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Stars and black holes from the very early universe

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A mechanism of the creation of stellarlike objects in the very early universe, from the QCD phase transition until big bang nucleosynthesis and somewhat later, is studied. It is argued that in the considered process, primordial black holes with masses above a few solar masses up to superheavy ones could be created. This may explain an early quasar creation with evolved chemistry in surrounding medium and the low mass cutoff of the observed black holes. It is also shown that dense primordial stars can be created at the considered epoch. Such stars could later become very early supernovae and, in particular, high redshift gamma bursters. In a version of the model, some of the created objects can consist of antimatter.

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I. INTRODUCTION

As is assumed, stars and galaxies were mostly formed recently at $z_{\rm form} \leq 10$. Though the star formation started much earlier at $z \approx 30$ for Pop III stars with zero metallicity, the fraction of baryons in these stars is believed to be very low. It was claimed [1] that "a fraction 10^{-3} of all baryons may have formed luminous objects by $z = 30$." Later it was concluded [2] that only 10^{-6} of all baryons were in stars at redshift $z \sim 24 - 19$, and the stellar fraction in baryons 10^{-3} was reached later, at $z \sim 15$–14. Confirmed by Yoshida *et al*. [3], these numbers are considered a standard for the star formation rate at reionization. Presently, around 30% of baryons are in stars and intergalactic gas in galaxy clusters.

The accepted history of the structure formation looks as follows. At inflation, primordial density fluctuations with flat Harrison-Zeldovich spectrum [4] were generated [5]. They remained frozen during the postinflationary radiation-dominated (RD) epoch. The RD epoch turned into the matter-dominated one at redshift $z_{\rm eq} \sim 10^4$ when initial density perturbations rose as the scale factor, $\Delta = \delta\varrho/\varrho \sim a(t)$. After Δ reached unity, the evolution became nonlinear and perturbations started to quickly rise. In this way, stars, galaxies, and their clusters are believed to have been formed.

The essential time scales are the following. With the Hubble constant $H_0 = 67.3 \pm 1.2\,{\rm km}/s/{\rm Mpc}$ and the high matter density parameter, $\Omega_m = 0.315 \pm 0.017$ [6] the Universe age is $t_U = 13.8 \pm 0.2\,{\rm Gyr}$. Galaxies and their clusters were mostly formed at $z = 2$–3, which corresponds to $t = 3.27$–$2.14\,{\rm Gyr}$.

Surprisingly, some stars in the MW are quite old with ages close to the Universe's age. For example, the age of BD $+ 17^o$ 3248 was estimated as $13.8 \pm 4\,{\rm Gyr}$, and the age of HE 1523–090 in the galactic halo was estimated as 13.2 Gyr. Moreover, recent observations indicate that the age of HD 140283 is 14.46 ± 0.31 Gyr [7], which exceeds t_U by 2 standard deviations. Probably these stars are pregalactic, formed independently of the galaxy and captured by the galaxy much later. There are several galaxies at high redshifts, e.g., the galaxy at $z \approx 9.6$ which was formed when the Universe was 0.5 Gyr old [8], and even the galaxy at $z \approx 11$, i.e., at 0.41 Gyr [9].

Another example of early formed objects is high redshift quasars. The maximum redshift of an observed quasar is 7.085; i.e., it was formed at $t \lesssim 0.75$ Gyr. Quasars are supposed to be supermassive black holes (BHs), and their formation in such short time looks problematic. The models of an early formation of supermassive BHs are reviewed in Refs. [10]. For some recent references, see Ref. [11]. However, all the scenarios meet serious problems. E.g., some scenarios [11] involve formation of very massive stars exploding as extremely powerful supernovae. Observations

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of very metal-poor stars imply that their patterns of elemental abundance are in good accord with the nucleosynthesis that occurs in stars with masses of $(20\text{–}130)M_\odot$ when they become supernovae [12]. The abundances are not consistent, however, with heavy element enrichment by supernovae originated from more massive stars in the range (130–300) $M_\odot$. It is inferred [12] that the first-generation supernovae came mostly from explosions of $\sim(20-130)M_\odot$ stars.

There are indications that every large galaxy and some smaller ones [13] contain a central supermassive black hole. The mass of the black hole may be larger than $10^9 M_\odot$ in giant elliptical and compact lenticular galaxies and about a few million $M_\odot$ in spiral galaxies like the MW. The mass of the BH in the MW center is about $\sim10^{-5}$ relative to the total MW mass. Normally, the BH mass is smaller in spiral galaxies and is correlated with the bulge mass but not with the total mass of the galaxy [14]. (The MW has a BH which lies below the value determined by this correlation; perhaps this is good: otherwise, the life on Earth could be threatened by the quasar radiation.)

