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HIDING OF THE CONSERVED (ANTI)BARYONIC CHARGE INTO BLACK HOLES

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Abstract

It is shown that the net amount of baryons evaporated by a black hole can be unequal to that of antibaryons, even if baryonic charge is microscopically conserved. This result is in contradiction with ref. [1], where just the opposite statement was made. The baryonic asymmetry of the Universe which can be generated by black hole evaporation in a specific mechanism first proposed by Zeldovich [2], is estimated.

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It was stated recently [1] that no baryonic excess in the outer space can be generated by the black hole evaporation [3] if baryonic charge is microscopically conserved. The authors of ref. [1] considered thermally emitted particles propagating through the gravitational field of the black hole, the C- and CP-violating processes of mutual particle transition in the gravitational field being permitted: $\mathcal{L}_{int} = \varphi_i^* V_{ij} \varphi_j$ (here φ_i stands for a field operator and R is the space curvature). Note, that this interaction conserves the total number of φ -particles of all types. Using the CPT-theorem and the generalisation [1,4] of the detailed balance condition to the case of violated time reversibility* one can rigorously show that the net baryonic flux from a black hole vanishes in this case. This is the result of ref. [1].

If however total particle number in the course of propagating through the black hole field is not conserved, the agruments of ref. [1], as they are, are not applicable because in this case the equations of movement become nonlinear and so the result can be invalid. It is shown in what follows that the mechanism, proposed several years ago by Zeldovich [2], does indeed produce nonvanishing ba-

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*) If there is no invariance with respect to time reversal, the detailed balance condition is no longer fulfilled. However the S -matrix unitarity enforces the equality of the total sum of probabilities of all direct and inverse processes in the thermal equilibrium. So balance is achieved by summing up all possible cycles and the corresponding relation among transition can be named the cyclic balance condition [4].

ryonic flux into the outer space and hiding the equal amount of antibaryons inside the black hole*.

Assume that there exists a heavy meson A which has (among others) the decay channels

$$A \to H\bar{L} \quad \text{and} \quad A \to \bar{H}L$$

where L is a light baryon and H is a heavy one. Because of C- and CP-violation the decay probabilities can be different

$$[\Gamma(A \to L\bar{H}) - \Gamma(A \to H\bar{L})] \,/\, \Gamma_{tot} = \Delta > 0 \qquad (1)$$

Of course some other decay channels and rescattering processes should be possible to provide this inequality.

Because of the larger mass of H, as compare to that of L, the probability of back-capture of H (and $\bar{H}$) by a black hole is larger. So the process of the A-meson evaporation and its subsequent decay in the gravitational field of the black hole leads to a baryonic excess in the outer world even if the baryonic number is strictly conserved. Particle scattering outside the black hole, which in principle could compensate the excess of light baryons, is negligible because the particle flux from the surface of black hole is small.

The following example explicitely confirms the above made statement. Let $m_A \simeq m_H \gg m_L$ and the black

*) First the idea of the Universe baryon asymmetry generation by the black hole evaporation was formulated by Hawking [3].

hole temperature is small enough so that $m_H \gg T \simeq m_L$.
The wave equation governing (for simplicity spinless) particle propagation in the gravitational field of a black hole is of the form (see e.g.ref. [6]):

$$\left[\partial_\xi^2 + \varepsilon^2 - V(\xi; \ell)\right] R^{\ell, \ell_3}(\xi; \varepsilon) = 0 \tag{2}$$

where $R^{\ell, \ell_3}(\xi; \varepsilon)$ is the particle radial wave function with an orbital momentum ℓ and its third component ℓ_3. The total wave function is decomposed in terms of $R^{\ell \ell_3}$ as follows $\Psi(\vec{r}, \varepsilon) = r^{-1} \sum_{\ell, \ell_3} Y_{\ell \ell_3}(\vartheta, \varphi) R^{\ell, \ell_3}(\xi; \varepsilon)$;
ε is the particle energy in the inverse gravitational radius units - $\varepsilon = E r_g = E \cdot 2MG$, M is the black hole mass and $G \simeq 0.6 \cdot 10^{-38} m_p^{-2}$ is the gravitational (Newton) constant. The potential V has the form

$$V(\xi; \ell) = (1 - \rho^{-1})\left[\ell(\ell+1)\rho^{-2} + (m r_g)^2 + \rho^{-3}\right] \tag{3}$$

where m is the particle mass, $\rho = r / r_g$, r is the usual radius-vector connected with ξ by the equation

$$\xi = \rho + \ln(\rho - 1) \tag{4}$$

It is essential that $V(\xi, \ell) \to 0$ as $\xi \to -\infty$ $(r \to r_g)$ and $V(\xi, \ell) \to (m r_g)^2$ as $\xi \to +\infty$ $(r \to +\infty)$. This means that in the vicinity of the black hole all evaporated particles are effectively massless and have the same (thermal) energy distribution $\sim \exp(-E/T)\left[1 \pm \exp(-E/T)\right]^{-1}$. However only those particles can propagate to infinity which have sufficiently high energy,

