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Induced galaxy formation

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Abstract

We describe the model of protogalaxy formation around the cluster of primordial black holes with a minimum extension of standard cosmological model. Namely, it is supposed, that a mass fraction of the universe $\sim 10^{-3}$ is composed of the compact clusters of primordial (relict) black holes produced during the phase transitions in the early universe. These clusters are the centers of the dark matter (DM) condensations. As a result the protogalaxies with a mass $2 \cdot 10^8 M_\odot$ form at the redshift $z = 15$. These induced protogalaxies contain the central black holes of mass $\sim 10^5 M_\odot$ and look like the dwarf spheroidal galaxies with a central density spike. Subsequent merging of the induced protogalaxies and ordinary DM haloes leads to the standard scenario of the large scale structure formation. Black holes merging gives the nowadays supermassive black holes and reproduces the observed correlations between their masses and velocity dispersions in the bulges.

Key words: black hole, cosmology, galaxies
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1 Introduction

The problem of galaxy formation with a supermassive central black hole (BH) becomes more and more intriguing and ambiguous in view of the discovery of distant quasars at redshifts $z > 6$ in Sloan Digital Sky Survey [1]. The maximum observed value of the red-shift $z = 6.41$ belongs to the quasar with a luminosity corresponding to the accretion onto BH with a mass $3 \cdot 10^9 M_\odot$ [2].

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The early formation of BHs with a mass $\sim 10^9 M_\odot$ meets a serious problem in the standard scenario of massive BH formation due to the dissipative evolution of dense star clusters [3], supermassive stars or gaseous disks [4]. For this reason the scenario with the massive black holes (PBHs) [5,6,7,8] become more attractive. These PBHs can be the centers of baryonic [9] and dark matter (DM) [10] condensation into the growing protogalaxies. It seems probable that this scenario of galaxy formation could coexist with the standard one. It is supposed that both the ordinary normal galaxies without a large central BH and induced protogalaxies around PBHs are both formed in the universe. Their subsequent multiple merging leads to the observable large scale structure.

An effective mechanism of massive PBHs formation and their clusterization was developed in [8,11,12]. As the basic example in this mechanism a scalar field with the tilted Mexican hat potential is used. The properties of the resulting PBH clusters appear to be strongly dependent on the value of an initial phase of the scalar field. In addition they depend on the tilt of the potential and the scale of symmetry breaking f at the beginning of the inflation. This clusters of PBHs could provide the initial density perturbations for induced protogalaxy formation.

In this paper we investigate the galaxy formation around the cluster of PBHs. We elaborate the dynamics of DM gravitationally coupled with a PBHs cluster. It is shown that galaxies could be formed in this model without any initial fluctuations in the DM. The initial mass profile $M_h(r_i)$ of the PBHs cluster is calculated following to [13] and has the form presented in the Fig. 1. For comparison the mass $M_{\rm DM}(r_i)$ of DM inside the same spherical shells are shown. The radius r_i denotes the physical size of a sphere at the moment t_i and the temperature T_i when this sphere is crossing the cosmological horizon. Note that the shells in the Fig. 1 are taken at different moments t_i. Therefore the shown mass of uniformly distributed DM doesn't follow the low $M_{\rm DM} \propto r^3$ as it must be for the fixed time. Any physical size at the temperature T_i is smaller than that at the current epoch at T_0/T_i times, where $T_0 = 2.7$ K is the current value of temperature.

There are several distinctive stages of BHs and galaxies formation in the considered scenario: (i) The formation of the closed walls of a scalar field just after inflation and their successive collapse into the cluster of PBHs according to [8,11]. The formation of the most massive BH in the center of the cluster after the horizon crossing. (ii) The detaching of the cluster central dense region from the cosmological expansion and its virialization. At this stage the numerous surrounding small BHs merge with the central BH and increase its mass. (iii) The detaching of the cluster outer region with the DM domination from the cosmological expansion and the protogalaxy growth. The termination of the protogalaxy growth due to interaction with the nearby ordinary DM fluctuations. (iv) The cooling of the intragalactic gas and star formation.