The mass of the black hole is typically 0.1% of the mass of the galactic bulge [15], while some galaxies may have a huge BH: e.g., NGC 1277 has a central black hole of $1.7\times10^{10}M_\odot$ or ~60% of its bulge mass [16]. This creates serious problems for the standard scenario of supermassive BH formation by accretion of matter to the central part of a galaxy. An inverted picture looks more plausible when first a supermassive black hole was formed which became a seed for subsequent galaxy formation. The mechanism of such early BH formation is discussed below.

As observed, the medium around early quasars contains a considerable amount of "metals" (i.e., of elements heavier than helium), see, e.g., Ref. [17]. According to the standard picture, only elements up to ^{4}He and traces of Li, Be, B were formed in the early universe during big bang nucleosynthesis (BBN), while heavier elements were created by stellar nucleosynthesis and dispersed in the interstellar space by the supernova explosions. This means that prior to the creation of quasars, efficient star formation processes should take place. These stars evolved producing supernovae, which later enriched space with metals.

The duration of presupernova stellar evolution is about 13 Myr for the stars with the initial mass $15\,M_\odot$ and 3.5 Myr for those with the initial mass $75\,M_\odot$ [18]. The lifetimes of ordinary stars are taken from their formation until supernova explosion (or collapse to a BH, cf. [18,19]). But ordinary stars are composed of 70% hydrogen, while the new types of stars considered here are initially almost pure helium, since they came from matter where BBN proceeded with much larger baryonic density than the standard one. (For this reason, we call such stars baryodense stars or BDSs.)

Nevertheless, separate calculations of the evolution of BDSs are unnecessary: each ordinary massive star, after hydrogen is burnt out in the central regions, has a helium core, which quickly reaches half the mass of the original star with accuracy ~10% [18]. Such helium core lives independently of the amount of hydrogen left in the envelope (moreover, almost all hydrogen in the outer layers of a red supergiant may be lost in the stellar wind [19], and we are left with a bare helium star, the so-called Wolf-Rayet star).Therefore, for BDSs, the existing calculations for the evolution of normal stars are valid, permitting us to find their lifetime on the stage of the helium core. Thus, we can find the lifetime of a $10\,M_\odot$ BDS, taking an ordinary star of $20\,M_\odot$ whose lifetime on the helium burning stage is 1.2 Myr. The ordinary star with $M = 15\,M_\odot$ corresponds to a He star of about $7\,M_\odot$, and an ordinary star of $75\,M_\odot$ corresponds to a He star of about $30\,M_\odot$. The lifetimes of these BDSs with masses 7 and $30\,M_\odot$ are, respectively, 2 and 0.5 Myr [18]. For $M > 75\,M_\odot$ the lifetime becomes almost independent of M since the luminosity is close to the Eddington limit and, hence, is proportional to M, as is also true for the nuclear energy supply.

Observations of high redshift gamma ray bursters (GRB) also indicate a high abundance of supernova at large redshifts. The highest redshift of the observed GRB is 9.4 [20], and there are a few more GRBs with smaller but still high redshifts. The necessary star formation rate to explain these early GRBs is at odds with the canonical star formation theory.

A recent discovery of an ultracompact dwarf galaxy [21] older than 10 Gyr, enriched with metals and probably with a massive black hole in its center, seems to disagree with the standard model but well fits the scenario discussed below.

II. EARLY FORMATION OF STELLARLIKE OBJECTS

We consider a model of formation of stellarlike objects in the very early universe which seems to resolve the above-mentioned problems. The model was suggested in Ref. [22] and further refined in Ref. [23]. The considered scenario is based on a slightly modified AD suggestion for the baryogenesis [24], where the general renormalizable coupling of the scalar baryon, χ, to the inflaton field Φ is introduced:

$$U(\chi,\Phi) = U_\chi(\chi) + U_\Phi(\Phi) + U_{\rm int}(\chi,\Phi). \qquad (1)$$

Here, $U_\Phi(\Phi)$ is the inflaton potential depending upon the model of inflation, $U_\chi(\chi)$ is a quartic potential, which has some flat directions (valleys), and the additional interaction term has the form

$$U_{\rm int}(\chi,\Phi) = \lambda_1|\chi|^2(\Phi-\Phi_1)^2, \qquad (2)$$

where Φ_1 is some value of the inflaton field which it passes during inflation, and λ_1 is a constant.

