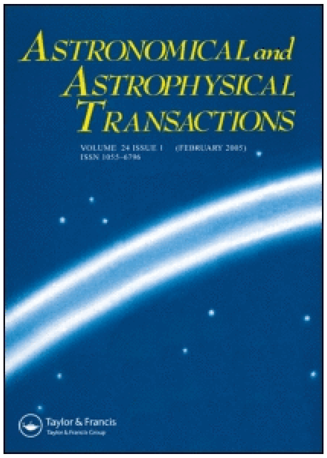

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ORIGIN OF CORRELATIONS BETWEEN CENTRAL BLACK-HOLE MASSES AND GALACTIC BULGE VELOCITY DISPERSIONS

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We argue that the observed correlations between central black-hole masses M_{BH} and Galactic bulge velocity dispersions σ_e in the form $M_{BH} \propto \sigma_e^4$ may witness the pre-Galactic origin of massive black holes. Primordial black holes would be the centres for growing protogalaxies which experienced multiple mergers with ordinary galaxies. This process is accompanied by the merging of black holes in the galactic nuclei.

Keywords: Correlations; Central black-hole masses; Galactic bulge-velocity dispersions

Recent observations (Kormendy and Richstone, 1995) demonstrated that no less than 20% of regular galaxies contain supermassive black holes (SMBHs) in their nuclei. Correlations are observed between the mass M_{BH} of the central SMBH in the galactic nucleus and velocity dispersion σ_e at the bulge half-optical-radius (Gebhardt et al., 2000):

$$M_{BH} = 1.2(\pm 0.2) \times 10^8 \left(\frac{\sigma_e}{200 \text{ km s}^{-1}}\right)^{3.75(\pm 0.3)} M_\odot. \tag{1}$$

We use the term ‘bulge’ in the same way as for elliptical galaxies and for central spheroidal parts of spiral galaxies. Note what another study (Ferrarese and Merritt, 2000) which is based on poorer observational data gives the correlation in the different form $M_{BH} \propto \sigma_e^{4.8(\pm 0.5)}$.

The origin of discussed correlations is quite uncertain. The simplest assumption that the growth of the SMBH mass depends on the bulge processes encounters the problem of different scales; the galactic bulge scale is a few kiloparsecs, whereas the linear scale of accretion disc around a SMBH is much less than 1 pc. Some deterministic mechanism (Silk and Rees, 1998) is needed for the huge mass transfer from the bulge to its innermost part. In these scenarios (Rees, 1984) the SMBHs are formed deep inside the gravitational potential well of the galactic or protogalactic nuclei.

In this report we explore the alternative approach by supposing that the observed correlations are stochastic in origin. Our basic assumption in the existence in the Universe

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of a pre-galactic population of black holes with masses $M_{PBH} \approx 10^5 M_\odot$ before the recombination time. The similar hypothesis of the existence of pre-galactic massive black-hole population was used by Fukugita and Turner (1996) for the interpretation of quasar evolution. A specific possibility (Zel'dovich and Novikov, 1967; Carr, 1975) is the formation of primordial black holes (PBHs) in the early Universe, or the formation of pre-galactic black holes during cosmological phase transitions (Rubin et al., 2001).

The supposed PBHs are mixed with dark matter owing to their cosmological origin. So the total mass $\sum M_{PBH}$ of these PBHs in any galaxy would be proportional to galactic dark-matter halo mass M. As a result the correlation $\sum M_{PBH} \propto M$ is primary in this model and the aforementioned observed correlations $M_{BH} \propto \sigma_e^4$ would be secondary and approximate in origin because of the complicated process of galactic formation. We may clarify this hypothesis as follows.

