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Prospects for detection of primordial black holes captured in cold dark matter haloes around massive objects

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Abstract. The capture of cold dark matter species, and especially primordial black holes, during the formation of gravitationally bound objects is analyzed. It is shown that the best conditions for an efficient gravitational capture were at the epoch preceding the galaxy formation, when the first astrophysical objects with masses of the order of Jeans mass 10^5–$10^6\,M_\odot$ were forming. Black hole haloes around old globular clusters, dark matter clusters and Population III stars are considered, and in each case the total mass of the halo and its luminosity due to the Hawking emission are found. Among all the objects considered, large ($M \gtrsim 10^5\,M_\odot$), nearby (within ~ 5 kpc from the Sun) globular clusters are shown to provide the best prospects for detection of the black holes. First, black hole haloes around the globular clusters have the highest brightness near 100 MeV, which is within the reach of EGRET capabilities, and provide distinct observational features. Second, globular clusters are extensively studied at other wavelengths and represent a well-defined target for γ-ray detectors. We have also considered the probability of detecting an isolated black hole bound to the Sun. Our estimates of the mass of gravitationally captured haloes are applicable to any cold dark matter particles.

Key words: black hole physics – Galaxy: globular clusters: general – cosmology: dark matter – gamma rays: theory

1. Introduction

The idea of primordial black holes (PBHs) was first proposed by Zel'dovich & Novikov (1966) and Hawking (1971) almost thirty years ago. According to these and subsequent works (for recent reviews see Halzen et al. (1991), MacGibbon & Carr (1991)) PBHs could have formed at the very early stages of expansion of the Universe from primary metric and density fluctuations with the length comparable to the horizon size at that time. In the case of scale-invariant initial inhomogeneities, black holes were formed with a power-law distribution over the vast range of masses: $dN_{\rm pbh}/dm \propto m^{-5/2}$.

It was discovered soon that PBHs can manifest themselves through the quantum evaporation process, opening the way to their direct detection and hence to studying physical conditions in the early Universe, inaccessible by other means. The evaporation time τ_e depends on the PBH mass m: $\tau_e \propto m^3$, so that all PBHs with masses less than $m_* \simeq 5\cdot 10^{14}$g have been completely evaporated (Halzen et al. 1991). Therefore, the mass spectrum nowadays peaks at black hole masses $m \simeq m_*$ and the corresponding temperature of the Hawking emission $T \simeq 20\,$MeV. Measurements of diffuse γ-ray radiation around 100 MeV place an upper limit on the average PBH density in the Universe (MacGibbon & Carr 1991): $\Omega_{\rm pbh} \lesssim \Omega_{\rm H} = 10^{-8}h^{-2}$, i. e., $N_{\rm pbh} \lesssim 10^4{\rm pc}^{-3}$ (where $\Omega_{\rm pbh}$ is the total density of PBHs in units of the critical density, h is the Hubble parameter in units of 100 km/s/Mpc), but the identification of integrated PBH contribution to the γ-ray background of complicated nature looks unlikely.

There is also a possibility to identify the presence of evaporating black holes in the Galactic halo, where PBHs are supposed to be clustered to the same degree as other cold dark matter (CDM) species. If the PBH density in the halo exceeds the average PBH density in the Universe by more than $4\cdot 10^5$ times, then a contribution to the γ-ray background from the halo is larger than a contribution from the rest of the Universe. In this case, as was shown by Wright (1996), an anisotropy of the Galactic diffuse γ-ray emission puts a stronger upper limit on the number of PBHs in the Universe than that inferred from observations of the extragalactic background.

The chances to observe the Hawking radiation from individual black holes with existing γ-ray and particle detectors also do not look promising. Previous proposals were actually based on the hope that we are lucky enough to "catch" a PBH moving through the Solar system in the close vicinity of the Earth ($\lesssim 1$ a. u.), or a nearby explosion at the final stage of evaporation (Halzen et al. 1991; Semikoz 1994). Given the above constraint on the PBH density, both events seem to be unlikely[1]. Instead of the passive strategy of waiting for serendipitous discovery, in this paper we present a systematic analysis of possible ways

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[1] The situation can be improved if evaporation products form an MHD plasma wind at the final stage of evaporation (Belyanin et al. 1996; Heckler 1997), or if a nonstandard (Hagedorn-type) model of particles applies (Cline & Hong 1992; Cline et al. 1997). The latter is, however, not supported by accelerator experiments.

for active PBH search, applicable even in the case when their density is significantly below the current upper limit. The paper summarizes three most realistic directions of this search, all based on the idea of gravitational capture: 1) PBH haloes around old globular clusters and dark matter clusters, 2) smaller haloes around Population III stars, and 3) PBHs gravitationally bound to the Sun. The universal nature of gravitational collapse and dynamics of gravitationally interacting systems, together with well-understood properties of the Hawking radiation for $T \simeq 20\,$MeV black holes, allow us to make quantitative estimates and definite predictions on the observational appearance of PBH haloes.

Of all the three cases listed above, the results for the PBH haloes around globular clusters are shown to be the most promising. First, they give the highest probability of PBH detection and provide definite observational signatures of PBH haloes. Second, they are most reliable in a sense of having the minimum number of model suggestions and uncertainties.

Though we mention only PBHs, our general estimates for the mass of gravitationally captured haloes are applicable to any CDM particles.

2. General features of gravitational capture

Among other dark matter species, interaction of PBHs with surrounding medium is the weakest one in the sense that it is entirely limited to a gravitational force, insufficient to confine such a black hole inside any astrophysical object even in the case of a head-on collision. So, the only way that leads to gravitationally bound PBHs is the capturing of them during the epoch of the object formation.

The calculations below are based on two assumptions. First, we restrict ourselves to the case of a spherically symmetrical cloud still allowing good quantitative estimates. Second, the expressions in Sects. 3–5 for the total mass of PBH haloes are obtained assuming a power-law profile for the average density of matter in the *final* state of the collapsing cloud. In particular, this includes r^{-2} density distribution in the case of globular cluster haloes, or a point-like mass ($\bar{\rho} \propto r^{-3}$) for haloes around isolated stars.

Throughout the paper, we will mainly deal with adiabatic collapse, when the density changes on a timescale much longer than the period of oscillations of PBHs in the potential well of an object. This gives a conservative estimate since any violation of adiabaticity, as a rule, increases the number of PBHs left in the halo after the object formation.

