Early Formation of Galaxies Induced by Clusters of Black Holes

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Received May 18, 2007; in final form, October 26, 2007

Abstract—A model for the formation of supermassive black holes at the center of a cluster of primordial black holes is developed. It is assumed that \( \sim 10^{-3} \) of the mass of the Universe consists of compact clusters of primordial black holes that were present at as a result of phase transitions in the early Universe. These clusters serve as centers for the condensation of dark matter. The formation of protogalaxies with masses in the order of \( 2 \times 10^8 \, M_\odot \) at redshift \( z = 15 \) containing clusters of black holes is investigated. The nuclei of these protogalaxies contain central black holes with masses \( \sim 10^5 \, M_\odot \), and the protogalaxies themselves resemble dwarf spherical galaxies with their maximum density at their centers. Subsequent merging of these induced protogalaxies with ordinary dark matter halos leads to the standard picture for the formation of the large-scale structure of the Universe. The merging of the primordial black holes leads to the formation of supermassive black holes in galactic nuclei and produces the observed correlation between the mass of the central black hole and the bulge velocity dispersion.

PACS numbers: 98.65.Dx, 95.35.+d, 95.35.+d, 95.35.+d, 98.35.Jk, 98.62.Js

DOI: 10.1134/S1063772908100016

1. INTRODUCTION

The problem of the formation of galaxies with supermassive black holes (BHs) in their nuclei is becoming more and more intriguing and unclear in connection with the discovery of distant quasars with redshifts \( z > 6 \) [1]. The maximum redshift, \( z = 6.41 \), is possessed by a quasar whose luminosity corresponds to accretion onto a BH with a mass of \( 3 \times 10^9 \, M_\odot \) [2]. Such early formation of BHs with masses \( \sim 10^9 \, M_\odot \) may prove to be a serious problem for standard (galactic) models for the formation of BHs, which assume the rapid dynamical evolution and gravitational collapse of central star clusters in galactic nuclei [3–6], the collapse of supermassive stars and gaseous disks in galaxies [7–10], multiple mergers of stellar-mass BHs in galaxies [11–14], or multiple mergers of galactic nuclei during collisions of galaxies in clusters [15–21]. All these scenarios lead to appreciable variations in the mass distribution of the BH clusters. In our earlier article [32], we choose model parameters leading to the formation of initially large clusters of BHs with masses for their central BHs \( \sim 4 \times 10^7 \, M_\odot \), which increased via accretion to masses \( \sim 10^9 \, M_\odot \), and so could explain the observed activity of distant quasars.

The development of a mechanism for the formation of initially massive BHs with their subsequent growth to masses of the order of \( \sim 10^9 \, M_\odot \) via the accretion of matter, or the initial birth of PBHs with modest masses, with their subsequent mergers into supermassive BHs in the process of hierarchical clustering of protogalaxies containing PBHs.
parameters of the potential and the initial conditions for the characteristics of the BH clusters. This is due not only to uncertainty in the observational data, but also to the complexity in taking into account certain effects. For example, the field walls that form have the topology of a sphere, while their geometry is very elongated. After such a wall passes below the horizon, due to internal tension, it not only takes on a spherical shape with time, but also strongly fluctuates, generating gravitational waves and waves of the scalar field. This efficiently decreases the total energy of the wall, and consequently the masses of BHs that form from it. This effect was approximately taken into account in [30], where it was shown that, for primordial BHs of arbitrary mass and a cluster of BHs, there will always be some parameters for the theory and initial conditions for which BHs and clusters of a given mass will be realized. Therefore, in the present study, we will not focus on specific numerical values for the parameters of a microscopic theory. A discussion of the influence of asphericity of the formed field walls can be found in [30, 31].

The mechanism for forming massive PBHs found in [25, 30, 31] is not restricted to some specific form of the potential. We show below that very different potentials, such as those in hybrid-inflation models, lead to the formation of massive PBHs. Moreover, it is not that easy to avoid their overproduction in the early Universe. Essentially, a consideration of any inflation model that uses a potential with two or more minima should take this mechanism into account.

In the current paper, we have chosen parameters of the potential that lead to relatively small clusters of PBHs. We propose that precisely such clusters could play an important role in the formation of the initial density fluctuations that then evolved into protogalaxies. Their merger with the more numerous ordinary protogalaxies lead to the observed large-scale structure. We consider the dynamics of dark matter and clusters of PBHs in their joint gravitational field. In this case, protogalaxies can also form without initial fluctuations in the density of dark matter. Both scenarios for the formation of supermassive BHs can coexist: massive clusters lead to the early activity of quasars [32], while less massive clusters (considered here) are responsible for the more numerous supermassive BHs observed in most structured galaxies.

Our scenario includes several stages in the formation of BHs and galaxies.

1. The formation of closed walls of the scalar field immediately after the end of inflation, and their collapse into clusters of PBHs in accordance with [25, 30]. The most passive PBHs form at the center of the cluster after intersection with the cosmological horizon.

2. Separation of the central, dense region of a cluster from the cosmological expansion and its virialization. A large number of less massive PBHs surrounding the central PBH merge with the latter, increasing its mass.

3. Separation of the outer regions of a cluster, where dark matter dominates, from the cosmological expansion and growth of a protogalaxy. The growth of the protogalaxy is ceased by interactions with ordinary dark-matter fluctuations.

4. Cooling of the gas and star formation, mergers of protogalaxies, and the formation of modern galaxies.

2. FORMATION OF PRIMORDIAL BLACK HOLES IN HYBRID INFLATION

Let us consider the mechanism for the formation of massive PBHs proposed in [33], using a hybrid-inflation model as an example. According to [34], the potential in the hybrid-inflation model has the form

$$V(\chi, \sigma) = \kappa^2 \left( M^2 - \chi^2/4 \right)^2 + \frac{\lambda^2}{4} \sigma^2 + \frac{1}{2} m^2 \sigma^2.$$  

Inflation continues while the field slowly moves along the valley $\chi = 0, \sigma > \sigma_c$. When the field $\sigma$ passes the critical point $\sigma_c = \sqrt{2\kappa M}/\lambda$, motion along the line $\chi = 0, \sigma < \sigma_c$ becomes unstable, and the field $\chi$ rapidly reaches one of the minima, $\chi_\pm = \pm 2M, \sigma = 0$ (Fig. 1). Inflation is ended by intense fluctuations of the field in the region of a randomly selected minimum. However, this well studied picture has serious inadequacies. During the inflation stage, when the field $\sigma, \chi$ moves along the line $\chi = 0$, space is divided into a multitude of causally unconnected regions. Due to quantum fluctuations, the scalar fields in these regions differ slightly from one another. Roughly $e^\xi \approx 20$ such domains form during each $e$-folding. Thus, at the end of inflation, space is divided into $e^{180} \approx 10^{78}$ causally unconnected domains. The magnitudes of the scalar fields in them are distributed chaotically about $\chi = 0, \sigma = \sigma_c$. Domains in which $\chi < 0$ tend toward the left minimum, $\chi_\pm = -2M, \sigma = 0$, while the remaining domains tend toward the right minimum, $\chi_+ = +2M, \sigma = 0$. Numerous field walls form between the domains, and we arrive at the known problem of wall dominance in the Universe [35].

The only possibility for our Universe to evolve to its present state is if the initial value of the field differed from zero at the beginning of inflation: $\chi_{in} \neq 0$. In the