The cosmological fluctuation power spectrum P(k) is the confined mass region can be approximated by the power law with the effective index $n = d(\ln[P(k)])/d(\ln k)$. The effective galactic mass (mass of L* galaxy) formed at the red shift z is (White, 1994)

$$M = M_0(1+z)^{-6/(n+3)}, \tag{2}$$

where M_0 depends on the shape of P(k) in the considered mass region. Velocity dispersion in the bulge is estimated as $\sigma_e^2 \approx GM/R$, where $R = [3M/4\pi\kappa\rho(z)]^{1/3}$, $\rho(z) = \rho_0(1+z)^3$, $\kappa = 178$ and ρ_0 is the current density of cold dark matter. For the PBH cosmological density parameter Ω_{PBH} and effective PBH merging in the galaxies, the preceding relations gives the final mass of the central SMBHs:

$$M_{BH} = \psi\Omega_{PBH}M = \psi\Omega_{PBH}\sigma_e^{12/(1-n)}M_0^{-(n+3)/(1-n)}\left(\frac{4\pi G^3\kappa\rho_0}{3}\right)^{-2/(1-n)}, \tag{3}$$

where the factor ψ is responsible for the possible additional growth of the central SMBH due to accretion.

We use the cold dark-matter power spectrum (Barden et al., 1986) P(k) normalized to the observed density fluctuation value of approximately 1 on the 10 Mpc scale. The primordial spectrum is assumed to be of the standard Harrison–Zel'dovich form. On galactic mass scales $M = 10^{10}$–$10^{12} M_\odot$ the value of n varies from -2.28 to -1.98 and M_0 varies from $2.5 \times 10^{16} M_\odot$ to $7 \times 10^{14} M_\odot$ respectively. From equation (3) it follows that

$$M_{BH} = (0.91-1.03) \times 10^8 \frac{\psi\Omega_{PBH}}{2 \times 10^{-4}}\left(\frac{\sigma_e}{200 \text{ km s}^{-1}}\right)^{(3.66-4.03)} M_\odot, \tag{4}$$

where the pair of coefficients 0.91 and 3.66 corresponds to $M = 10^{10} M_\odot$, and the pair of coefficients 1.03 and 4.03 corresponds to $M = 10^{12} M_\odot$. The considered model is in a good agreement with observation data (1). The fluctuation spectrum on the galactic scale, $n \approx -2$, completely defines the power index $\alpha \approx 4$ in the relation $M_{BH} \propto \sigma_e^\alpha$. There are definite astrophysical limitations (Dokuchaev and Eroshenko, 2001) on the number and mass of PBHs. We consider the case $\Omega_{PBH} \approx 10^{-4}$ in accordance with all the limits.

The necessary requirement of the above model is multiple merging of PBHs with mass M_{PBH} into the single SMBH with mass M_{BH} during the Hubble time. It is known that for a single black hole with mass $M_{PBH} \ll 10^7 M_\odot$ the dynamic friction in the galactic halo is ineffective. Nevertheless, for the PBHs formed early, the process of dark-matter secondary accretion is possible (Gunn, 1977). As a result the PBHs would be 'enveloped' by the dark-matter halo with a mass of a typical dwarf galaxy and a steep density profile

$\rho \propto r^{-9/4}$. Indeed (White, 1994), the gravitationally bound objects formed at red shifts z_{col} from the density fluctuations at the moment of matter–radiation equality according to

$$\delta_{eq} = \frac{\delta_c(1 + z_{col})}{1 + z_{eq}}, \tag{5}$$

where z_{eq} is the red shift of equality and $\delta_c = 1.686$. In the uniform Universe the PBH with mass M_{PBH} produces this fluctuation inside the sphere containing the total mass $M = M_{PBH}/\delta_{eq}$. We shall call this combined spherical volume 'PBH + halo' by 'induced halo' (IH).

The growth of IH terminates at the epoch of nonlinear growth of ambient density fluctuations with the same mass M at IH but originating from the ordinary cosmological perturbation spectrum P(k) with the rms fluctuation $\delta^{fl}_{eq}(M)$ on the mass scale M:

$$\delta^{fl}_{eq}(M) = \frac{M_{PBH}}{M}. \tag{6}$$

We use for P(k) and $\delta^{fl}_{eq}(M)$ the well-known expression (Barden et al., 1986) and solve numerically equation (6) relative to the independent variable M with M_{PBH} as parameter. See Figure 1 for calculated relations for $M(M_{PBH})$ and $z_{col}(M_{PBH})$ according to equation (5). For $M_{PBH} = 10^5 M_\odot$ we find that $z_{col} \approx 10$ and $M = 2 \times 10^7 M_\odot$. As a result up to epoch $z \approx 10$ the PBHs with mass $M_{PBH} \approx 10^5 M_\odot$ had time to capture an additional mass which exceeds the PBH mass by about 200 times. It is easily verified that for $\Omega_{PBH} \approx 10^{-4}$ the contribution IHs to the total galactic mass is negligible.

