Evolution of the cluster of primordial black holes within the Fokker-Planck approach

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Abstract

The calculation results of the evolution of the cluster of primordial black holes based on the Fokker-Planck equation with neglecting of the gas accretion onto black holes are presented. In addition, we consider how a massive black hole located within the cluster center affects on its evolution. Despite it creates an additional potential in the central region of the cluster and might capture surrounding black holes, a negligible growth rate of a central black hole was shown for 1 Gyr. Furthermore, we find a significant (approximately tenfold) expansion of the cluster.

Introduction

There is a large number of theoretical works on the formation of primordial black holes (PBHs) [1]. In our work, we consider those predicting the formation of PBHs as clusters. This mechanism was proposed in [2] where a collapse of large closed domain walls was discussed.

In our work, we use the orbit-averaged Fokker-Planck equation in energy space for study of a dynamical evolution of the PBHs cluster. We take into account that the cluster might have a wide range of masses. Furthermore, we include in our simulations a massive black hole (CBH) in the cluster center which creates the potential in the central region and captures black holes with low angular momentum.

The Fokker-Planck equation

The orbit-averaged Fokker-Planck equation in the energy space can be written [3]:

$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E}\left(m_i D_E(E,f)\, f_i + D_{EE}(E,f)\,\frac{\partial f_i}{\partial E}\right) - \nu(E,f)N_i, \qquad (1)$$

where N_i is number density in the energy space $N_i(E) = 4\pi^2 p(E) f_i(E)$, f_i and m_i is the distribution function and mass of i-th type of the mass of PBHs, E is the energy per unit mass $E = v^2/2 + \phi(r)$, νN_i is a lose-cone term describing the capture of PBHs (with angular momentum less than $L_{lc} = 2cr_g$) by the CBH. The expression for each term included in (1) can be found in [3].

All coefficients included in equation (1) also depend on the gravitational potential which have the expression in the spherical symmetric case:

$$\phi(r) = -4\pi G\left(\frac{1}{r}\int_0^r dr'\, r'^2\rho(r') + \int_r^\infty dr'\, r'\rho(r')\right) - \frac{GM_\bullet}{r}, \qquad (2)$$

where $M_\bullet$ is the mass of the CBH and $\rho(r)$ is the mass density:

$$\rho(r) = 4\pi\sum_i \int_{\phi(r)}^0 dE\, f_i(E)\sqrt{2(E-\phi(r))}, \qquad (3)$$

where the summation over all types of PBH masses is performed. In order to study the dynamical evolution of a self-gravitating system (e.g. PBH cluster), it is necessary to solve both the Fokker-Planck equation (1) and the Poisson equation (2).

