Quasars formation around clusters of primordial black holes

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We propose the model of first quasars formation around the cluster of primordial black holes (PBHs). It is supposed, that mass fraction of the universe $\sim 10^{-3}$ is composed of the compact clusters of PBHs, produced during the phase transitions in the early universe. The clusters of PBHs become the centers of dark matter condensation. As a result, the galaxies with massive central black holes are formed. In the process of galaxies formation the central black holes are growing due to accretion. This accretion is accompanied by the early quasar activity.

1. Introduction

The discovery of distant quasars with the redshifts $z > 6$ in the Sloan Digital Sky Survey [1] provides new questions in the problem of galaxy formation. The maximum observed quasar redshift $z = 6.41$ corresponds to accretion on the black hole (BH) with the mass $3 \cdot 10^9 M_\odot$ [2]. The early formation of BHs with masses $\sim 10^9 M_\odot$ puts serious difficulties on the BH formation scenario due to the dissipative evolution of star clusters [3], supermassive or gaseous disks [4]. In addition it is difficult to reconcile the shape of the quasar redshift distribution with the hypotheses of slow continuous BH growth in the processes of their merging or accretion [5, 6]. For these reasons the scenario of PBHs origin [7, 8] becomes more attractive. These PBHs can be the centers of baryon [9] and dark matter (DM) [10] condensations into the growing galaxies.

The new effective mechanism of PBHs formation was developed in [11, 12, 13]. This model predicts the specific cluster structure and properties of the forming PBHs [13, 14]. In the current paper we will use this model for describing the formation of galaxies around the clusters of PBHs. It is the clusters of PBH who could play the role of the initial density perturbations. As the basic example, a scalar field with the tilted Mexican hat potential was accepted. Properties of PBHs clusters appear to be strongly dependent on the initial phase of the scalar field. In addition they strongly depend on the tilt of the potential and the scale of symmetry breaking $f$ at the beginning of the inflation. Here we elaborate the dynamics of DM coupled with a PBH cluster by gravity. It is shown that the galaxies could be formed in this case even in the absence of the primordial fluctuations in the DM. We will use here the same values of parameters as in the [11, 12], which are in the agreement with observations.

The initial mass profile $M_h(r_i)$ of PBHs cluster and the DM mass profile $M_{DM}(r_i)$.

Figure 1: The initial mass profile $M_h(r_i)$ of PBHs cluster and the DM mass profile $M_{DM}(r_i)$.
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The density in the local center is so high that a lot of PBHs appear to be inside their common gravitational radius $r_g = 2GM/c^2$. The total mass appears inside the horizon is $4.3 \times 10^7 M_\odot$. So the whole range of masses and radii shown in the Fig. [1] is not realized. As a result we obtain the initial mass distribution of PBHs with the much more massive PBHs than it could be expected. In fact, the satellite PBHs of smaller masses increase this value in several orders of magnitude. The next Sections are devoted to the investigation of mutual evolution of DM (uniformly distributed from the beginning) and the cluster of PBHs with distribution according to the Fig. [1]. Note that the PBHs themselves contribute to the DM, but we don’t consider them as the main DM part.

There are several stages of PBHs and galaxies formation: (i) The formation of the closed walls of scalar field just after inflation and their collapse into the cluster of PBHs according to [14]. Formation of the most massive BH in the center of the cluster after the horizon crossing. (ii) The detaching of the central dense region of the PBHs cluster from the cosmological expansion and its virialization. Many of surrounding small BHs merge with a central most massive BH and increase its mass. (iii) The quasars ignition due to accretion onto the central BH. (iv) Detaching of the outer cluster region where DM dominates from the cosmological expansion and further galaxy growth. Stop of the galaxy growth due to interaction with the surrounding DM fluctuations originated from the inflation. (v) The gas cooling and star formation.