The AD baryogenesis proceeds as follows. At inflation, χ may reach large values along the flat directions of U_χ.

When inflation ends, χ evolves down to the minimum of the potential, which is supposed to be at $\chi = 0$. On the way down, χ acquires some "angular momentum" in the complex plane $[\mathrm{Re}\,\chi, \mathrm{Im}\,\chi]$.This happens either due to quantum fluctuations in the direction orthogonal to the valley or because of mismatch of the flat directions of the χ^4 and χ^2 terms in potential U_χ. This angular momentum is proportional to the baryonic charge of χ: $B_\chi \sim i[(\partial_0\chi^*)\chi - \chi^*\partial_0\chi)]$. It is released later into baryonic charge of quarks in B-conserving decays of χ. This process could lead to a huge cosmological baryon asymmetry, $\beta = N_B/N_\gamma$, much larger than the observed canonical value, $\beta \approx 6 \cdot 10^{-10}$.

An addition of a U_{int} term (1) strongly changes the evolution of χ. When $\Phi \neq \Phi_1$, the effective mass of χ is positive, so the gates to the valleys are closed and χ rests near $\chi = 0$. Hence, the baryogenesis in most of the space proceeds with normal low efficiency producing the observed small value of β. However, during the time when the gates to the valley are open, i.e., when Φ is close to Φ_1, the baryonic scalar χ may "rush" to large values. The probability of this process is low, and so the bubble with large baryonic asymmetry would occupy a small fraction of space forming some compact objects with large baryonic number. The details can be found in Ref. [23].

The perturbations initially induced by such process are predominantly isocurvature ones; i.e., they have large variation of the baryonic number $\delta B/B \gg 1$ with small perturbations in the energy density, $\delta\varrho/\varrho \ll 1$. The situation drastically changes after the QCD phase transition (p.t.) at $T \sim 100\,\mathrm{MeV}$. After that, light quarks turn into heavy baryons and excessive baryonic number contained in high-B bubbles lead to the creation of compact objects with log-normal mass distribution:

$$\frac{dN}{dM} = C_M \exp\,[-\gamma \ln^2(M/M_0)], \tag{3}$$

where C_M, γ, and M_0 are constant parameters. The form of the distribution is determined by the exponential expansion and is model independent, but the parameter values are model dependent.

If $\delta\varrho/\varrho$ in such bubbles is larger than unity at horizon, they would form primordial black holes (PBHs) created at the first seconds or even at a fraction of a second of the universe life. If $\delta\varrho/\varrho < 1$ at the horizon crossing, a PBH would not be formed but instead some stellarlike objects would be created. The value of $\delta\varrho/\varrho$ at horizon depends upon β, which is not a constant but more or less uniformly distributed over different bubbles; β may be negative, so a noticeable amount of compact antimatter objects may exist in the Galaxy. Their phenomenology is considered in Ref. [25].

Distribution (3) naturally explains some observed features of the distribution of stellar mass black holes in the Galaxy. It was found [26] that the masses of the black holes are best described by a narrow distribution at $(7.8 \pm 1.2)\,M_\odot$. This result agrees with Ref. [27], where a peak around $8\,M_\odot$, a paucity of sources with masses below $5\,M_\odot$, and a sharp dropoff above $10\,M_\odot$ are observed. These features are not explained in the standard model.

Moreover, simple modifications of the interaction potential (2) would lead to a more complicated mass spectrum of the PBHs and other early formed stellar-type objects. For example, taking U_{int} in the form

$$U_{\mathrm{int}}(\chi, \Phi) = \frac{\lambda_1}{M_2^2}|\chi|^2(\Phi - \Phi_1)^2(\Phi - \Phi_2)^2, \tag{4}$$

we come to a two-peak mass distribution observed in Refs. [26,27] but not explained otherwise [28].

Evolved chemistry in the early formed quasars may be explained by stronger production of metals during BBN due to much larger $\beta = N_B/N_\gamma$. The standard BBN essentially stops at ^{4}He because of very small β. However, in the model considered here, β may be much larger than the canonical value, even being close or exceeding unity. A BBN with high β was considered in Ref. [29], where it was shown that the outcome of metals is noticeably enhanced, though the calculations have been done only for moderately large β up to 0.001. The predictions of the standard BBN are not distorted because the unusual abundances of light elements are concentrated only in a tiny fraction of space and their diffusion out is very short.