Consider first an adiabatic collapse of the cloud in the simplest case when distribution of matter inside it remains the same function of radius, but with density increasing with time. If there are some weakly interacting particles bound in the gravitational well, their orbital radii decrease according to the conservation of the adiabatic invariant for radial motion

$$I = \frac{1}{\pi}\int_{r_{\min}}^{r_{\max}} mV_r dr = \frac{1}{\pi}\int_{r_{\min}}^{r_{\max}} \sqrt{2m\left(E-U-\frac{J^2}{2mr^2}\right)}dr, \quad (1)$$

where $r_{\min}$ and $r_{\max}$ are minimum and maximum distances of the particle from the center of the cloud, V_r is the radial velocity, E and U are total and potential energies, J is an angular momentum.

Let us introduce the dimensionless radius $x \equiv r/r_0$, where r_0 marks the position of minimum of the effective potential $U_{\rm eff} = (J^2/(2mr^2)+U)$, that is, the radius of a circular orbit for a given angular momentum J. For the power-law potential $U = kr^\alpha$, parameter r_0 satisfies the relation

$$kr_0^{\alpha+2} = \frac{J^2}{\alpha m} = \text{const}, \quad (2)$$

so that, despite both k and r_0 change in the adiabatic collapse, their combination on the left-hand side of (2) remains invariant. In terms of the dimensionless radius x Eq. (1) takes the form

$$I = \frac{1}{\pi}\int_{x_{\min}}^{x_{\max}} \sqrt{2m(\tilde{E}-\tilde{U}_{eff}(x))}dx,$$
$$\tilde{U}_{eff}(x) = \frac{J^2}{2mx^2} + kr_0^{\alpha+2}x^\alpha. \quad (3)$$

It follows from (2) that $\tilde{U}_{eff}(x)$ does not change during contraction, provided the potential remains power-law with the same index. So, the only parameter $\tilde{E} = Er_0^2$ completely defines the phase trajectory (and hence $x_{\max}$ and $x_{\min}$). As the invariant I is conserved, all three values, $\tilde{E}$, $x_{\max}$, and $x_{\min}$, should be constant. One may conclude then that the orbital shape, described by the elongation parameter $K = r_{\max}/r_{\min}$, preserves in the case of an adiabatic contraction. Expression (2) can be rewritten to relate r_0 to the average density ρ inside this radius:

$$kr_0^{\alpha+2} = \text{const} \quad \Rightarrow \quad \rho(r_0)r_0^4 = \text{const}. \quad (4)$$

Here and below in this paper $\rho(r)$ denotes the *average* density of some species of matter, defined as its total mass enclosed within a sphere of radius r divided by $(4/3)\pi r^3$. Eq. (4) can be rewritten to relate $\rho_{\rm pbh}$ to the average density inside this radius[2]:

$$\rho_{\rm pbh}(r_0)/\rho \propto \rho^{3/4}/\rho = \rho^{-1/4}. \quad (5)$$

However, our primary interest is to follow the evolution of PBHs bound inside the radius R enclosing the constant mass M. To do this, consider the general case of PBHs on non-circular orbits. Suppose that there is a spatially homogeneous initial excess of density of matter in a spherical volume of radius R against a homogeneous background (“top hat” fluctuation). Let $\mathcal{F}$ and $\mathcal{F}_v$ be the distribution functions of PBHs in the phase space and in the velocity space respectively, where $\mathcal{F}$ is normalized to the total number density of PBHs, and $\mathcal{F}_v$ is normalized to unity.

[2] For black holes on circular orbits the relation (4) is valid in an arbitrary potential as well, which follows directly from the conservation of J during the collapse: $r_0 M(r_0)$ = const, or $r_0 \propto \rho^{-1/4}$, where $M(r_0)$ is the total mass of the cloud within the radius r_0.

The average density of black holes on bound orbits lying inside the radius R is

$$\rho_{\rm pbh} \simeq \frac{3m}{4\pi R^3}\int_{r<R}\int_{V<V_{\rm e}} \mathcal{F} d^3V d^3r = \frac{3mN_{\rm pbh}(R)}{4\pi R^3}\int_{V<V_{\rm e}} \mathcal{F}_v d^3V. \quad (6)$$

Here $V_{\rm e}(R)$ is an escape velocity for the mass enclosed within the radius R ($V_{\rm e} \propto R$ in our case), $N_{\rm pbh}(R)$ is the *total* number of PBHs inside a volume of radius R (including those on orbits lying partially outside this volume), and the last equality is for the case when $\mathcal{F}$ can be factorized. The latter is a natural assumption for our homogeneous initial conditions. Below in this paper we will consider highly anisotropic velocity distributions, when in d dimensions the dispersion is much larger than $V_{\rm e}$ and is negligible in others, so that Eq. (6) yields $\rho_{\rm pbh} \propto R^d$.

Starting from these initial conditions, let us follow the evolution of average PBH density as the cloud collapses. It can be easily verified that the average density of PBHs captured within the given radius R is equal within a factor of two to the average density of turning points $r_{\rm max}$ inside this radius. The evolution of the latter quantity is easy to calculate. As was shown above (see the discussion after Eq. (3)), the ratio $x_{\rm max} = r_{\rm max}/r_0$ remains constant during the collapse. Therefore, one may study the evolution of the density of points $r_{\rm max}$ in the same way as if all PBHs were on circular orbits of radii r_0. So, consider $\rho_{\rm pbh}(R) \propto R^d$ distribution of black holes on circular orbits and transform it into the distribution over $J \propto R^2$: $N_{\rm pbh}(J) \propto J^{(3+d)/2}$. Here $N_{\rm pbh}(J)$ is the total number of PBHs with angular momentum less than J. As a result of conservation of $J \propto (RM(R))^{1/2}$ the initial distribution preserves, so that we arrive at $N_{\rm pbh}(R) \propto (RM(R))^{(3+d)/4}$. Therefore, the evolution of average relative PBH density inside the constant-mass shell is

$$\rho_{\rm pbh}/\rho \propto M^{(d-1)/4} R^{(3+d)/4} \propto \rho^{-\frac{3+d}{12}}, \quad (7)$$

which is valid for any power-law density profile.