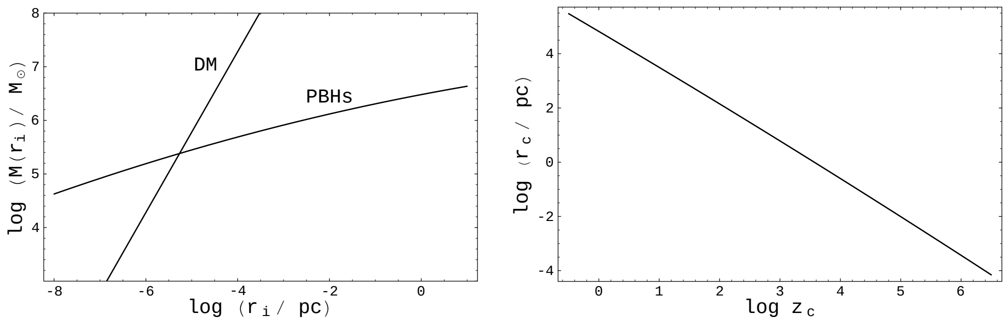

Fig. 1. In the left panel are shown the initial mass profile $M_h(r_i)$ of the PBHs cluster and the mass profile $M_{\rm DM}(r_i)$ of DM. In the right panel the virial radius r_c of a protogalaxy is shown as a function of redshift z.

The merging of protogalaxies and the birth of the nowadays galaxies.

An alternative scenario could be based on the formation large and very massive PBHs clusters. In this case each current galaxy contains only one PBH grown during accretion. This possibility is considered in a separate paper [14].

2 Gravitational dynamics of BH cluster and DM

Let us describe the gravitational dynamics of cluster consisting of the PBHs and DM. The results of the forthcoming calculations are applicable both for an inner part of the cluster (composed mainly from the PBHs and collapsing at radiation dominated stage), and for the outer regions of the cluster, where the DM is the main dynamical component. The outer regions of the cluster are detached from the cosmological expansion at the matter dominated epoch.

Consider a spherically symmetric system with a radius $r < ct$ consisting of PBHs with a total mass M_h inside the radius r, radiation density ρ_r, DM density $\rho_{\rm DM}$ and cosmological constant density ρ_Λ. The radiation density (and obviously the density of Λ-term) is homogeneous. Therefore the fluctuations induced by PBHs are of the type of entropy fluctuations. We use the Newton gravity because the scales under consideration are less then the universe horizon scale. At the same time we take into account the prescription of [15] to treat the gravitation of homogeneous relativistic components $\rho \to \rho + 3p/c^2$. The evolution of shells obeys the equation

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

with 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 $\varepsilon_r + 3p_r = 2\varepsilon_r$,

$\varepsilon_\Lambda + 3p_\Lambda = -2\varepsilon_\Lambda$. In the parametrization $r = \xi a(t) b(t)$, the ξ is a comoving length, $a(t)$ is a scale factor of the universe normalized to the present time t_0 as $a(t_0) = 1$ and function $b(t)$ describes the deflection of the cosmological expansion from the Hubble law. Parameter ξ is connected to the mass of DM inside a considered spherical volume (excluding BHs mass) by the relation $M_{\rm DM} = (4\pi/3)\rho_{\rm DM}(t_0)\xi^3$. Function $a(t)$ obeys the Friedman cosmological equation, 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

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

where $\Omega_{r,0}$ is a radiation density parameter, $\Omega_{m,0} \simeq 0.3$, $\Omega_{\Lambda,0} \simeq 0.7$, and $h = 0.7$. By using the second Friedman equation (for $\ddot{a}$) one can rewrite (1) in the following form

$$\frac{d^2 b}{dz^2} + \frac{db}{dz} S(z) + \left(\frac{1+\delta_h}{b^2} - b \right) \frac{\Omega_{m,0}(1+z)}{2E^2(z)} = 0, \tag{3}$$

where function

$$S(z) = \frac{1}{E(z)} \frac{dE(z)}{dz} - \frac{1}{1+z} \tag{4}$$

and the value of fluctuation $\delta_h = M_h / M_{\rm DM}$. In the limiting case $\Omega_\Lambda = 0$ the (3) is equivalent to the equation obtained in [16]. We start tracing the evolution of cluster at a high redshift z_i when the considered shell crosses the horizon $r \sim ct$. Initial conditions for the evolution are presented in the Fig. 1.