$E > m$. So in the case considered the flux of A and H particles at large distance from the black hole is exponentially $(\sim \exp(-m/T) \ll 1)$ suppressed whereas the backcapture of L-particles is not so overwhelmingly large. The flux of L and $\bar{L}$-particles at infinity is thus not small and because of larger amount of L produced, as compare to that of $\bar{L}$ (see inequality (1), the net flux of baryonic charge is nonzero. There is of course some supression of A-decays due to the slowing down of time in the vicinity of a black hole but it results only in a power law suppression and not in an exponential one. To make this more precise, consider the wave function of L and $\bar{H}$ produced by the A decay in the gravitational field of the black hole:

$$\psi_{L\bar{H}}(\vec{r},\vec{r}\,';\varepsilon_L,\varepsilon_H)=\frac{1}{rr'}\sum_{\substack{\ell\ell_3\\ \ell'\ell_3'}} Y_{\ell\ell_3}(\vartheta,\varphi)Y_{\ell'\ell_3'}(\vartheta',\varphi')R_{L\bar{H}}^{\ell\ell_3;\ell'\ell_3'}(\xi,\xi';\varepsilon_L,\varepsilon_H) \tag{5}$$

where ξ is connected with r through expression (4). It can be shown that $R_{L\bar{H}}$ satisfies the equation

$$\left[\partial_\xi^2+\varepsilon_L^2-U_L(\xi;\ell)\right]\left[\partial_{\xi'}^2+\varepsilon_H^2-U_H(\xi';\ell')\right]R_{L\bar{H}}^{\ell\ell_3;\ell'\ell_3'}(\xi,\xi';\varepsilon_L,\varepsilon_H)= \tag{6}$$

$$=2if r_g^2\,\frac{r_g}{r}\left(1-\frac{r_g}{r}\right)\delta(\xi-\xi')\sum_{\ell_A,\ell_{3A}}R_A^{\ell_A,\ell_{3A}}(\xi;\varepsilon_L+\varepsilon_H)\,\mathcal{D}(\ell_A,\ell_{3A};\ell,\ell_3;\ell',\ell_3')$$

where f is the coupling constant of $AL\bar{H}$ -transition, R_A is the wave function of A-meson; R_A satisfies eq. (2) with the substitution $m_A \to m_A - i\Gamma_A/2$, Γ_A being the total decay width of A-meson. The derivation and solution of the coupled equations (2) and (6) is discussed in a longer paper submitted to ZhETP where the following estimate for the baryon charge produced by the black hole evaporation in the case of $m_{AH}\tau_g > 1$ and $m_L\tau_g < 1$ was obtained

$$B = N_L - N_{\bar{L}} \simeq \Delta \, \frac{\Gamma_A}{m_A} \left(\frac{M_0}{m_g}\right)^2 N_{eff}^{-1} \tag{7}$$

Here $N_{L(\bar{L})}$ is the total amount of light baryons (antibaryons) evaporated by the black hole, Δ is defined by expression (1), $m_g \simeq 10^{19}$ GeV is the Planck mass, N_{eff} is the effective number of different particle species evaporated by the black hole, $N_{eff} \simeq 10 \div 100$, and M_0 is the initial value of the black hole mass, the following condition being valid $T = m_g^2 / 8\pi M_0 > m_L$.