Now we relax our requirement that the shape of potential is conserved in the collapse, and suppose that potential evolves from one power-law to another. In this case the orbital shape changes, but the dependence (7) of PBH density on ρ remains the same, with only the coefficient of proportionality being varied. In general, the latter should be calculated numerically. However, there are two important special cases, $U = kr^2$ (homogeneous cloud) and $U = kr^{-1}$ (point mass), when the integral (1) may be evaluated analytically:

$$I = \frac{(K-1)^2}{4\,K} J \quad \text{and} \quad I = \frac{(\sqrt{K}-1)^2}{2\sqrt{K}} J, \quad (8)$$

respectively. These special cases are natural choices for the initial and final states of a collapsing cloud. As both I and J remain constant, initial and final elongation parameters are related to each other as follows:

$$\frac{(K_i+1)^2}{K_i} = 2\frac{K_f+1}{\sqrt{K_f}}; \quad (9)$$

and for $K_i \gg 1$ one obtains

$$K_f \simeq \frac{K_i^2}{4} + K_i. \quad (10)$$

Relations (9), (10) and (4) allow us to follow changes in the shape of the orbit and its size in the process of formation of a compact object from initially homogeneous cloud. Consider a test particle on a highly elongated orbit just approaching the edge of the cloud. Though during the subsequent contraction the most distant point of the orbit is located outside of gravitating mass, the particle still spends some fraction of time in a non-stationary potential, which leads to further decrease of $r_{\rm max}$. To analyze this effect, we introduce another particle with the same angular momentum but on the circular orbit with radius r_0. As follows from (4), product of r_0 and mass enclosed within this radius is conserved, so after the collapse is completed, the size of an orbit becomes $(r_{\rm max}/r_0)^3$ times smaller. For a particle in quadratic potential $r_{\rm max} = \sqrt{K_i} r_0$, and the final radius of a circular orbit is $r_0' = r_{\rm max}/K_i^2$. In the potential $U \propto r^{-1}$ another relation is valid: $r_{\rm max}' = (K_f+1)r_0'/2$, therefore

$$\frac{r_{\rm max}'}{r_{\rm max}} = \frac{K_f+1}{2\,K_i^2} \simeq \left(\frac{1}{8} + \frac{1}{2\,K_i}\right), \quad (11)$$

where an approximate equality is for $K_i \gg 1$. As follows from Eq. (11), highly elongated orbits shrink approximately by 8 times. This "central drag" effect increases proportionality coefficient in Eq. (7) by a factor $(r_{\rm max}/r_{\rm max}')^{(3+d)/4}$.

Another typical situation is when the final state corresponds to the $\rho \propto r^{-2}$ density distribution (the logarithmic potential). For this case the above factor was calculated numerically, and the results are used in the next section.

What happens in the case of a non-adiabatic contraction? The quantitative description of a gravitational capture requires exact knowledge of the collapse dynamics and goes beyond the topic of this paper. However, qualitative difference from the above picture is evident: non-adiabatic contraction of the cloud leads to an enhancement of the capture rate and to an increase in the elongation parameter K. In the simplest, free-fall, case particles behave as if they were frozen in the shells of a constant mass, so that the ratio $\rho_{\rm pbh}/\rho$ remains constant.

3. PBH haloes around globular clusters

It was shown in the previous section that CDM (and in particular, PBHs) to some extent follows the collapse of ordinary matter. Therefore, it is reasonable to search for PBHs haloes around massive visible objects. At the same time, galaxies are not suitable for this purpose because they have a low average density and contain a significant fraction of gas which interacts with cosmic rays producing energetic γ-quanta and hence hiding true PBH emission from the view. Moving to smaller scales, we note that properties of globular clusters are much more favorable. Namely, they contain no or little gas and may have sufficiently large densities. Small angular sizes of globular clusters, comparable to the resolution of modern γ-ray detectors, may also help to distinguish their emission against the background of both galactic and extragalactic origin simply by subtracting its average level calculated for a nearby portion of the sky.

Of course, all considerations above are applicable to the oldest clusters which were formed before PBHs attain significant velocity dispersion, i.e. prior to the formation of galaxies. Otherwise, the efficiency of capturing is small according to (6). In addition, only those of them that have kept their CDM haloes until now could be observed as sources of γ-radiation. Leaving aside the mass loss due to "evaporation" and stellar evolution, this corresponds to the requirement that a considerable fraction of PBHs is confined closer than the tidal radius R_t. The average cluster density ρ_t inside R_t is approximately equal to the maximum density in the Galactic environment along the orbital path of the cluster; outer parts that have lower density are stripped out by the tidal forces. For the globular cluster crossing galactic disk one has $\rho_{\rm t} \sim 10^{-22}$g/cm^3.

3.1. Total mass of PBH halo

Let us assume that Jeans instability at mass scale $\sim 10^6 M_\odot$ enters nonlinear regime at redshift $z_n \sim 50$ (Primack 1993; Tegmark et al. 1997). After that time, the evolution of PBH orbital distances follows Eq. (4). In the case of the flat Universe with an average density equal to the critical value $\rho_{\rm c} = 3(1+z)^3 H^2/(8\pi G)$, where H is the present-day Hubble parameter, we obtain

$$\frac{\rho^{'}_{\rm pbh}}{\rho_{\rm pbh}} \simeq 2\left(\frac{\rho_t}{\Omega_{\rm CDM}\rho_{\rm c}}\right)^{3/4} \qquad (12)$$

where the prime denotes quantities after the contraction is completed and the factor 2 is added to take into account the "central drag" effect due to the transition to $\rho \propto r^{-2}$ density profile, which is calculated numerically following the way described in the previous section (Eqs. (9)-(11)). $\Omega_{\rm CDM}$ is the density of cold dark matter in units of the critical density; later in this work we assume $\Omega_{\rm CDM} \simeq 0.6$ for numerical estimates (Primack 1993). The above equation provides an expression for the total mass of PBHs initially captured inside a tidal radius:

$$\frac{M_{\rm pbh}}{M_{\rm b}} \simeq \frac{2\Omega_{\rm pbh}}{\Omega'_{\rm b}}\left(\frac{\rho_{\rm c}}{\Omega^3_{\rm CDM}\rho_t}\right)^{1/4}. \qquad (13)$$