The moment t_s of the expansion termination $\dot{r} = 0$ corresponds to the condition $db/dz = b/(1+z)$ (according to the definition of b). We accept that after the termination of expansion of specific shell, it is virialized and contracted from maximum radius r_s to the radius $r_c = r_s/2$. Therefore, average density of DM in the virialized object ρ is 8 times larger comparing with the DM density at the moment of maximum expansion of its shell $\rho = 8\rho_{m,0}(1+z_s)^3 b_s^{-3}$, where $b_s = b(t_s)$ and an effective (virial) radius of the object $r_c = (3M_{\rm DM}/4\pi\rho)^{1/3}$. Results of the numerical solution of (3) are shown in the Fig. 1 (right panel) and Fig. 2 (left panel). Let us consider the fate of spherical shells beginning from the center of the cluster. It is obvious (and confirmed by numerical calculations) that more dense inner spherical shells stop their expansion earlier than the outer ones. As it was discussed earlier the BH with a mass $M_c = 2.7 \cdot 10^4 M_\odot$ forms in the center of the cluster at the moment t_i. The shells near the center are very dense and are detached from the cosmological expansion at the radiation dominated epoch.

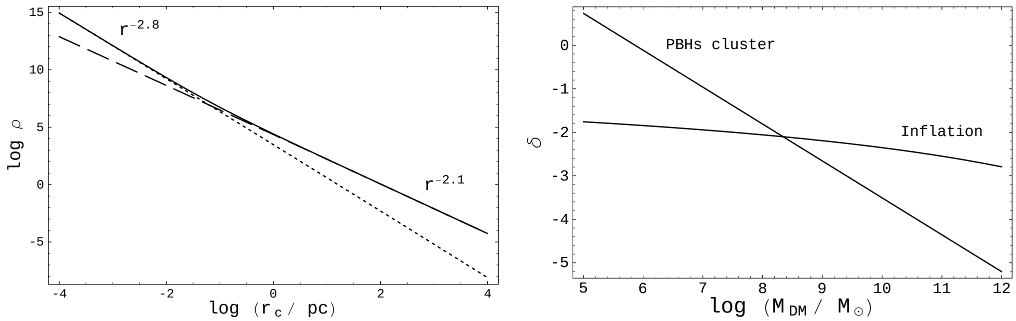

Fig. 2. In the left panel are shown the final density profiles (5) of a protogalaxy (ρ in the units $M_{\odot}/pc^3$) in dependence of the distance from the cluster center r_c for DM (dashed line), for BHs (dotted line) and for their sum (solid line). The corresponding asymptotic power laws are also labeled. In the right panel the r.m.s. density perturbation at the moment $t_{\rm eq}$ of matter–radiation equality produced by the cluster of PBHs and by inflation.

The process similar to the 'secondary accretion' could take place for the early formed PBHs. As a result the PBHs would be 'enveloped' by the DM halo. We will call these DM haloes the induced protogalaxies. 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

$$\rho_{\rm DM}(r) = \frac{1}{4\pi r^2}\frac{dM_{\rm DM}(r)}{dr}, \tag{5}$$

where function $M_{\rm DM}(r)$ is determined by the solution of (3). By analogy with the DM case one can obtain the profile of the BHs density and of the total density. The results are shown in the Fig. 2 (left panel), where density is expressed in units $M_{\odot}/pc^3$ and radial distance is measured in parsecs.

