of the cores of the majority of stars may be one of the difficulties in this model [48]—there is still no clarity in this issue.

(iii) Imshennik's mechanism [45, 49] also depends on the value of the angular momentum of central star regions before the collapse, and the emerging neutron star cannot disintegrate if this value is overly small. Here, there has remained one more as-yet-unexplored issue. The merger of a neutron-star binary [21] must inevitably proceed under the effect of gravitational radiation (we know this from observations of binary pulsars in the Milky Way Galaxy), but it is unclear at the present time whether the same radiation of gravitational waves (which efficiently carries away the angular momentum) may in principle cause the disintegration of a hot neutron protostar [50].

Per average galaxy, the frequency of gamma-ray bursts is two or three orders of magnitude less than the frequency of supernova outbursts; however, we cannot rule out the possibility that gamma-ray bursts accompany the collapse of massive stars if some special, quite exotic, conditions hold simultaneously (see, for example, [51, 52]). Since the mechanism of supernova explosion in the collapse has yet to be clarified, the theory of gamma-ray burst has to overcome more significant difficulties. We cannot rule out the possibility that the exoticism in a collapse does not concern the prevalent conditions exclusively: possibly, unknown exotic particles emerge under special conditions of a collapse, and it is these exotic particles that generate bursts [19]. If, for example, axion-like particles whose decay involves photon emission off the stellar core were formed in a collapse, then we would observe a supernova outburst in the presence of a massive envelope [53] or a powerful gamma-ray burst in the rare case of the absence of an envelope [54]. Such particles cannot be "conventional" hypothetical axions, since their properties must be substantially different from the properties of the latter; however, the constraints that were obtained from astrophysical data [55] should be respected. There is yet another exotic possibility, that which is associated with the process involving the formation of quark cores of neutron stars in a collapse. This process was proposed long ago in [56] (for relevant references and new ideas, see [57]).

In the near future, there will arise the possibility of recording the spectra of neutrinos and gravitational waves from star collapses. Together with terrestrial astronomical observations of supernovae and gamma-ray bursts and their observations performed beyond the atmosphere over all ranges of the electromagnetic spectrum, this will contribute to solving the most challenging problems of modern astrophysics and the physics of fundamental interactions.

8. CONCLUSION

I have tried to show how supernovae aid fundamental physics. On one hand, they demonstrate that the properties of a cosmological vacuum are nontrivial. On the other hand, problems associated with explaining the mechanism of the explosion of core-collapse supernovae require performing a thorough analysis of the properties of matter at supernuclear densities and taking into account effects of all known interactions. Possibly, resort to new exotic particles is also necessary here.

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