Results

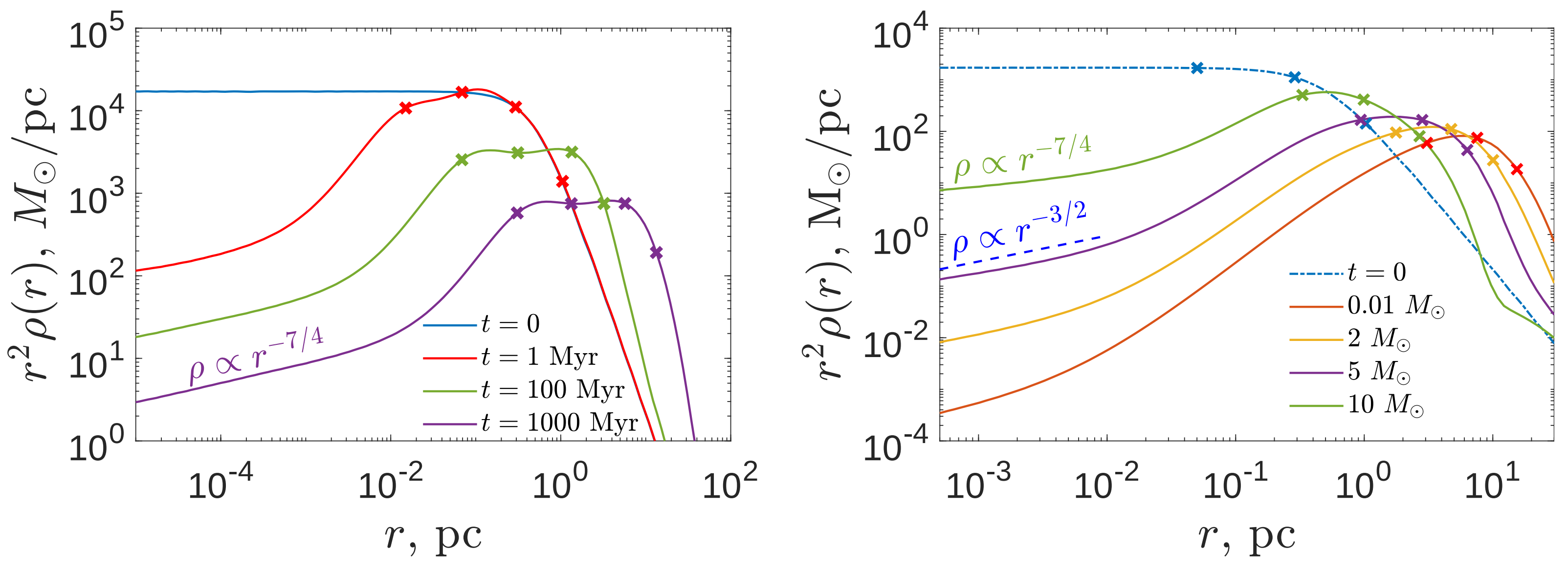
We use the following initial density profile for each type of PBHs:

$$\rho_i(r) \propto \left(\frac{r}{r_0}\right)^{-2}\left[1+\left(\frac{r}{r_0}\right)^2\right]^{-3/2}, \qquad (4)$$

where $r_0 = 0.5$ pc. We choose the mass spectrum in the form [4]:

$$\frac{dN}{dM} \propto \frac{1}{M_\odot}\left(\frac{M}{M_\odot}\right)^{-2}, \qquad (5)$$

where the range of PBHs masses is from $10^{-2}M_\odot$ to $10M_\odot$. We take the bin width such that the total masses of each component of PBHs are equal to each other. And we choose the mass of the CBH $M_\bullet = 100M_\odot$ and the total cluster mass $M_{\text{tot}} = 10^5 M_\odot$.



(a) (b)

Figure 1: (a): the evolution of the density profile is shown. The crosses of each line from left to right correspond to radii containing 1, 10, 50 and 90% of the total cluster mass, respectively. (b): the solid lines show the final density profiles of different PBHs mass types of the cluster at $t = 1$ Gyr. The dash-dotted line corresponds to the initial distribution (the same for all mass types). The crosses correspond to radii containing 10, 50 and 90% of the total mass of each PBHs type.

The evolution of density profile is presented in figure 1a. After small time ~ 1 Myr, the cusp $\rho \propto r^{-7/4}$ is established in the central region of the cluster. Then, the cluster starts to expand and the most right red cross from the initial point ~ 1 pc goes to the purple cross ~ 10 pc at $t = 1$ Gyr.

Figure 1b illustrates the redistribution of the total mass of each PBHs type. It is seen at $t = 1$ Gyr, the radius containing 90% of the heaviest PBHs mass corresponds the radius containing 10% of the lightest PBHs mass. Thus, the significant changes have occurred in the structure of the cluster by the final moment of time, heavy PBHs are located closer to the cluster center than light ones. In fact, heavy PBHs are surrounded by light mass components of the cluster.