The total mass of protogalaxy is growing with time because more and more distant shells are detached from the cosmological expansion and are virialized around the central most massive BH. The growing of protogalaxy is terminated at the epoch of nonlinear growth of the ambient density fluctuations with the same mass M as a considered system of BHs and DM. These fluctuations are originated in a standard way from the inflationary cosmological perturbations with the spectrum $P(k)$ [17,18]. The laws of growth for both types of fluctuations during the matter dominated epoch are very similar. The condition for the termination of a typical induced protogalaxy growth is

$$\delta_{\rm eq}^{\rm DM}(M_{\rm DM}) = \delta_{\rm eq}^{h}(M_{\rm DM}). \tag{6}$$

The r.h.s of this equation is an amplitude of fluctuation caused by the BH cluster. Respectively the l.h.s. denotes the Gaussian fluctuations. The value of fluctuations produced by the cluster $\delta_{\rm eq}^{h}(M_{\rm DM}) = 2.5\delta_i(M_{\rm DM})$ is shown in Fig. 2

(right panel) together with the Harrison-Zeldovich spectrum. The factor 2.5 corresponds to the entropy perturbation growth to the moment $t_{\rm eq}$ according to the Meszaros solution.

Numerical solution of (3) and (6) gives the termination of the protogalaxy growth at the redshift $z = 15$ with a final mass of induced protogalaxy $M_{\rm DM} = 2.2 \cdot 10^8 M_\odot$. So the whole range of masses and radii shown at Figures is not realized. After this moment the structure formation proceeds by the standard scenario: small (ordinary and induced) protogalaxies are assembled into the larger ones and then into the clusters and superclusters. Being formed, the induced protogalaxies looks like dwarf spheroidal galaxy with a central DM spike shown in the Fig. 2 and a central BH. Some of these induced protogalaxies could escape merging and survive till now in the form of rare dwarf galaxies.

In previous calculations we demonstrate that massive induced protogalaxy with the mass $2.2 \cdot 10^8 M_\odot$ is formed around the PBHs cluster at $z = 15$. There are a lot of smaller neighboring protogalaxies, both ordinary and induced ones, in its vicinity. The coalescences of these protogalaxies results in the formation of nowadays galaxies. The induced protogalaxies are massive enough to be settled down to the galactic center during the Hubble time under influence of the dynamical friction. The fate of BHs inside the central few parsecs of the forming host galaxy is rather uncertain. We will suppose the multiple BHs merging into a single BH during the Hubble time. Note that the dynamical friction must supply a very effective mechanism of merging at a final stage because the density of induced protogalaxies $\rho \propto r^{-2.8}$ strongly growing toward the center up to the small distance r_h from PBH where $M_{\rm DM}(r_h) = M_h$ according (5). For example, according to our calculations $M_{\rm DM} = 7 \cdot 10^4 M_\odot$ is contained within the radius $r_h \sim 8 \cdot 10^{-5}$ pc providing the density $\rho \sim 2 \cdot 10^{15} M_\odot$ pc^{-3}. Using the Chandrasekhar time (see e. g. [19]) for the dynamical friction of BH with the mass $M_{\rm BH} = 7 \cdot 10^4 M_\odot$ we obtain an estimation for the characteristic time for BH spiralling down from the radius r_h, $t_f \sim 36$ days. The BHs of a larger mass would be spiralling down even faster. As a result the late phase of BHs merging lasts very fast and so the probability of simultaneous existence in the galactic nucleus of three or more BHs is rather low. Thus as rule the galactic center contains only a single supermassive BH. On the contrary, a galaxy as a whole could contain a substantial amount of massive PBHs which were nucleated initially far from the galactic center [8,11,12].