The usual value of $\beta = 6 \times 10^{-10}$ is established from the analysis of the light element abundances and from the angular fluctuations of cosmic microwave background (CMB). However, these data do not exclude much larger values of β in a small fraction of the universe volume. The CMB spectrum could be distorted at very high multipoles far outside the reach of the existing detectors, while some anomalies in primordial light element abundances might be observed but with low probability.

Depending upon β_B, inside the bubbles and the bubble size, R_B, such high baryon density objects could form either PBHs, or a kind of star, or a disperse cloud of gas with unusually high baryonic number. The selection between these possibilities depends upon the Jeans mass of the objects.

It is convenient to specify the initial conditions at the moment of the QCD p.t. in the primeval plasma. After such p.t. the (quasi)isocurvature density perturbations initially with $\delta\varrho \approx 0$ lead to the density contrast $\delta\varrho = \beta_B N_\gamma m$ if densities (and temperatures) of photons inside and outside the bubbles are assumed to be equal. The relative density contrast is

$$\delta\varrho/\varrho_c \approx 0.2\beta_B(m/T), \tag{5}$$

where $\varrho_c = 3H^2 m_{Pl}^2/(8\pi)$ is the cosmological energy density, and β is normalized to the present day values of baryon and photons densities, where the heating of the photons by e^+e^- annihilation is taken into account, while N_B is supposed to be conserved in the comoving volume, and the baryon diffusion out of the bubble is neglected.

The temperature and the type of the QCD p.t. at high baryonic chemical potential can be very much different from the usual cosmological one with $\mu = 0$. There is mostly an agreement in the literature that p.t. at high μ is first order at smaller temperature about 50 MeV, see, e.g., Ref. [30] or the webpage for a huge collection of phase diagrams for QCD phase transitions [31]. However, there is a conflicting statement that a large μ may stop the phase transition [32], which is at odds with other publications. We assume that p.t. was first order and took place in the early universe, keeping the p.t. temperature as a free parameter.

At the QCD p.t., the universe is dominated by relativistic matter, so $H = 1/(2t)$ and the cosmological energy density is

$$\varrho_c = \frac{3H^2 m_{Pl}^2}{8\pi} = \frac{\pi^2 g_* T^4}{30}, \tag{6}$$

where g_* is the number of the relativistic degrees of freedom. The temperature of the QCD p.t. T_Q is not well known. It is somewhere in the interval $T_{\rm QCD} = 100$–200 MeV. Below p.t. but above 100 MeV, $g_* = 17.25$, while below 100 MeV, $g_* = 10.75$. Thus, the relation between the cosmological time and temperature is

$$t/\mathrm{sec} = 0.7 \cdot 10^{-4} \left(\frac{10.75}{g_*}\right)^{1/2} \left(\frac{100\,\mathrm{MeV}}{T}\right)^2. \tag{7}$$

The mass inside horizon $l_h = 2t$ is

$$\begin{aligned} M_h &= m_{Pl}^2 t = 10^5 M_\odot (t/\mathrm{sec}) \\ &= 14 M_\odot \left(\frac{10.75}{g_*}\right)^{1/2} \left(\frac{100\,\mathrm{MeV}}{T}\right)^2. \end{aligned} \tag{8}$$

We denote the universe age, t, the temperature, T, and the radius of the bubbles, R_B at the moment of the QCD p.t. as t_Q, T_Q, and R_Q, respectively. The radius is a stochastically distributed quantity, whose distribution is analogous to Eq. (3). The baryon asymmetry inside the bubbles β is also a stochastic quantity, which we assume to be uniformly distributed between $\beta_{\rm max}$ and $\beta_{\rm min}$.

The bubble will form a PBH at horizon crossing if its radius is smaller than the gravitational radius of the bubble, $r_g = 2M_B/m_{Pl}^2$, where the bubble mass is

$$M_B = \frac{4\pi}{3} R_B^3 \varrho_B = \frac{4\pi^3 g_*}{90} R_B^3 T^4 (0.2\beta m/T). \tag{9}$$

Hence, the condition of PBH formation is

$$0.2\beta \frac{m}{T}\left(\frac{R_B}{2t}\right)^2 > 1. \tag{10}$$

So for $\beta \sim 1$, the bubble would become a PBH at the QCD p.t. if $R_Q/(2t_Q) = 1$. If $\beta_{\rm max} = 1$, then the smallest mass of PBHs would be equal to the mass inside horizon at $t = t_Q$. Taking $T_{\rm QCD} = 150\,\mathrm{MeV}$, we find that the PBH mass should be above $5\,M_\odot$, which is very close to the limit below which black holes are not observed [26,27]. No other explanation for this cutoff has been found.