Here the index b refers to baryonic matter and $\Omega'_{\rm b} < 1$ is the mass fraction of it inside the tidal radius. This fraction can not be inferred from Eq. (13) as the dark matter density is dominated by particles that are not captured in the region of interest but only pass it in their orbital motion. However, we may estimate this parameter assuming that CDM is redistributed to form r^{-2} density profile in the region that takes part in the formation of a cluster, with transition to constant density $\Omega_{\rm CDM}\rho_{\rm c}$ at the edge. Then $\Omega'_{\rm b} \simeq (\Omega_{\rm b}/\Omega_{\rm CDM})(\rho_t/(\Omega_{\rm CDM}\rho_{\rm c}))^{1/2}$ for $\Omega'_{\rm b} \ll 1$. Since the above assumption leads most likely to an overestimation of Ω'_b, it gives (together with Eq. (13)) a rather conservative expression for the mass of PBHs in the cluster

$$M_{\rm pbh} \simeq \frac{2\Omega_{\rm pbh}}{\Omega_{\rm b}}\left(\frac{\Omega_{\rm CDM}\rho_{\rm c}}{\rho_t}\right)^{3/4} M_{\rm cl}$$

$$\simeq 3\cdot 10^{-2} M_\odot \frac{M_{\rm cl}}{10^6 M_\odot}, \qquad (14)$$

where $M_{\rm cl}$ is the stellar mass of a cluster. For the numerical estimate throughout the paper we take $\Omega_b = 0.03$, $\Omega_{\rm pbh} = 10^{-8}h^{-2}$, $h = 0.7$, and the critical density ρ_c corresponding to $z = 50$.

Note that according to (14) the surface brightness of a globular cluster due to PBH γ-ray emission alone ($\propto \int \rho_{\rm pbh} dl$ along the line of sight) is somewhat less than expected for the PBH halo of a typical galaxy, say, the Milky Way inside the Solar galactocentric radius. At the same time, total brightnesses for the nearest cluster and the nearest large galaxy M31 are practically equal, to say nothing of an interstellar gas and other poorly known sources of energetic quanta which may dominate the galactic emission. Thus, one may conclude that globular clusters are the best places to start a search for PBHs.

Consider now how many chances this old PBH population has to survive until present time. One cause for secondary losses is the decrease of globular cluster mass that leads to the expansion of PBH orbits outside the tidal radius and arises from two processes: a violent mass loss at the late stages of massive stars' evolution and the star loss due to two-body collisions and the influence of gravitational shocks (see, e. g. Lightman & Shapiro 1978; Spitzer 1987; Gnedin & Ostriker 1997). The first of them has negligible effect as the majority of stars belongs to the red dwarf population and does not undergo any kind of explosion. The second process leads to a star loss time exceeding or comparable to the age of the Universe. This effect is insignificant for large globular clusters with current mass $M_{\rm s} \gtrsim 10^5 M_\odot$ that are primary candidates for detection of PBH haloes (see the discussion below).

Another cause of secondary losses is an interaction with stars: when a heavy object moves through a cloud of lighter particles it experiences tidal friction, in other words, it "heats" the particles until they escape from the cloud. Let us assume that some volume contains stars of equal masses M, and the volume density in stars is $\rho_{\rm s}$. The volume is filled also by "dust particles" with masses m and density ρ_d. Moving in the gravitational field of a star, a particle is deflected by an angle α given by

$$1 - \cos\alpha = \frac{2G^2M^2m^4s^2}{J^4 + G^2M^2m^4s^2}, \qquad (15)$$

where J is an angular momentum and s an impact parameter. Given the relative velocity at the infinite distance, $\mathbf{V}$, one may integrate the above equation to obtain the friction force

$$\frac{d}{dt}(M\mathbf{U}) = -\int n_v d^3\mathbf{V}\int_0^{s_{\max}}(1-\cos\alpha)m\mathbf{V}2\pi sV\,ds$$

$$= -2\pi m\int n_v d^3\mathbf{V}\frac{G^2M^2}{V^3}\mathbf{V}\ln(1+\Lambda). \qquad (16)$$

Here $\mathbf{U}$ is the velocity of a star, n_v is the particle number density in the velocity space, $\Lambda = V^4 s^2_{\max}/(G^2M^2)$, and a lower limit in the integral over s is taken to be zero because the contribution from particles with small s that formally penetrate into the star is insignificant, $\sim V/V_{\rm e} \ll 1$, where $V_{\rm e}$ is the escape velocity at the star's surface. Although Λ depends on V, it is also very large, so that the logarithm is practically constant and may be approximated as $\ln(1+\Lambda) \simeq 2\ln N_{\rm s}$, where $N_{\rm s}$ is the total number of stars in the cluster. Then expression (16) takes the form similar to the Newtonian law of gravitation and is easily integrable in velocity space

$$\frac{d}{dt}(M\mathbf{U}) = -4\pi\rho_d(V<U)\frac{G^2M^2}{U^3}\mathbf{U}\ln N_{\rm s}, \tag{17}$$

$\rho_d(V<U)$ is the density of particles that have velocities less than U. The equation obtained may be treated as an expression for the rate of "dust" kinetic energy gain as well, and our last step is to estimate the time required to expel dark matter from the cluster,

$$\begin{aligned}\tau &\simeq \frac{N_{\rm s}}{\ln N_{\rm s}}\frac{1}{\sqrt{12\pi G\rho_{\rm s}}} \\ &\simeq 1.4\cdot10^{11}\frac{N_{\rm s}}{10^6}\left(\frac{10^{-22}\text{g/cm}^3}{\rho_{\rm s}}\right)^{1/2}\text{yr},\end{aligned} \tag{18}$$

where we have substituted U for the virial velocity and assumed $\rho_d(V<U)=\rho_d$. The result shows that most of the cluster's volume with $10^{-22}\text{g/cm}^3 \lesssim \rho \lesssim 10^{-20}\text{g/cm}^3$ preserves initially captured dark matter. However, no central brightening is expected for the dense core of a globular cluster which should be free of PBHs. If actually observed, this feature may be considered as an argument in favor of the PBH model of γ-ray emission.

