Neutrino limitation on primordial black holes inside the earth

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There can be no primordial black holes, of any mass, in the interior of the earth, because of limitations on their neutrino emission and on an increase in their mass by accretion.

Primordial (relic) black holes[1,2] formed in an early stage of the Big Bang are entries on a long list of potential candidates for the role of dark matter in the universe. Astrophysical limitations[3] do not rule out the possible existence of a small number of primordial black holes in the interior of the earth. They might have arrived there, for example, in the epoch in which the solar system was formed.

The gravitational interaction of a black hole with surrounding matter would outweigh the (interatomic) electromagnetic interaction if the mass of the black hole satisfied $M>(e^2/Gm_n)\simeq 2\times 10^{12}$ g, where m_n is the mass of a nucleon. A black hole which has a mass satisfying this condition and which is moving at a velocity v in the material of the earth, with a density ρ, would be decelerated by gravitational dynamic friction and would settle at the center of the earth over a time scale

$$\tau=\frac{v^3}{9\pi G^2 M\rho \ln \Lambda}\simeq 10^6\left(\frac{M}{10^{15}\ \text{g}}\right)^{-1}\left(\frac{\rho}{10\ \text{g/cm}^3}\right)^{-1}\left(\frac{v}{10\ \text{km/s}}\right)^3 \text{yr}, \quad (1)$$

where $\ln \Lambda$ is the gravitational (Coulomb) logarithm. An accretion of surrounding matter on a relic black hole would occur in a classical manner, without quantum scattering, if the gravitational radius of the black hole, $r_g=2GM/c^2$, exceeded the size of a nucleon, i.e., if $M>\hbar c/Gm_n\simeq 2.8\times 10^{14}$ g. In the inner core of the earth,[4] where the density of matter is $\rho_c\simeq 10$ g/cm^3, where the temperature is $T_c\simeq 4\times 10^3$ K, and where iron ($A=56$) is predominant, a black hole with a mass M would be gravitationally dominant within a radius $r_h=GMAm_n/kT_c$. Under the conditions prevailing at the center of the earth, the absorption of energy released in the course of accretion would lead to a convective heat transfer near the black hole. This convection would render the accreting gas adiabatic. A transition from convective to radiant heat transfer would occur only at $r\gg r_h$. Another distinctive feature arises because the duration of the orbital motion around a black hole is short in comparison with the time scale of the Coulomb energy loss of the plasma ions in a region $r\leqslant 10^2 r_g$. As a result, there would be a "slow" spherical accretion with friction in this region;[5] the trajectories of ions would be nearly regular helices contracting on the black hole, and the accretion efficiency would be at a maximum. Specifically, in the case of a nonrotating black hole we would have $\eta=L/\dot{M}c^2\simeq 0.057$, where L is the accretion luminosity of the black hole, and $\dot{M}$ is the accretion rate. The Eddington limit on the luminosity of a black hole, $L_E=2\pi m_p c^3 r_g/\sigma_T$—the value at which the rate of increase of the mass of the black hole, $\dot{M}_E=L_E/\eta c^2$, is at a maximum—is reached at

$$M > \frac{10}{\eta} \frac{m_p c^2}{G \sigma_T \rho_c} \left(\frac{kT_c}{A m_n c^2} \right)^{3/2} \simeq 1.0 \times 10^{13} \text{ g}. \quad (2)$$

Competing with accretion is a decrease in the mass of the black hole because of its quantum evaporation.[6] Superradiation[7,8] and accretion effectively slow the rotation of the black hole.[9] The rate of decrease in mass of a nonrotating black hole in the course of its quantum evaporation with an effective temperature $kT_{\text{ev}} = (\hbar/4\pi)(c/r_g) \simeq 10.6(\text{M}/10^{15} \text{ g})^{-1}$ MeV is, according to numerical calculations,[10,11]

$$\dot{M}_{\text{ev}} = a(M) \left(\frac{c^2}{GM} \right)^2 \hbar, \quad (3)$$

where the coefficient $a(M)$ has a value of 4.47×10^{-4} at $M \simeq 10^{14}$ g and is proportional to the number of particle species created. The condition for an increase in the mass of the black hole, $\dot{M} = \dot{M}_{\text{ev}} + \dot{M}_E > 0$, leads to the inequality

$$M > M_0 = \left[\frac{2}{3} \frac{\eta}{\alpha} \frac{m_e}{m_p} a(M) \right]^{1/3} \frac{e^2}{G m_e} \simeq 1.1 \times 10^{14} \text{ g}. \quad (4)$$

All black holes with masses $M > M_0$ from Eq. (4) grow by "eating" the interior of the earth in accordance with an exponential law $M \propto \exp(t/\tau_E)$, where $\tau_E = (\eta/4\pi) \times (\sigma_T c/G m_p) \simeq 2.6 \times 10^7$ yr. This time scale for the increase in the mass of the black hole, τ_E, is so short in comparison with the age of the earth, 4.5×10^9 yr, as to rule out the possibility that there would be primordial black holes with masses $M > M_0$ inside the earth. The interval of black-hole masses which still remains, $M < M_0$, can also be ruled out if we make use of calculations of the fluxes of atmospheric neutrinos[12,13] (these calculations agree with observations) and the idea of detecting the neutrino emission from small black holes inside the earth.[14]