There are definite astrophysical limitations on the number and mass of PBHs: The universe age limit gives for PBH cosmological density parameter $\Omega_h < 1$. The possibility of tidal destruction of globular clusters by the PBHs gives the PBH mass limit $M_h < 10^4 M_\odot$ if these PBHs provide the major contribution to the DM [15]. The contribution of accreted PBHs into the background radiations gives approximately $\Omega_h \lesssim 10^{-2}$ for $M_h \sim 10^8 M_\odot$ [16]. The limit $\Omega_h < 0.01$ for $10^7 M_\odot < M_h < 10^3 M_\odot$ is obtained from the VLA observations of the lensing of compact radio–sources [17]. In this paper we consider the case $\Omega_h \sim 10^{-3}$ which is in accordance with all aforementioned limits.

In the following the subscript ‘0’ marks the values of a current time $t_0$, ‘eq’ corresponds to the time $t_{eq}$ of matter–radiation equality, and ‘i’ to the time of horizon crossing respectively. We consider the flat cosmological model with the density parameters $\Omega_{m,0} = 0.3$, $\Omega_{\Lambda,0} = 0.66$, $\Omega_{b,0} h^2 = 0.02$ and $h = 0.7$.

2. Gravitational dynamics of cluster

Let us consider the gravitational dynamics of PBHs cluster and the DM. The results of this section are applicable as for the inner part of the cluster, composed mainly of PBHs and collapsing at radiation dominated stage, and for outer regions of the cluster, where the DM is the main dynamical component. The later regions are detached from the cosmological expansion at the matter dominated epoch. The spherical symmetry is supposed. This approximation is rather good for the inner regions because the considered density fluctuations have a large amplitude in comparison with the standard inflationary generated fluctuations.

Consider a spherically symmetric system with the radius $r < ct$, consisting of PBHs with the total mass $M_h$ inside the radius $r$, the radiation density $\rho_r$, the DM density $\rho_{DM}$ and the cosmological $\Lambda$–term density $\rho_{\Lambda}$. The radiation density (and obviously the density of $\Lambda$-term) is homogenous. Therefore, the fluctuations induced by the PBHs are of the type of entropy fluctuations. Because the scale under consideration is less than the cosmological horizon scale we use the Newtonian gravity but take into account the prescription of [18] to treat the gravitation of homogenous relativistic components $\rho \rightarrow \rho + 3p/c^2$. The evolution of spherical shells obeys the following equation

$$\frac{d^2r}{dt^2} = -\frac{G(M_h + M_{DM})}{r^2} - \frac{8\pi G \rho_r r}{3} + \frac{8\pi G \rho_{\Lambda} r}{3} \quad (1)$$

with the approximate initial conditions at the moment $t_i$: $\dot{r} = -Hr$, $r(t_i) = r_i$. During the derivation of Eq. (1) it was taken into account, that $\dot{\varepsilon}_r + 3\varepsilon_r = 2\varepsilon_r$, $\dot{\varepsilon}_{\Lambda} + 3\varepsilon_{\Lambda} = -2\varepsilon_{\Lambda}$. In the parametrization $r = \xi a(t) b(t)$, the $\xi$ is the comoving length, $a(t)$ is the scale factor of the universe normalized to the present moment $t_0$ as $a(t_0) = 1$ and the function $b(t)$ characterizes the deflection of the cosmological expansion from Hubble law. The $\xi$ connected to the mass of DM inside considered spherical volume (excluding BHs mass) by the relation $M_{DM} = (4\pi/3) \rho_{DM}(t_0) \xi^3$. Function $a(t)$ obeys the Friedman equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}(\varepsilon_r + \varepsilon_m + \varepsilon_{\Lambda}), \quad (2)$$

which can be rewritten as $\dot{a}/a = H_0 E(z)$, where redshift $z = a^{-1} - 1$, $H_0$ is the current value of the Hubble constant and function

$$E(z) = [\Omega_{r,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}]^{1/2}. \quad (3)$$

Here $\Omega_r$, $\Omega_m$ and $\Omega_{\Lambda}$ is the density parameters (fractions of density to critical density $\rho_c = 3H^2/(8\pi G)$) of radiation (in sum with relativistic neutrino), non-relativistic matter (DM and baryons) and $\Lambda$–term, respectively. The $\Lambda$–term affects the evolution of perturbations only at the redshift $z \lesssim 10$. Relations $t(z)$ and $z(t)$ can be easily obtained from the solution of the equation (2).