3.2. Luminosity of PBH haloes and prospects for detection

The total mass of PBHs may be converted into the expression for their total luminosity given the initial mass spectrum $dN_{\rm pbh}/dm_{\rm i} = Cm_{\rm i}^{-5/2}$ and luminosity of a single black hole (MacGibbon & Webber 1990)

$$L \equiv \frac{dm}{dt}c^2 = \frac{A}{m^2} \simeq 8\cdot10^{16}\left(\frac{10^{15}\,\text{g}}{m}\right)^2 \text{erg s}^{-1}, \tag{19}$$

about $\beta \simeq 0.09$ of which comes in γ-rays. Here A is almost independent of m for masses $m \gtrsim 5\cdot10^{14}$ g that make the main contribution to the observed luminosity above 100 MeV. According to Eq. (19), the present-day mass m of a black hole is related to its initial mass as $m_{\rm i} = (m^3+m_*^3)^{1/3}$, and all PBHs with masses less than $m_* = (3At_0/c^2)^{1/3} \simeq 4\cdot10^{14}h^{-1/3}$ g have been completely evaporated. Here t_0 is the age of the Universe. The total γ-ray luminosity of the halo

$$\begin{aligned}L_{\rm pbh} &= \beta\int\frac{dm}{dt}\frac{dN_{\rm pbh}}{dm_{\rm i}}\frac{dm_{\rm i}}{dm}\,dm \\ &= \beta C\int\frac{A dm}{(m^3+m_*^3)^{3/2}}\end{aligned} \tag{20}$$

can be expressed via the total mass of PBHs in the halo

$$M_{\rm pbh} = C\int\frac{m^3 dm}{(m^3+m_*^3)^{3/2}} \tag{21}$$

Table 1. Upper limits on PBH masses

Cluster	$M_{\rm pbh}/M_\odot$	$M_{\rm pbh}/M_{\rm cl}$
NGC 5139	5	$2\cdot10^{-6}$
NGC 6656	2	$4\cdot10^{-6}$
NGC 6397	1	$8\cdot10^{-6}$
NGC 6544	1	$1\cdot10^{-5}$
NGC 6553	5	$2\cdot10^{-5}$

using integration by parts:

$$L_{\rm pbh} = \beta\frac{M_{\rm pbh}}{2m_*}L(m_*) = \frac{\beta}{4}HM_{\rm pbh}c^2. \tag{22}$$

Substituting $M_{\rm pbh}$ from Eq. (14) yields

$$\begin{aligned}L_{\rm pbh} &\simeq 5\cdot10^{33}\,\Omega_{\rm CDM}^{3/4}h^{1/2}\left(\frac{z_n}{50}\right)^{9/4} \\ &\times\frac{\Omega_{\rm pbh}}{\Omega_{\rm H}}\frac{M_{\rm cl}}{10^6M_\odot}\,\text{erg s}^{-1},\end{aligned} \tag{23}$$

where we put $\Omega_{\rm b}=0.03$; $z_n \gg 1$.

The source that luminous could be detected from the distance 5 kpc, provided $\Omega_{\rm pbh} = \Omega_{\rm H}$ and the sensitivity $10^{-8}\,\text{s}^{-1}\,\text{cm}^{-2}$ in the 100 MeV range is reached. The latter value corresponds to the EGRET sensitivity (Thompson et al. 1995). Thus, EGRET observations of nearby massive globular clusters are strongly encouraged. Among best candidates having the distance from the Sun less than 5 kpc and the total mass in excess of $10^5\,M_\odot$ we can mention NGC 5139, NGC 6121, NGC 6397, NGC 6544, NGC 6553, NGC 6656, NGC 6809. Five clusters from the above list have been actually observed with EGRET during a search for millisecond pulsars (Michelson et al. 1994). However, the sensitivity of the search was not better than $\simeq 10^{-7}\,\text{s}^{-1}\,\text{cm}^{-2}$, and only an upper limit on the luminosity of clusters above 100 MeV was established, which ranged from $1.1\cdot10^{35}$ erg s^{-1} for NGC 6544 to $5.3\cdot10^{35}$ erg s^{-1} for NGC 5139. These observations place the upper limits on the total mass of PBHs and their mass ratio in the observed clusters, which are summarized in Table 1. The future GLAST mission, to be launched in 2005, will be able to detect PBH haloes around globular clusters provided the PBH abundance is close to the Hawking limit.

We note also a possibility that there are far more numerous massive dark clusters in our Galaxy (Carr & Lacey 1987; Sánchez-Salcedo 1997). In this case at least some of them should be detected by EGRET if the PBH density is close to the Hawking limit $\Omega_{\rm H}$.

Finally, we calculate the surface brightness of a globular cluster halo and compare it with background produced by PBHs over the lifetime of the Universe. In the case of the flat Universe (the Hubble parameter $H = 2/3t$) and initial mass spectrum $dN_{\rm pbh}/dm_{\rm i} \propto m_{\rm i}^{-5/2}$, the energy density ε of γ-ray background follows the equation

$$\frac{d\varepsilon}{dt} = -4H\varepsilon + \beta\Omega_{\rm pbh}\rho_{\rm c}\frac{L(m_*)}{2m_*}, \tag{24}$$

where the last term is the emissivity per unit volume, and m_* and $\Omega_{\rm pbh}$ are functions of time. This equation has a simple solution which we express in terms of brightness per solid angle

$$I_\Omega^{\rm u} = \beta \frac{ct_0}{2\pi} \frac{L(m_*)}{2m_*} \Omega_{\rm pbh}\rho_{\rm c}. \tag{25}$$

Here all variables take their current values. This is to be compared with the surface brightness for a globular cluster, obtained from Eq. (22):

$$I_\Omega^{\rm cl} = \beta \frac{R_{cl}}{3\pi} \frac{L(m_*)}{2m_*} \frac{M_{\rm pbh}}{(4/3)\pi R_{cl}^3}. \tag{26}$$

The surface brightness measure $\int \rho_{\rm pbh} dl$ is equal to $2ct_0\langle\rho_{\rm pbh}\rangle_u$ for the background, where the PBH density is averaged over the whole Universe, and is given by $(4/3)R_{cl}\langle\rho_{\rm pbh}\rangle_{cl}$ for a globular cluster, where the density is averaged over the cluster of radius R_{cl}. The values are close to each other for $R_{cl} = 150$ pc. However, as the observer points closer to the cluster core with the maximum achievable density $\sim 10^{-20}$g/cm^3 (see (18)), the surface brightness becomes about an order of magnitude larger. Taking into account a small angular size of the core, we conclude that observations of Galactic globular clusters carried out with sufficient angular resolution and sensitivity may reveal γ-ray emission of PBHs even if their density is two orders of magnitude lower than current upper limit.

4. Haloes around Population III stars

Besides the globular clusters, another kind of objects at least that old could be present in the Galaxy. There is strong, though indirect, observational evidence for the epoch of a star formation within the redshift interval $10 \lesssim z \lesssim 10^2$, which could lead to a buildup of the first generation of stars, Population III stars (see recent papers by Hairman & Loeb 1997; Gnedin & Ostriker 1997; Tegmark et al. 1997; Miralda-Escudé & Rees 1997 and references therein). Their existence provides possibility to explain a high ionization level and nonzero metallicity of the intergalactic gas at redshifts $z \sim 5$ (Songaila & Cowie 1996). Population III stars are potentially much more numerous than globular clusters, which may compensate for smaller sizes of their PBH haloes. It is not the tidal radius that limits the size of the dark matter halo around an isolated star, but close encounters with other stars. Given the typical Galactic stellar density, it is easy to estimate this size: $r_{\rm h} \sim 10^{-2}$ pc. In addition, not every star is able to keep the halo: those that explode at the final stages of evolution should be excluded from our consideration. So, only red dwarfs with masses $\simeq 0.8 M_\odot$ and average halo density $\rho_{\rm h} \sim 10^{-17}$g/cm^3 are left.