The difference between the neutrino-emission rate $d\dot{N}_\nu/dE$ found numerically[10,11] and the blackbody rate $(d\dot{N}_\nu/dE)_{\text{BB}}$ is taken into account by introducing an approximating factor

$$K(x) = \frac{d\dot{N}_\nu}{dE} \left(\frac{d\dot{N}\nu}{dE} \right)^{-1}_{\text{BB}} = 1 - \frac{25}{27} \exp[-(7x)^4], \quad (5)$$

where $x = (1/8\pi)(E/kT_{\text{ev}})$. In (5) we have made use of the circumstance that the cross section for absorption of the neutrinos which are produced by the hole[8,10] is $\sigma_\nu = 27\pi(GM/c^2)^2$ in the geometric-optics limit $x \to \infty$, while it is $\sigma_\nu = 2\pi(GM/c^2)^2$ in the infrared limit $x \to 0$. The factor $K(x)$ leads to a fit of $d\dot{N}_\nu/dE$ within a few percent. Solid curve 1 in Fig. 1 shows the resultant flux of atmospheric ν_μ's and $\bar{\nu}_\mu$'s at sea level from the lower hemisphere.[12,13] Dashed curve 2 shows the resultant flux (F_ν) of neutrinos and antineutrinos of a common type at the surface of the earth from an evaporating black hole with an emission temperature $kT_{\text{ev}} = 10$ MeV and a corresponding mass $M \simeq 10^{15}$ g at the center of earth. The flux maximum $(F_\nu)_{\max} = 0.93 c^{-1} \cdot \text{cm}^{-2} \cdot \text{MeV}^{-1}$ is independent of M. It is reached at an energy $E_m = 4.0 kT_{\text{ev}}$ (horizontal dashed line 3). Solid curve 4 is the spectrum of the most energetic solar neutrinos, from the $^3\text{He} + p$ reaction, in the standard solar model.[15] It follows from this figure that neutrino emission of an isolated black hole at the center of the earth would be detected if the mass of the hole satisfied

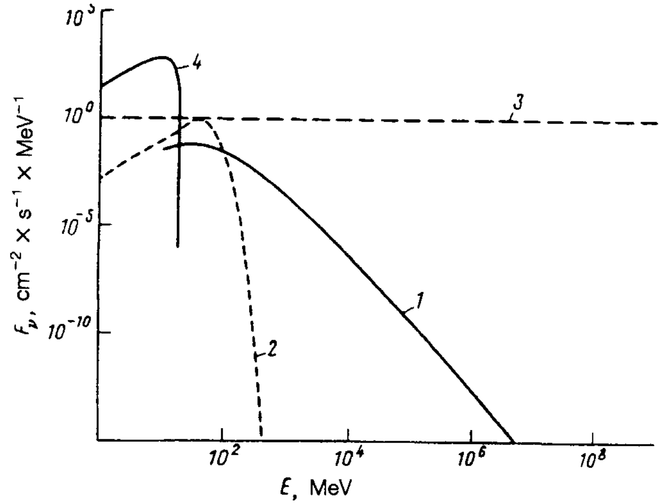

FIG. 1. Total fluxes at sea level. 1—Of atmospheric ν_μ's and $\bar{\nu}_\mu$'s from the lower hemisphere; 2—of ν_μ's and $\bar{\nu}_\mu$'s from an evaporating black hole with $kT_{\text{ev}} = 10$ MeV and $M \simeq 10^{15}$ g at the center of the earth. Line 3 shows the position of the maxima of this flux at various values of M, and curve 4 is the spectrum of the most energetic solar neutrinos, from the $^3\text{He}+p$ reaction.

$M < 10^{15}$ g. Since this mass interval overlaps the interval $M > M_0$ found above, from Eq. (4), the possible existence of black holes of any mass inside the earth can be ruled out completely.

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[1] Ya. B. Zel'dovich and I. D. Novikov, Astron. Zh. **43**, 758 (1966).
[2] S. W. Hawking, Mon. Not. R. Astron. Soc. **152**, 75 (1971).
[3] A. G. Polnarev and M. Yu. Khlopov, Usp. Fiz. Nauk **145**, 369 (1985) [Sov. Phys. Usp. **28**, 213 (1985)].
[4] S. W. Hawking, Nature **248**, 30 (1974); Commun. Math. Phys. **43**, 199 (1975).
[5] F. D. Stacey, *Physics of the Earth* (Wiley, New York, 1969).
[6] V. S. Berezinsky and V. I. Dokuchaev, Astrophys. J. **361**, 492 (1990).
[7] Ya. B. Zel'dovich, JETP Lett. **14**, 180 (1971).
[8] A. A. Starobinskiand S. M. Churilov, Zh. Eksp. Teor. Fiz. **65**, 3 (1973) [Sov. Phys. JETP **38**, 1 (1973)].
[9] D. N. Page, Phys. Rev. D **14**, 3260 (1976).
[10] D. N. Page, Phys. Rev. D **13**, 198 (1976).
[11] J. H. MacGibbon and B. R. Webber, Phys. Rev. D **41**, 3052 (1990).
[12] L. V. Volkova, Yad. Fiz. **31**, 1510 (1980) [Sov. J. Nucl. Phys. **31**, 784 (1980)].
[13] T. K. Gaisser *et al.*, Phys. Rev. D **38**, 85 (1988).
[14] A. R. Trofimenko Astrophys. Space Sci. **168**, 277 (1990).
[15] J. N. Bahcall, *Neutrino Astrophysics* (Cambridge U. Press, Oxford, 1989).

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