The considered cosmological model is flat: $\Omega_r + \Omega_m + \Omega_{\Lambda} = 1$. By using the second Friedman equation
Let us consider the fate of spherical shells by moving our attention from the center of the cluster to outer regions. It is obvious (and supported by numerical calculations) that inner more dense shells stop expansion early than outer shells. As was discussed before, a BH with the mass $M_{c} = 4.3 \cdot 10^{9}M_{\odot}$ forms in the center of the cluster at the moment $t_i$. The subsequent shells,

$\delta_{h} > 1$ ($M_{DM} < M_{h}$), are very dense too. These shells are detached from the cosmological expansion at the radiation dominated epoch. In general, these shells accreted by the central BH in the process of two–body relaxation of BHs. This effect will be considered below. The boundary value $\delta_{h} = 1$ corresponds to the masses $M_{h} = M_{DM} = 3.3 \cdot 10^{8}M_{\odot}$.

For the outer shells where the fluctuation is small $\delta_{h} < 1$, the known Meszaros solution is true, according to which the fluctuation growth till the moment $t_{eq}$ is equal to 2.5. For the early formed PBHs it is possible the process analogous to the 'secondary accretion'. As a result the PBHs would be 'enveloped' by the DM halo. We call these haloes as induced galaxies (IG). The density profile does not follow the secondary accretion law $\rho \propto r^{-9/4}$ because the central mass is not compact. After virialization the distribution of DM is

$$\rho_{DM}(r) = \frac{1}{4\pi r^{2}} \frac{dM_{DM}(r)}{dr},$$

where function $M_{DM}(r_c)$ is determined by the solution of (4). In analogy with the DM, one can obtain the profile of the BHs density and of total density. The corresponding results are shown in the Fig. 3 where density is expressed in units $M_{\odot}/pc^{3}$ and distance from the center is in pcs. As can be viewed from the Fig. 3 at the Sun distance from the Galaxy center $r = 8$ kpc the total local mass density is 0.7 Gev cm$^{-3}$. Therefore, some characteristics of the obtained galaxy are similar to the our Galaxy. But the considered induced galaxy is more dense at its center and hosting the supermassive BH.

The resultant structure of induced galaxy is the following. Inside radius $r = 10$ pc from the induced galaxy center the mass of BHs (including a central supermassive BH) is $2.9 \cdot 10^{8}M_{\odot}$. Inside the same radius the mass of DM is $3.4 \cdot 10^{8}M_{\odot}$. At the larger distances
the density profile of DM is well approximated by the power law
\[ \rho(r) = 2.2 \cdot 10^4 \left( \frac{r}{10 \text{ pc}} \right)^{-2.2} M_\odot \text{pc}^{-3}. \] (9)

The density profile (9) differs from the Navarro-Frenk-White [20] and other proposed profiles, obtained from the numerical simulation of haloes formation (without primordial cluster of BHs) but corresponds to these profiles at intermediate scales where power index \( \approx -2 \). An interesting properties is the diminishing of mean velocity \( V_e = (GM/2R)^{1/2} \) of IGs in time (with decreasing of \( z \)). Such a behavior is a consequence of the shape of perturbation spectrum produced by clusters of BHs (see next Section).