Let us discuss the possible way of formation of such stars inside large clouds of mass comparable to that of a globular cluster (this corresponds to the Jeans mass after the recombination epoch). Since dynamics of the process is still poorly understood, we consider two scenarios. "Optimistic" one implies that the stars were formed during the free-fall contraction of a large cloud. This case is similar to the gravitational capture during the formation of an isolated object (see the previous sections), and expressions (7) and (14) may be used without modification giving ($d = 0$)

$$M_{\rm pbh} \simeq \frac{2\Omega_{\rm pbh}}{\Omega_{\rm b}} \left(\frac{\Omega_{\rm CDM}\rho_{\rm c}}{\rho_0}\right)^{3/4} \left(\frac{\rho_0}{\rho_{\rm h}}\right)^{1/4} M_{\rm s} \tag{27}$$

for the mass of captured PBHs, where $M_{\rm s}$ is mass of the star, ρ_c and $\rho_0 \simeq 10^{-23}$ g/cm^3 are, correspondingly, the critical density and the density of a protostellar cloud at the moment when the star formation begins. Expression (27) does not take into account the "central drag" effect, which we consider later.

Another, "pessimistic", scenario implies the formation of stars in an adiabatically contracting large cloud, so that all captured PBHs had completed several orbital cycles and achieved a significant dispersion of radial velocity ($d = 1$ in Eq. (7)). When the contraction of a protostellar cloud starts, the latter soon begins falling towards the center due to a rapidly growing density, and all the PBHs inside it that have velocities less than the escape velocity become trapped. In the beginning of this regime the density of a small (protostellar) cloud and that of the large one are still of the same order. Therefore, the ratio of escape velocity from the small cloud to oscillatory velocity in the large cloud, equal to the ratio of their radii $R_{\rm small}/R_{\rm large}$, provides a good estimate for the relative fraction of captured particles. It is not necessary to take care of whether the particle is geometrically inside the protostellar cloud, as the relatively small escape velocity guarantees that it is very close to the turning point. Thus, $\simeq (M_{\rm s}/M_{\rm cl})^{1/3}$ fraction of all PBHs having turning points within the volume of a protostellar cloud are captured by its gravity. With the described modifications one gets the "pessimistic" estimate for the PBH halo mass

$$M_{\rm pbh} \simeq \frac{2\Omega_{\rm pbh}}{\Omega_{\rm b}} \left(\frac{\Omega_{\rm CDM}\rho_{\rm c}}{\rho_0}\right)^{3/4} \times \left(\frac{M_{\rm s}}{M_{\rm cl}}\right)^{1/3} \left(\frac{\rho_0}{\rho_{\rm h}}\right)^{1/3} M_{\rm s}. \tag{28}$$

A valuable fraction of particles have orbits that are not too elongated, hence, the result of the "central drag" will be somewhere between the maximum effect (11) and no effect at all. At the same time, initial stages of collapse of the protostellar cloud are most likely nonadiabatic, leading to more efficient gravitational pull and to more elongated orbits. It is reasonable therefore not to take into account the nonadiabatic stage while making pessimistic estimate, but to include the "central drag".

Let us discuss now the consequences of an additional decrease of orbital sizes in the case of fixed $r_{\rm h}$. The average density inside the sphere of radius r is proportional to r^{-3} if all mass is concentrated in a central object. After the corresponding substitution in Eq. (7) we obtain the following dependence

$$M_{\rm pbh}(r) \propto r^{\frac{3+d}{4}}. \tag{29}$$

So, the "central drag" will result in the increase of a halo mass by $8^{3/4}$ times ("optimistic" case) or by 8 times ("pessimistic" case). Finally, we obtain an expression for the γ-ray luminosity of the PBH halo

$$L_{\rm h} \simeq 8^{3/4}\frac{2\Omega_{\rm pbh}}{\Omega_{\rm b}}\left(\frac{\Omega_{\rm CDM}\rho_{\rm c}}{\rho_0}\right)^{3/4}\left(\frac{\rho_0}{\rho_{\rm h}}\right)^{1/4}\beta\frac{M_{\rm s}}{2m_*}L_* \sim 4\cdot 10^{27}\,{\rm erg\,s^{-1}} \quad (30)$$

in the "optimistic" scenario (for $\Omega_{\rm pbh} = \Omega_{\rm H}$ this estimate corresponds to $\sim 10^{11}$ PBHs captured in the halo of a star[3]) and

$$L_{\rm h} \simeq 8\frac{2\Omega_{\rm pbh}}{\Omega_{\rm b}}\left(\frac{\Omega_{\rm CDM}\rho_{\rm c}}{\rho_0}\right)^{3/4}\left(\frac{M_{\rm s}}{M_{\rm cl}}\right)^{1/3}\left(\frac{\rho_0}{\rho_{\rm h}}\right)^{1/3}\beta\frac{M_{\rm s}}{2m_*}L_* \sim 2\cdot 10^{25}\,{\rm erg\,s^{-1}} \quad (31)$$

in the "pessimistic" one, which is approximately $2\cdot 10^2$ times lower than the value (30). The numerical values in (30) and (31) are obtained using the same choice of parameters as in (23).

