Charge asymmetry of the universe as a consequence of evaporation of black holes and of the asymmetry of the weak interaction

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The possibility is demonstrated of the onset of an observable charge asymmetry of the universe as a result of evaporation of cosmological black holes and violation of CP invariance in weak interaction.

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The ratio of the baryon density to the photon density in the universe, of the order of 10^{-8}—10^{-9}, which has remained constant during the course of the evolution, is a most important dimensionless quantity. It is not surprising that during the entire time of the existence of the big-bang theory of the universe there have been unceasing attempts to derive this quantity as a consequence of laws of physics and of some simple and natural initial conditions.[1–5]

In particular, the idea was advanced that the charge asymmetry of the universe is connected with the asymmetry revealed in the interaction and decay of elementary particles.[6,7] Taking into account the theory of evaporation of black holes[8,9] and the possibility of formation of primary black holes,[10–14] it is possible to obtain a charge-symmetrical world from a symmetrical singular state without violating the law of baryon-charge conservation, in that form in which this law is formulated in the theory of elementary particles and has been verified in experiment.

The actual scheme reduces to the following: assume that an appreciable fraction of the initial charge-symmetrical matter, during the earlier stage, has been accumulated up to the instant of time t_1 in black holes of mass M.

These black holes are then evaporated with a characteristic evaporation time t_2.

We assume further that there exist heavy neutral particles A_L and A_S, similar to K_L and K_S mesons, and also heavy neutral baryons H and $\bar{H}$ with a mass on the order of (but smaller than) the mass of A_L or A_S. The masses A and H are much larger than the baryon (neutron) mass, so that in the decay of a stationary or slow $A \rightarrow H+\bar{N}$ we obtain a slow H and an ultrarelativistic $\bar{N}$.

Let the decay

$$\begin{tikzcd}[row sep=tiny] & H+\bar{N} \\ A_L \arrow[ur] \arrow[dr] & \\ & \bar{H}+N \end{tikzcd}$$

or

$$\begin{tikzcd}[row sep=tiny] & H+\bar{N} \\ A_S \arrow[ur] \arrow[dr] & \\ & \bar{H}+N \end{tikzcd}$$

be the result of a weak CP-violating interaction, so that the ratio $(\bar{H}+N)/(H+\bar{N})$ summed over A_L and A_S is much larger than unity. At the same time, owing to the large mass, the "weak" interaction leads to a decay probability on the order of the mass A. Let the black-hole mass be such that its temperature is also of the order of the mass A (in the units in which Planck's constant $\hbar$, the speed of light c, and Boltzmann's constant k are equal to unity). As the result of the evaporation of A_L and A_S and of their decay, a mixture H, $\bar{H}$, N, $\bar{N}$ is produced at a distance on the order of several times r_g. The numbers of the baryons and antibaryons produced per unit time are equal

$$w_H + w_N - w_{\bar{H}} - w_{\bar{N}} = 0.$$

However, the asymmetry manifests itself in the fact that the baryons are predominantly ultrarelativistic, inasmuch as between the baryons $N > H$, and the antibaryons are essentially slow $\bar{N} < \bar{H}$ (the symbols $N\ldots$ denote here the densities of the corresponding particles). The probability of the inverse capture of a black hole by a gravitational field is larger for a slow particle than for an ultrarelativistic one. Taking into account the predominant capture of antibaryons, the black hole (under the assumptions made) emits predominantly baryons. The baryon charge of the evaporated matter is compensated for by the negative baryon charge of the black hole, and this charge is separated from our space as a result of evaporation.

We carry out the calculation, choosing arbitrarily the most convenient parameters and omitting the dimensionless numerical factors.

We denote by F the four-fermion weak-interaction constant, and by Γ the decay probability. In order of magnitude $\Gamma = FM_H^3$ and the condition $\Gamma = M_H$ yields $M_H = F^{-1/2}$.