Finally let us calculate the growth of the central BH under the process of the two-body relaxation of surrounding smaller BHs in the inner region of the induced protogalaxy. The BHs cluster is composed of the BHs of different masses. So the important factor of relaxation evolution is the mass segregation: the concentration of more massive BHs at center of the cluster. This makes the comprehensive analytical treatment very complicated. We use an approximate approach by considering BHs of different masses as independent homological subsystems evolving in a total gravitational field. This approach is widely used in a study of evolution of the multicomponent star clusters. The time of two-body relaxation is [20]

$$t_{\rm rel} \simeq \frac{1}{4\pi} \frac{v^3}{G^2 m^2 n \ln(0.4N)}, \tag{7}$$

where $v \sim (GM_{\rm tot}/r_c)^{1/2}$ is a virial velocity, $M_{\rm tot} = M_{\rm DM} + \sum M_{\rm BH} N_{\rm BH}$, N is a total number of BHs and n is a number density of BHs inside the shell respectively. In the evaporating model [20] the lifetime of the cluster $t_e \simeq 40 t_{\rm rel}$. The gravitational collapse of the remaining cluster begins when a central part of the cluster reached the relativistic state. A mean value of t_e is calculated and expressed through a redshift z from the relation $t(z) = t_e$. The corresponding relaxed shells are collapsing and merging with a central BH (having initial mass $2.7 \cdot 10^4 M_\odot$). It appears that collapse of an additional shells gives rather small contribution the mass of a central BH. Indeed, the mass of a central BH to the moment $z = 15$ of the growth termination of induced protogalaxies is $M_{\rm BH} = 6.9 \cdot 10^4 M_\odot$. At the moment $z \simeq 1.7$ (when galaxies with the mass $M_{\rm DM} = 10^{12} M_\odot$ are formed) the BH mass is $M_{\rm BH} = 7.2 \cdot 10^4 M_\odot$. If the induced galaxy is survived up to nowadays ($z = 0$), it has a central BH with the mass $M_{\rm BH} = 7.3 \cdot 10^4 M_\odot$. So we expect that the main contributions to the mass growing come from the accretion of surrounding media and the merging of the central BHs of the coalesced induced protogalaxies.

3 Discussion

In this paper we describe the new model of galaxy formation initiated by the cluster of primordial black holes. Clusters of different total mass may be formed through the mechanism of massive primordial BHs formation [12,13]. Respectively the described induced protogalaxies would have the different masses. For numerical calculations we choose parameters of PBHs clusters corresponding to the formation of small protogalaxies. This model predicts the very early epoch of galaxy and quasar formation. The other prediction is the existence of numerous BHs of intermediate mass beyond the dynamical centers of galaxies and in the intergalactic medium. One of such BHs may be observed by the Chandra telescope in the galaxy M82 [21].

More definitely, the considered model predicts the formation of induced protogalaxy at $z = 15$ with the following parameters: the halo DM mass $M_{\rm DM} = 2.2 \cdot 10^8 M_\odot$, the virial radius 2.1 kpc, the central BH mass $M_{\rm BH} = 7.2 \cdot 10^4 M_\odot$ and the total BHs mass in the protogalaxy $M_{\rm BH} = 7.1 \cdot 10^5 M_\odot$. We suppose that large galaxies observed now are originated through the hierarchical clustering of these dwarf protogalaxies. The process of multiple merging occurs in a stochastic manner and leads to the correlations between the central supermassive BHs masses and galactic bulge velocity dispersions [10].

It is worth to estimate the probability to find a nowadays galaxy without a supermassive BH in the framework of the considered model. The induced protogalaxies and the most common small protogalaxies produced by the standard inflation scenario have masses around $M_{\rm DM} = 10^8 M_\odot$. Meanwhile the nowadays galaxies have masses of the order of $M_{\rm DM} = 10^{12} M_\odot$. Each collision of an induced protogalaxy with an protogalaxy originated from the standard inflation perturbations produces protogalaxy of the next generation with a massive BH in its center. So 10^4 collisions have been happened up to now. Let us suppose that the amount of induces protogalaxies is $\sim 0.1\%$ comparing with the most common ones. The corresponding probability to find the galaxy without a supermassive BH is much less than $0.999^{10000} \simeq 4.5 \cdot 10^{-5}$. Hence even a very small fraction of induced protogalaxies is able to explain the observable abundance of active galactic nuclei and quasars.

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