The source of luminosity (30) may be detected by EGRET from the maximum distance of the order of 3 pc. An average distance to the nearest Population III star is highly uncertain. A rough estimate can be made, for example, from the following considerations. According to Miralda-Escudé & Rees (1997), the observed metallicity of $Z \simeq 2\cdot 10^{-4}$ in the Lyα forest absorption lines requires approximately one supernova per 5000 $M_\odot$ of baryons. At the same time, this number of high-mass (and therefore UV-bright) stars is more than enough to reionize the Universe. To find the number of low mass stars we need to know the initial mass function. For a standard stellar mass function, there is approximately 100 $M_\odot$ of low mass stars per one supernova. This corresponds to $\sim$ 2% of baryons turned into stars of the first generation. At the time of formation of present galaxies these stars behaved like collisionless matter and should have been captured in galactic haloes. Then the total mass of the Population III stars in the Galaxy is of the order of $10^9\ M_\odot$ (Miralda-Escudé & Rees 1997). Assuming that these stars are distributed like CDM in the Galactic halo, we obtain that the nearest star is at a distance of $\sim$ 10 pc from the Sun. Therefore, the detection of PBH haloes around these stars requires the increase of the sensitivity by a factor of 10, as compared with EGRET. The definite signature of such stars is their high velocity. Any fast-moving low luminosity and low metallicity star found in optical/IR observations in the solar neighborhood would be a good candidate for the PBH halo search. Such stars are in fact directly observed (Gould et al. 1997; Fuchs & Jahreiß 1998). Fuchs & Jahreiß (1998) identified 15 halo subdwarfs within 25 pc from the Sun, five of them being located closer than 10 pc.

5. PBHs in Solar system

Although the detection of 100 MeV γ-ray emission from the globular clusters or isolated Population III stars would be an important step towards the discovery of PBHs, the only compelling evidence is an observation of a single nearby PBH with well-pronounced proper motion. With modern γ-ray detectors such observations are only possible for objects not farther than a few a. u. away, i. e. moving across or bound inside the Solar system. The first case is practically ruled out because it is extremely improbable. To investigate the second possibility we apply the approach developed in the above sections to the case of formation of the Sun.

Let us denote by $\mathcal{F}$ the PBH number density in the phase space in the beginning of collapse of the protosolar cloud. Under assumption that $\mathcal{F}$ is constant in the spatial volume of the protostellar cloud and in the volume of velocity space bounded by escape velocity, $V \le V_{\rm e} = \sqrt{2GM_\odot/R_{\rm i}}$, we calculate the number of initially captured PBHs

$$N_i = \left(\frac{4\pi}{3}\right)^2 R_{\rm i}^3 V_{\rm e}^3 \mathcal{F} = \left(\frac{4\pi}{3}\right)^2 (2GM_\odot R_{\rm i})^{3/2}\mathcal{F}, \quad (32)$$

where the initial radius $R_{\rm i}$ of the cloud is a free parameter. During the subsequent contraction the majority of black holes are lost and the exact quantitative estimate of the losses depends on details of the collapse dynamics. To avoid unnecessary complication, one may adopt a simple model which incorporates two stages: an adiabatic contraction and a free-fall stage which leads to η times decrease of cloud's radius. Then, for 3-dimensional dispersion of PBH velocities expression (7) gives the estimate for the final number of PBHs within the fixed radius $R_{\rm s}$

$$N_{\rm s} = 8^{3/2} N_i \left(\frac{\eta R_{\rm s}}{R_{\rm i}}\right)^{3/2} \simeq 8^{3/2}\frac{16\pi^2}{9}(2GM_\odot \eta R_{\rm s})^{3/2}\mathcal{F}, \quad (33)$$

where the relation $\rho \propto R^{-3}$ is used and factor $8^{3/2}$ is due to the "central drag" as follows from (29). Generally speaking, orbits of captured PBHs are not too elongated initially, but may be stretched later, during the free-fall stage if it occurs. Thus, an inclusion of the factor $8^{3/2}$ is only valid for $\eta \gg 1$.

In what follows, we will substitute $(4\pi/3)^{-1} n_{\rm pbh} D_v^{-3}$ for the numerical estimate of $\mathcal{F}$, where $n_{\rm pbh}$ is the PBH spatial density in the region where the Sun formed and D_v is local dispersion of their velocities at the time of formation. There are two natural assumptions about specific numerical values of $n_{\rm pbh}$ and D_v. In one variant, PBHs trace the density distribution in the Galactic halo which is supposed to consist mostly of CDM. In this case the velocity dispersion $D_v \simeq 300\,{\rm km\,s^{-1}}$, and PBHs are clustered to the same degree as the CDM in the Galactic halo. Another possibility is that PBH density in the Galactic disk is considerably higher (one may suppose that CDM is at least as abundant here as baryonic matter (Bahcall et al. 1992)). In this case velocity dispersion is introduced by closely passing stars: $D_v \simeq 10\,{\rm km\,s^{-1}}$. For the following estimates we take $n_{\rm pbh} \sim 5\cdot 10^8\ {\rm pc^{-3}}$ and $n_{\rm pbh} \sim 5\cdot 10^9\ {\rm pc^{-3}}$ respectively.

For the sake of definiteness we consider $R_{\rm s} = 1$ a. u. that roughly corresponds to the sensitivity of EGRET. Then Eq. (33) gives

$$N_{\rm s} \sim 10^{-27}\left(\frac{n_{\rm pbh}}{\rm pc^{-3}}\right)\left(\frac{c}{D_v}\right)^3 \quad \text{for } \eta = 1, \quad (34)$$

[3] This number could be severely constrained if a PBH from the residual halo, captured inside a neutron star, causes its collapse with subsequent release of a huge amount of energy, giving rise to the γ-ray burst (Derishev et al. 1998a, 1998b). Then, the observed burst rate places an upper limit of less than 10^6–10^7 black holes closer than 10^{-2} pc to the star.

and

$$N_{\rm s} \sim 3 \cdot 10^{-26} \left(\frac{n_{\rm pbh}}{\rm pc^{-3}}\right) \left(\frac{c}{D_v}\right)^3 \eta^{3/2} \quad \text{for } \eta \gg 1. \qquad (35)$$

In the case when capturing occurs directly from Galactic halo population, the above expressions give negligibly small number of nearby PBHs, $\sim 5 \cdot 10^{-10}$ and $\sim 10^{-8}\eta^{3/2}$ respectively. The second formula requires unreasonably high $\eta \sim 10^5$ to compensate the numerical factor. On the other hand, capturing from the disk population gives much better results: $\sim 2 \cdot 10^{-4}$ or $\sim 4 \cdot 10^{-3}\eta^{3/2}$ PBHs closer than 1 a.u. from the Sun. In this case, an inclusion of even minor free-fall stage (which almost certainly took place during the formation of the Solar system) leads to a rather high probability to find a PBH by means of already existing instruments.