We choose next the evaporation temperature $T = M_H$, from which we obtain for the mass of the black hole $r_g = GM = T^{-1}$, where G is the gravitational constant, so that

$$M = G^{-1} M_H^{-1} = G^{-1} F^{1/2}.$$

The evaporation time of such a black hole is equal to

$$t_2 = M : r_g^2 T^4 = M^3 G^2 = G^{-1} F^{3/2}.$$

At the instant t_2, in accordance with the theory of the expanding universe, we have

$$\rho = (Gt^2)^{-1} = GF^{-3}.$$

Immediately after the evaporation, we obtain particles with energy on the order of T and having a density on the order of ρ/T; the density of the baryons (more accurately, of the baryon charge) is a fraction α of the total particle density. It is assumed that while α is smaller than unity it is of the order of unity; α does not contain any small factors of the type G/F or m_N/m_A.

Thus, at the instant of evaporation t_2 we have

$$B = \alpha n = \alpha G F^{-5/2}.$$

In the course of the establishment of the thermodynamic equilibrium in a medium with a given energy density ρ, a new temperature T_e is produced (e stands for equilibrium), with a corresponding equilibrium photon density

$$\rho = T_e^4 , \qquad \gamma = T_e^3 = \rho^{3/4} = G^{3/4}F^{-9/4} .$$

We thus obtain

$$B/\gamma = a(G/F)^{1/4} = a(G\hbar^2/Fc^2)^{1/4} .$$

A formula containing $G^{1/4}$ was proposed before as an empirical one, or else with a different motivation.[1]

The last formula was already written in dimensional units: $G = 6.7 \times 10^{-8}$ $\mathrm{cm^3\,g^{-1}\,sec^{-2}}$ and $F = 2\times 10^{-49}$ erg cm^3; the numerical result is

$$B/\gamma = a \times 5 \times 10^{-9},$$

which in itself is satisfactory. The instant t_2 at which the evaporation terminates turns out to be approximately 1 sec, which does not contradict the picture of nucleosynthesis and a Planck-type spectrum. The quantity B/γ is written out explicitly, but many dimensionless factors have been left out in the course of the calculation.

However, the main shortcoming of the concept consists in the assumptions made, of the existence of primary black holes of precisely the required mass, and of the existence of heavy particles A and H with the required decay properties. An outstanding example of how an astronomer can make predictions in nuclear physics is the level of the C$^*_{12}$ nucleus, obtained by Hoyle from requirements of nucleosynthesis theory. However, the situation in cosmology is much more confused and therefore there are few chances that the predictions concerning the black holes, A and H will be justified.

Yet the question of the origin of the ratio B/γ is important also for the subsequent evolution of the universe. If B/γ is expressed in terms of the physical constants G and F, then it might seem that the fluctuations of this ratio should be very small in volumes corresponding to the mass of the sun or larger. Thus, the semi-fantastic hypothesis concerning the earlier stage, which cannot be directly investigated, may turn out to be essential for processes in our own vicinity.

The foregoing result can be interpreted to mean that it is not excluded that the observed charge asymmetry is produced as a result of evaporation of cosmological black holes and the violation of CP invariance in weak interactions.

However, if particles with properties A do not exist in reality and the CP violation is limited to ultraweak mixing of K_1^0 and K_2^0, then evaporation of black holes can yield only a charge-symmetrical mixture of particles and antiparticles. In this case, the formation and evaporation of black holes will decrease the initial asymmetry. The presently observed asymmetry in this variant of the theory limits the possible fraction of matter, β, which is converted into black holes. Under the usual assumptions ($p = \epsilon/3$, finite number of particle species) we obtain $\beta \ll 1$ if $M > \sqrt{\hbar c/G}\,(10^9)^{-3/2} = 3\times 10^8$ g. In this variant, the restriction on the number and mass of the cosmological black holes is more stringent in the region of small M in comparison with other considerations.

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