To evaluate the average baryon number density in the universe we proceed as follows. The energy density in the early universe is

$$\rho(t) = \frac{3}{32\pi} \, \frac{m_g^2}{t^2} \tag{8}$$

If the contribution of the primordial black holes with mass M into ρ is equal to $\varkappa\rho$ $(\varkappa < 1)$ then the number density of such black holes is

$$n_{BH} = \varkappa \rho(t) / M \tag{9}$$

The value of $\varkappa$ is unknown; in what follows we assume that it is of order of unity. The baryon number density to the moment of the black holes evaporation, 7

$t = \tau_{BH} \approx (10^4/3N_{eff})\, M^3 m_g^{-4}$ is

$$n_B = n_{BH} B \simeq \varkappa B \rho(\tau_{BH}) M^{-1} \qquad (10)$$

After the black hole evaporation the thermodynamic equilibrium is established in the primeval plasma, the temperature being defined by the equation

$$\rho = \frac{\pi^2 N}{15} T^4 \qquad (11)$$

where N is the number of different particle species present in the plasma. In what follows we assume that $N \simeq N_{eff}$ (see eq. (7)). Now the following result for the inverse specific entropy per baryon can be obtained

$$\beta = \frac{n_B}{(\rho/T)} = \frac{\varkappa B}{T}\left[\frac{15\rho(\tau_{BH})}{\pi^2 N}\right]^{1/4} \simeq 0.1\varkappa\Delta \frac{\Gamma_A}{m_A} N^{-3/4}\left(\frac{m_g}{M}\right)^{1/2} \qquad (12)$$

The increase of β for small M is connected with the assumption that $n_{BH} \sim M^{-1}$ (see eq. (9)). A reasonable order of magnitude estimate of the parameters in r.h.s. of eq. (12), i.e. $(\Gamma_A/m_A) N^{-3/4} \simeq 10^{-2}$, $\Delta \simeq 10^{-4}$ (probably smaller), gives $\beta \simeq 10^{-7}\varkappa\, (m_g/M)^{1/2}$. Comparing this with the known value, $\beta \simeq 10^{-9\pm1}$, we conclude that the discussed mechanism can provide the observed baryonic asymmetry of the Universe if primordial black holes with the mass $M = 10^{4\pm2} m_g \simeq 10^{-3} \div 1\,g$ give noticeable contribution into total energy density. Remind however that expression (7) was derived under assumption that $\tau_g m_{A,H} > 1$, this means that the results obtained could be valid if there existed A-meson and H-baryon heavier than $10^{-4\pm 2}\, m_{\mathcal{P}} \simeq 10^{+15}$ GeV.

It is easy to see that in the case of large $m_A \tau_g$ and $m_H \tau_g$ and small $m_L \tau_g$, considered up to now, the resulting baryonic asymmetry proved to be the largest. If $m_H \tau_g < 1$ then the value of B (eq. (7)) would be suppressed by the extra factor $(m_H - m_L)\tau_g$ and to get the desired value of β the heavy baryon H should be heavier than $10^{-(4\pm 2)}\, m_{\mathcal{P}}$. The case of small $m_A \tau_g$ is even less favorable because the baryonic charge generation is further suppressed by the slowing down of the A decay rate due to the γ-factor, $\gamma = m_A / E_A \simeq m_A / T \simeq m_A \tau_g$. These statements are valid if $\varkappa(\tau) < 1$. If however at some $t = t_1 < \tau$ $\rho_{BH} / \rho_{tot} \approx 1$ then the energy density is dominated by nonrelativistic black holes and the low of the universe expansion changes

$$\rho_{tot}(t) \simeq \rho_{BH}(t) = \frac{3}{32\pi} \frac{m_{\mathcal{P}}^2}{t^2} \left(\frac{t}{t_1}\right)^{1/2} \qquad (13)$$

In this case β is $(\tau / t_1)^{1/8}$ times larger as compare to that given by eq. (12):

$$\beta \simeq 0.1\, \Delta N^{-3/4} \frac{\Gamma_A}{m_A} \left[10^2 \frac{m_{\mathcal{P}}}{M}\right]^{1/8} (t_1 m_{\mathcal{P}})^{-1/8} \qquad (14)$$

and the observed value of β can be obtained if $M \lesssim 10^{18\pm 3}\, m_{\mathcal{P}} (m_{\mathcal{P}} t_1)^{-1}$. The lower bound on the mass of A-meson and of the heavy baryon is now not so large as in the preceeding case, $m_{H,A} > 10^{-13\pm 3}\, m_{\mathcal{P}} (t_1/t_{\mathcal{P}})$ and in principle it is possible to get the necessary result for β without inventing superheavy particles.

In conclusion I would like to note that the discussed mechanism of the explanation of the universe baryonic asymmetry is seemingly not so beautiful as the possibility which naturally arises in Grand Unified Theories with baryonic charge nonconservation. But if the proton instability is not discovered in the nearest future, the model considered here will look much more attractive. There is a possibility, of course, that both mechanisms are operative.

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