Complicated dynamics of the inner Solar system (interactions with planets) may alter the above conclusions. Consider, for instance, PBH-Earth interactions in the case of a large inclination of PBH orbit. The average energy gain for the particle deflected by an angle α is proportional to $1 - \cos\alpha$ and hence, is of order $m_{\rm pbh} V_{\rm II}^4/(4V_{\rm orb}^2)$ (see (15)), where $V_{\rm II}$ is Earth's escape velocity and $V_{\rm orb}$ the orbital velocity of a black hole. After multiplication by Coulomb logarithm $\simeq \ln(1{\rm a.u.}/R_\oplus)$ and the probability of a close encounter $\sim (R_\oplus/1{\rm a.u})^2$ we obtain an order of magnitude estimate for the energy gain rate:

$$\frac{d}{dt} m_{\rm pbh} V_{\rm orb}^2 \sim 10^{-10} m_{\rm pbh} V_{\rm orb}^2 \quad {\rm yr}^{-1}, \qquad (36)$$

provided $V_{\rm orb} \simeq 30\,{\rm km\,s}^{-1}$ and the orbital period is of order 1 year. Therefore, a PBH has good chances to avoid significant increase of its orbital distance, as the above expression indicates. However, in the region of gravitational influence of massive planets (Jupiter and Saturn) the situation is different and this zone is free of PBHs even if they were present there initially. Yet at larger distance the expulsion time again exceeds the age of the Solar system. In addition, a small fraction of PBHs on nearly circular orbits with low inclination may occupy "resonant" positions, changing orbital parameters in accordance with motion of planets.

Finally, we discuss the future prospects for PBH search in the Solar system. Long-term observations with existing instruments will increase the effective detection distance, because PBHs have very elongated orbits and spend some time much closer to the Sun, where they could be observed. The great improvement in sensitivity, if it allows to detect a PBH up to the Neptune orbit, will make the detection inevitable in the case when the capturing from disk population is possible and will give a valuable chance to discover a PBH even in the case of capturing from the Galactic halo component.

It is easy to obtain the expressions for the amount of CDM in the Solar system by analogy with Eq. (35). If there is a disk component of CDM, we arrive at

$$M_{\rm CDM}(R) \sim 10^{-13}\eta^{3/2} \left(\frac{R}{1\,{\rm a.\,u.}}\right)^{3/2} M_\odot. \qquad (37)$$

This corresponds to $\sim 2 \cdot 10^{-11}\eta^{3/2} M_\odot$ of nonluminous matter inside the Neptune orbit, which is about five orders of magnitude below the current upper limit (Anderson et al. 1995) provided $\eta \lesssim 10$.

On the other hand, the amount of CDM can be constrained by apparent nondetection of PBHs within 1 a. u. from the Earth, since there should be $\sim 5 \cdot 10^{14}\, \Omega_{CDM}/\Omega_{\rm pbh}$ gram of CDM per each black hole. If one assumes that $\Omega_{\rm pbh} \gtrsim 10^{-4}\Omega_{\rm H}$ this already gives more stringent (indirect) limit on dark matter bound to the Sun than that derived from measurements of spacecraft trajectories.

6. Discussion

We have shown that the detection of the quasi-stationary 100 MeV radiation from evaporating black holes of masses of order $m_* \simeq 5 \cdot 10^{14}$ g is already possible with EGRET sensitivity provided the density of PBHs is close to the Hawking limit, $\Omega_{\rm pbh} \simeq \Omega_{\rm H}$. The key idea that leads to the conclusion so different from previous results (Halzen et al. 1991; Semikoz 1994) is to search for PBH haloes captured by massive objects at the epoch of their formation. We have derived simple but accurate enough expressions for the number of PBHs captured during the contraction of gas + CDM clouds. Throughout the paper, we tried to give *conservative* estimates for the efficiency of gravitational capture and to indicate explicitly the degree of uncertainty of numerical results.

Our calculations show that the best conditions for an efficient capture were at the epoch when the first gravitationally bound objects formed. The result is obvious since black holes had very small velocity dispersion at that time. Among several types of objects able to accumulate and keep large PBH haloes, globular clusters provide the best prospects for PBH detection. They have at least three advantages as compared with other objects considered.

- First, PBH haloes around nearby large globular clusters seem to have the highest brightness which is within the reach of EGRET capabilities.
- Second, globular clusters are well studied at other wavelengths and represent a well-defined target for γ-ray detectors (as opposed to the case of dark matter clusters, Population III stars or isolated nearby PBHs).
- Third, the specific observational feature of PBH-produced γ-ray halo around globular clusters is the dim central part or, at least, the absence of the central brightening – a signature we consider to be attributed to dark matter component.

In addition, the estimates for the efficiency of gravitational capture by globular clusters are most reliable in a sense of having the minimum number of model-dependent suggestions and uncertainties.

With future improvements in both sensitivity and angular resolution, the above proposal has the potential to detect the presence of PBHs with density as low as two orders of magnitude below the current upper limit.

As for other objects considered in the paper (dark clusters, isolated Population III stars and individual nearby black holes), the best results are expected for dark matter clusters in the Galaxy which may have masses in a wide range (Gurevich et al. 1997; Carr & Lacey 1987; Sánchez-Salcedo 1997). Note that the probability of detection increases with mass of dark clusters, since the brightness of the nearest object is proportional to the cubic root from its mass, other conditions being equal. This fact explains why observations of isolated Population III stars offer lesser success.

Since the existence of the above three kinds of hypothetical sources is not confirmed by observations at other wavelengths, the best strategy for today would be to perform repeated observations of unidentified sources from the second EGRET catalog (Özel & Thompson 1996) and future γ-ray surveys. Also, it is desirable to carry out γ-ray observations of nearby halo dwarfs already identified (Fuchs & Jahreiß 1998). For PBH emission the following signatures are expected:

1. Any PBH-originated source of the kind described in this paper should have an extremely stable photon flux with known spectrum which is a convoluton of Planckian curves and peaks near 100 MeV.
2. Any detectable proper motion of such a source will definitely point to a nearby single PBH.
3. To check the hypothesis of an isolated Population III star it makes sense to search for an optical/IR counterpart in the EGRET error box. An optical source is expected to be a red dwarf moving with very high peculiar velocity.

The prospects of PBH detection in the Solar system are still largely unclear as they are sensitive to the existence of questionable Galactic disk component of CDM in addition to widely accepted spherical halo component. However, technical progress and/or long-term observations soon will turn the situation to the better. Moreover, the current upper limit on the amount of dark matter bound to the Sun undoubtfully indicates that the search for PBHs is an easier way to put constraints on the non-luminous component of the Solar system as compared with the direct measurements, unless $\Omega_{\rm pbh} < 10^{-4}\Omega_{\rm H}$.

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