3. Termination of induced galaxies growth

The growth of a virialized region terminates at the epoch of nonlinear growth of the ambient density fluctuations of the same mass \( M \) (originated from the standard inflation) as the our combined system of PBHs plus the DM halo. The laws of growth for the both fluctuations at the matter dominated epoch are the same [14]. Therefore, the condition of the growth termination of a typical induced galaxy is the equality of r.m.s. perturbations \( \delta_{eq}(M_{DM}) \), produced by the PBHs cluster, and the inflationary r.m.s. perturbations \( \sigma_{eq}^\text{DM} (M_{DM}) \), both depending on the DM mass scale \( M_{DM} \):

\[ \nu \sigma_{eq}^\text{DM} (M_{DM}) = \delta_{eq}^h (M_{DM}), \] (10)

where \( \nu \) is the perturbations peak height, in this section we consider only mean perturbation with \( \nu = 1 \). The statistical properties of the inflationary Gaussian perturbations are determined by the power spectrum \( P(k) \). We use the power spectrum of the DM from [21]:

\[ P(k) = \frac{A k}{(1 + 1.71 u + 9 u^{1.5} + u^2)^2}, \] (11)

where \( u = k / (\Omega_{m,0} + \Omega_{b,0})^{-2} \text{ Mpc}^{-1} \), and \( k \) is the comoving wave vector in Mpc\(^{-1} \) units. The initial spectrum is supposed to be the Harrison–Zeldovich spectrum. The normalizing constant \( A \) corresponds to the value 0.9 of r.m.s. fluctuations at 8 Mpc scale. The r.m.s. perturbation at the mass scale \( M \) corresponding to the radius \( R \) is

\[ \sigma_{eq}^\text{DM}(M(R)) = \frac{1}{2\pi^2} \int_0^\infty k^2 dk P(k)W(k,R), \] (12)

where \( W(k,R) \) is a filtering function. The evolution of the cosmological perturbations in the universe with

\[
\begin{align*}
\frac{\partial}{\partial t} \rho &= -3H \rho \\
\frac{\partial}{\partial t} \rho \delta &= \Delta \rho \\
\Delta &= \frac{\rho}{\rho_{DM}}
\end{align*}
\]

the \( \Lambda \)-term at the matter dominated epoch can be obtained from [11] or simply from the equation [22]

\[ \delta(t)/\delta(0) = g(z)/(1+z), \]

where

\[ g(z) \approx \frac{5}{2} \Omega_m (\Omega_m^{1/17} - \Omega_\Lambda + (1+\Omega_m)/2) (1+\Omega_\Lambda/70)^{-1}. \] (13)

From the numerical solution of (10) we obtain the mass of the DM halo at the moment of growth termination \( M_{DM} = 1.8 \cdot 10^{12} M_\odot \). The expansion stops at the redshift \( z = 1.64 \). Note that growth termination does not mean the termination of large scale structure formation. This means only the termination of the contraction under the influence of PBHs cluster. After this moment the structure formation proceeds by the standard hierarchical clustering scenario: galaxies are assembled into larger ones, clusters and superclusters. Therefore, the large scale structures in the our model is the same as in the standard cosmological scenario.

The formed induced galaxies looks like the giant elliptical galaxies with a small ellipticity. They have the central DM spike shown in the Fig. 9 and central supermassive BH.