If $\beta > 1$, PBH formation with smaller masses corresponding to $R_Q/(2t_Q) < 1$ is also possible. In this case, PBHs would be formed practically instantly, when massless quarks turned into massive baryons and the density contrast jumped from zero to that given by Eq. (5). For PBH formation, the condition $\beta > 5(T_Q/m)(2t_Q/R_{BQ})^2$ should be fulfilled, as is seen from Eq. (10). According to a simple version of the model [22,23], very large β is unlikely, though not excluded, and the formation probability of lighter PBHs is most probably small.

Heavier PBHs originated from the bubbles whose radius was larger than horizon at QCD p.t., $R_Q/(2t_Q) > 1$. As mentioned above, PBHs would be created if at the horizon crossing $\delta\varrho/\varrho > 1$. Assuming that this occurred at the RD stage when the scale factor rose as $a(t) = a_Q(t/t_Q)^{1/2}$, the temperature dropped as $T = T_Q(a_Q/a)$, and the bubble expanded as $R_B(t) = R_Q a(t)/a_Q$, we find that the moment of the horizon crossing is given by $t_h = R_Q^2/4t_Q$. The corresponding temperature is $T_h = T_Q(t_Q/t_h)^{1/2}$ and we find that a PBH would be formed if

$$0.2\beta \frac{m}{T_Q}\frac{R_Q}{2t_Q} > 1. \tag{11}$$

This condition is not precise. It may happen that $\delta\varrho/\varrho$ reached unity before the horizon crossing and the rise of $R_B(t)$ would slow down, but for the moment we neglect these subtleties.

The difference between conditions (10) and (11) reflects the difference of physics in PBH formation. In the first case, a PBH is formed when the density inside a small bubble with $R_B < l_h$ suddenly rises up and the bubble collapses, while the second case is the usual story of PBH creation in cosmology. As one should expect, conditions (10) and (11) coincide at $R_Q = 2t_Q$. However, our approach is oversimplified, and the formation of a PBH with $R_Q < 2t_Q$ at QCD p.t. may be more complicated because the phase transition and the rise of the density contrast could be terminated or postponed by the effects of general relativity. The problem of the bubble formation at phase transitions and, in particular, of black holes, was studied in Ref. [33].

The bubbles which did not become PBHs formed all kinds of compact stellarlike objects or low density clouds. The evolution of such objects depends upon the ratio of the bubble mass to its Jeans mass. Initially, their properties can be quite different from normal stars. For example, the initial temperature inside the bubble could be smaller than the temperature of the cosmological matter outside because nonrelativistic matter cools faster during expansion. Correspondingly, the external pressure would be larger than the internal one. Later, when the bubbles decoupled from the expansion and started to shrink due to their own gravity, their temperature gradually became larger than the outside temperature, and the situation would be closer to normal astrophysics.

The mass of BDSs is roughly equal to the mass inside their radius, R_Q, at the QCD p.t.:

$$M_{\rm BDS} = \frac{4\pi R_Q^3}{3}\frac{\varrho_Q \delta\varrho_Q}{\varrho_{cQ}} = \xi^3 \beta (m_{Pl}^2 t_Q)\frac{0.2m}{T_Q}, \qquad (12)$$

where $m_{Pl}^2 t_Q \approx 3.5 M_\odot (200\ {\rm MeV}/T_Q)^2$ is the mass inside horizon (8) at the QCD p.t., and the density contrast is given by Eq. (5). If $0.2m/T_Q = 1$, then $M_{\rm BDS} = 3.5\, M_\odot \xi^3 \beta$, the temperature when $\delta\varrho/\varrho_c = 1$ is $T_1 = 0.2\beta m$, and the condition that will not become a PBH is $\beta\xi < 1$.