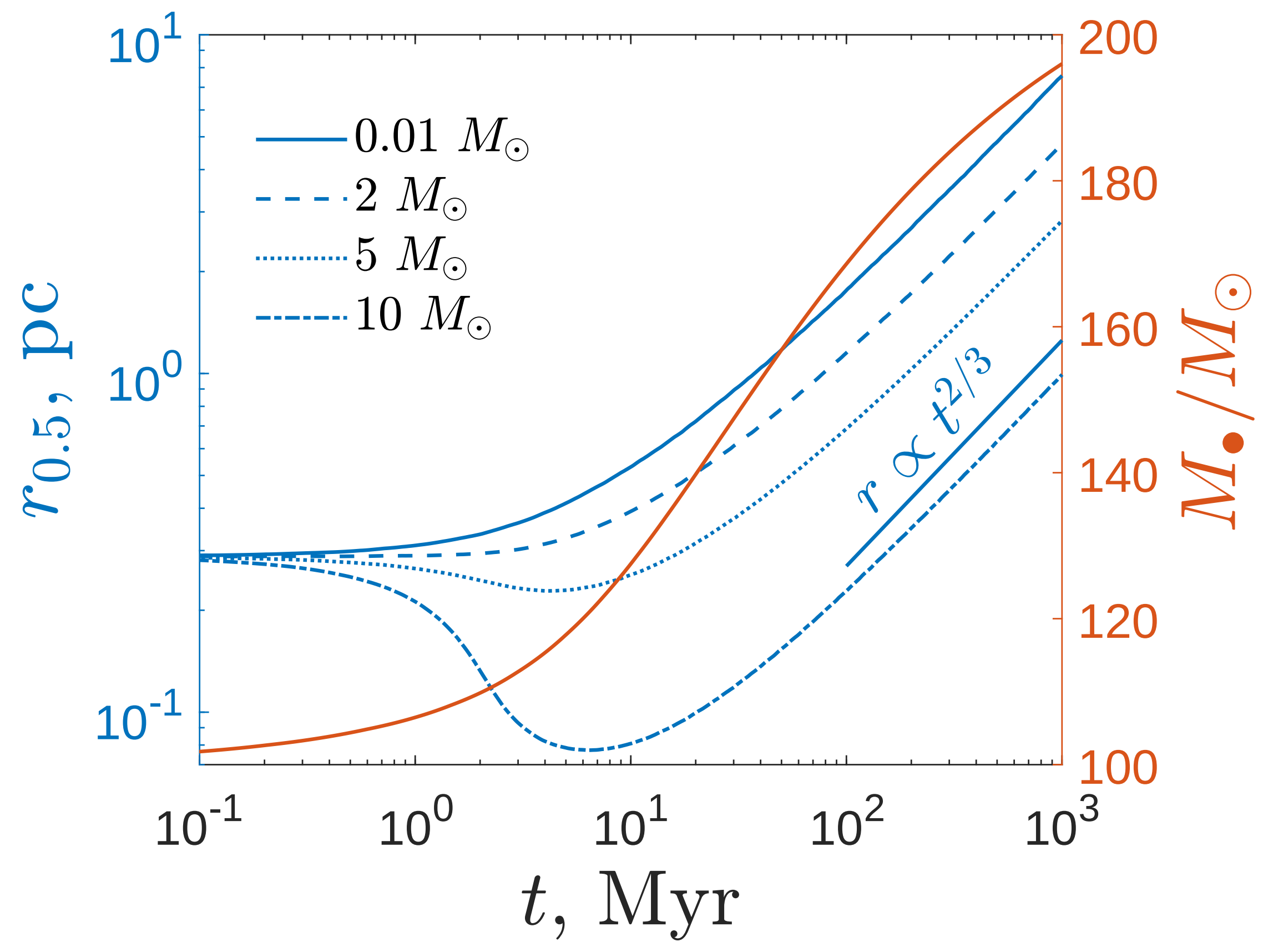


Figure 2: The blue lines (and the blue axis) show the evolution of the radius containing 50% of the mass of each PBHs type. The red line (and the red axis) shows the growth of the central black hole.

The evolution of the radius containing 50 percent of the mass of each PBHs type and the growth of the CBH are presented at the figure 2. It is seen that at the first moment of the evolution, the heavy PBHs are compressed towards the center, but then the cluster expands according to $r \propto t^{2/3}$. The CBH mass increases mainly within the first 100 Myr when the cluster has not expanded much yet.

Conclusion

The dynamical evolution of the PBHs cluster is described within the framework of the orbit-averaged Fokker-Planck equation. We present the behavior of the density profile with time. It is obtained that the cluster size has increased by ~ 10 times for 1 Gyr, and the CBH mass has increased by ~ 2 times.

References

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