4. Evolution of quasar activity

In view of the discovery of distant quasars with the redshifts \( z > 6 \), let us discuss the properties of induced galaxies at these redshifts. The described model of induced galaxies can easily explain the \( M_Q = 3 \cdot 10^9 M_\odot \) supermassive BHs at \( z = 6 \) (the age of the universe...
t_6 = 9 \cdot 10^8 \text{ year}. In this model there are supermassive BHs formed at the radiation dominated epoch long before the galaxies formation. Initially there is at least \( M_c = 4.3 \cdot 10^7 M_\odot \) or even larger (if there is an adsorption of surrounding smaller BHs from cluster by the most massive one) BH at the cluster center. Let us suppose that this BH radiated at the Eddington limit, \( L_E = 1.3 \cdot 10^{46} \text{erg/s} \). This BH grows exponentially with a characteristic time \( t_E = 4.5 \cdot 10^8 \eta \text{ yrs} \), where \( \eta \) is the effectiveness of the accretion matter–energy transformation. The time of growth from \( M_c = 4.3 \cdot 10^7 M_\odot \) to \( M_Q = 3 \cdot 10^9 M_\odot \) is \( \Delta t = t_E \ln (M_Q/M_c) \approx 2 \cdot 10^8 \text{ year for } \eta \sim 0.1 \). This means that QSO activity began at the moment \( t_6 - \Delta t \approx 7 \cdot 10^8 \text{ yr} \), corresponding to the redshift \( z = 7.3 \). At this redshift the induced galaxies have the virial mass \( 4.3 \cdot 10^{11} M_\odot \), the virial radius 40kpc, the mean virial velocity 140 km/s and the mean virial temperature \( T_v = m_p v^2/3 \approx 2 \cdot 10^6 \text{ K} \), where \( m_p \) is the proton mass. These values were obtained from the numerical solution of the equation (4). For these parameters the radiative cooling mechanism for the gas in the induced galaxies is effective. This provide the cool gas flows necessary for the accretion.

The very popular model of quasars ignitions is the gas flow onto the central black hole due to the tidal interactions during the merging of galaxies. In our model the tidal interactions are produced at the time of termination of the induced galaxies growth considered in the preceding Section. In general, the density distribution of surrounding inflationary perturbations are not spherically symmetric themselves and with respect to the induced galaxy center. This causes the strong tidal forces, instabilities and gas supply to the central region necessary for the effective accretion and quasar activity. We expect the maximum activity at the time of the termination of the induced galaxies growth at \( z \sim 1.6 \). This epoch is in agreement with the observable shape of quasar redshift distribution.

For the more detailed description of induced galaxies formation it is important to take into account distributions both the induced galaxies (or initial PBHs clusters) and inflation perturbations. For simplicity, let us consider only the Gaussian distribution of inflation perturbations over \( \nu \). In a mean \( \nu = 1 \), the fluctuations produced by BHs cluster till \( z = 1.6 \) prevail over the standard inflation perturbations. But there are the less common fluctuations with \( \nu > 1 \) which exist at the discussed redshifts \( z = 6, 7, 3 \) and larger. These rare fluctuations responsible in the our model for the tidal forces and quasar ignition at large \( z \). From the numerical solution of (4) we can obtain the virial mass of induced galaxies in dependence of the redshift \( M_{DM}(z) \). Substituting this function into (10) we get the dependency over \( \nu(z) \). The \( \nu(z) \) is the required peak height of the inflationary fluctuation for the termination of the induced galaxies growth and quasar ignition. The distribution of probabilities of these events is calculated as

\[
f(z) = -d \int_{\nu(z)}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\nu^2/2} d\nu' = \frac{1}{\sqrt{2\pi}} e^{-\nu^2(z)/2} \frac{d\nu(z)}{dz}
\]

and shown in the Fig. 5. This Figure shows the distribution law of the quasar ignition events distribution beyond the redshift \( z = 1.6 \).

5. Conclusion

In this paper we describe the new model of quasar formation initiated by the earlier formation of the cluster of PBHs. This model provides the early formation of large galaxies with the massive BHs in their centers. Nowadays these galaxies could be seen as distant quasars. The main calculated parameters of typical galaxy are the following: the galaxy mass \( 2 \cdot 10^{12} M_\odot \), the central BH mass \( 4 \cdot 10^7 - 10^9 M_\odot \). The density profile of these induced galaxies is a near isothermal, \( \rho \propto r^{-2.2} \). The induced galaxies could be the cause of the of early quasar activity. The model predicts the rapid decay of the quasar activity at redshifts \( z \gtrsim 10 \). The alternative scenario could be based on the formation of the less massive PBHs clusters. In this case each nowadays galaxy contains numerous BHs originated from the dwarf induced galaxies aggregated in a single galaxy in the process of hierarchical clustering. This possibility will be considered in a separate paper.

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