Let us consider a bubble with the mass close to the solar one and $T_1 \sim 50\,{\rm keV}$. The energy density at the moment when $\delta\varrho = \varrho$ would be about $10^8\ g/{\rm cm}^3$. The thermal energy of a solar mass B bubble taken at the moment when its Jeans mass dropped down to $M_\odot$ is determined by the thermal energy of nucleons, $E_{th} = 3T/2$. Taking $T = 50\,{\rm keV}$, though the temperature may drop down due to the BDS initial expansion, we find the internal energy of this "star" to be

$$E_{\rm therm}^{(\rm tot)} = \frac{3TM_{\rm BD}}{2m_N} \approx 10^{29}{\rm g} \approx 10^{50}{\rm erg}. \qquad (13)$$

In this example, with $\varrho \sim 10^8\ g/{\rm cm}^3$ a BDS has properties similar to those of the core of a red giant at the initial stage of its evolution. The main source of energy under these conditions would be helium-4 burning, $3\,^4{\rm He} \to {}^{12}{\rm C}$. However, the temperature $T \sim 50\,{\rm keV}$ is noticeably larger than that of the red giant core, $T_{\rm rg} \sim 10\,{\rm keV}$. Since the probability of the above reaction exponentially depends on T, its rate at $T\sim$ 50 keV is 10 orders of magnitude higher than at $T_{\rm rg}$ [34]. The lifetime of such helium flash in the BD star would be extremely short. Naively taking these numbers, we obtain a lifetime of about a few hours instead of millions of years discussed in Sec. I for He stars. However, this simple estimate can be wrong by several orders of magnitude because the efficiency of the process is very much different from that in a normal giant star. Since the hydrodynamic time is $\sim G_N \varrho^{-1/2}$, i.e., less than a second, the initial BD ball would expand and cool down quickly to a normal $T_{\rm rg}$ well before He is exhausted. Thus, a BDS would be formed with the properties similar to normal He stars. Still, a fraction of helium would be burnt very quickly at the very beginning, and other nuclear reactions, which could occur later, would be presumably insignificant for the full lifetime of the star, since later nuclear reactions are even faster. More accurate estimates demand the development of the astrophysics of BD balls, which are quite different from the standard stars, at least initially.

III. DISCUSSION

The main presently observable cosmological impact of BDSs is the enrichment of the interstellar space by metals as a result of their fast evolution and subsequent explosion in the distant past. In addition, there could be formed peculiar stars of huge age made of ordinary matter, early black holes, and gamma bursters observed today. Moreover, BDSs could give birth to old low mass cold helium red dwarfs, dead white dwarfs, and neutron stars.

Normal single stars may either evolve to core collapse with the He core mass $2\,M_\odot \lesssim M_{\rm He} \lesssim 40\,M_\odot$ or to pair-instability supernovae at $M_{\rm He} > 40\,M_\odot$ [18]. The lifetime of a massive star with $M_{\rm He} > 40\,M_\odot$ is less than 1 Myr during the stage of He burning [18].

Such a massive star can produce a supernova within a Myr after recombination. With $\varrho_c = 10^{-29}\ g/{\rm cm}^3$ and $\Omega_b = 0.05$, the present day cosmological density of baryons is $\varrho_b = 5 \cdot 10^{-31}\ {\rm g/cm}^3$. At recombination, it would be 9 orders of magnitude higher, i.e., $\varrho_b = 5 \cdot 10^{-22}\ g/{\rm cm}^3$. If a BDS lives a bit less than a Myr, then at the moment of its supernova explosion, ϱ_b would be the same as the present day density in the dense regions of gaseous disk of our Galaxy. That is, a BD-supernova explosion occurs in an environment that we understand reasonably well, except for the fact that the interstellar medium had a different chemical composition. Even if not all details are understood, we observe the metal-enriched composition of the interstellar medium coming presumably from the remnants of such explosions.

However, in the case of BDSs, their own chemical composition should also be contaminated with metals due to the nonstandard BBN as well as the chemical composition of the interstellar medium, due to the stellar wind and the BD-supernova explosion. We observe that ordinary supernova remnants (SNR) are associated with star forming regions. A few tens of thousands of years after explosion, the uniform interstellar medium would be swept up into a thin wall of the SNR bubble with a mass of thousands of solar masses. With sufficient abundance of metals, it would catastrophically cool down generating thousands of young stars. Supernova remnants do not produce very massive stars, but they naturally give birth to small ones, with masses around $1\,M_\odot$ and less, just as it is necessary for the "prehistoric" star HD 140283.

Thus, the described scenario leads to interesting consequences, such as the formation of stellar mass PBHs, of supermassive BHs, and the first supernovae which could lead to formation of peculiar stars like HD 140283. This helps to resolve the problems of the early formation of black holes, quasars, GRBs, the first stars, and the enrichment of interstellar space by metals at high redshifts. At the tail of distribution (3), supermassive PBHs could be created, which might serve as galaxy formation seeds. Another interesting and testable prediction is compact stellar-type antimatter objects, which might populate the galactic halo.

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