So we demonstrate that massive IHs with mass $2 \times 10^7 M_\odot$ are formed around the PBHs. These IHs are massive enough to sink down to the galactic centre during the Hubble time under the influence of dynamic friction. Although the fate of nested PBHs inside the central parsec of the host galaxy is rather uncertain, we shall assume that multiple PBHs merge into a single SMBH during the Hubble time. Note that dynamic friction must be very effective for

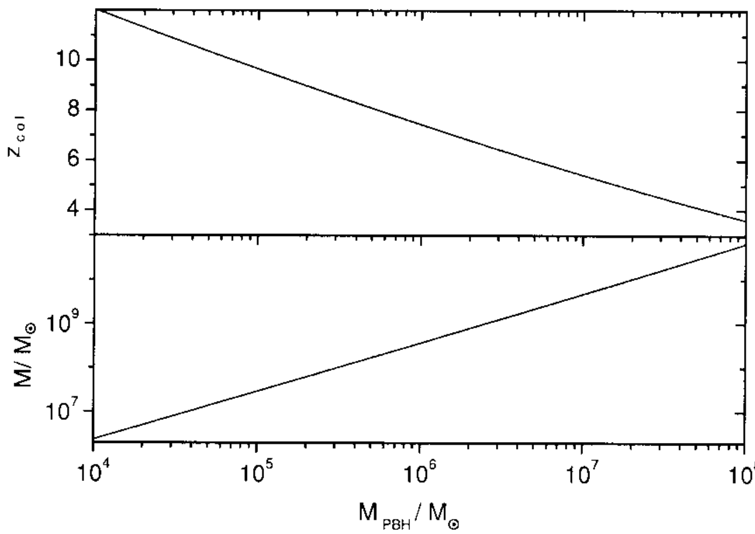

FIGURE 1 Red shift of induced halo formation z_{col} (M_{PBH}) as a function of its mass M (M_{PBH}) from the numerical solution of equation (6).

merging because the IH density $\rho \propto r^{-9/4}$ strongly grows towards the centre and is smoothed out only at small distances from the PBH.

Our assumption of multiple merging of PBHs may be violated in the galaxies of late Hubble types. The central SMBH masses in Sa, Sb and Sc galaxies are less on average than in E and S0 galaxies. In our model this is related to the relatively late formation of Sa, Sb and Sc galaxies when the main part of PBHs do not have enough time to sink to the galactic centre. In particular, about 10^2 PBHs of mass $M_{PBH} \approx 10^5 M_{\odot}$ can inhabit our Galaxy.

The coalescence of PBHs in the galaxies must be accompanied by a strong burst of gravitational radiation. The projected interferometric detector LISA is capable of detecting this coalescence. So there is a good possibility of verifying the considered model using the LISA detector.

In conclusion we discuss why the PBHs with masses of about $10^5 M_{\odot}$ are very probable candidates for independent black-hole population. Non-compact objects (neutralino stars) of mass about $(0.1–1)M_{\odot}$, consisting of weakly interacting non-baryonic dark-matter particles such as neutralinos were proposed by Gurevich et al. (1997) for the explanation of microlensing events in Large Magellanic Clouds. The hypothesized neutralino stars originated from the cosmological fluctuations with a narrow sharp maximum of about 1 in the spectrum on some small scale. In addition to neutralino stars the same maximum in the spectrum of cosmological fluctuations produces (Dokuchaev and Eroshenko, 2002) also the massive PBHs with mass about $10^5 M_{\odot}$. So the hypothesized dark-matter neutralino stars and PBHs may be indirectly connected through their common origin from the same cosmological fluctuations. The spectrum with a sharp maximum on some scale arises in some inflation models for example in the model described by Starobinsky (1992). At the same time the spectrum beyond the maximum may be of the standard Harrison–Zel'dovich form and reproduce the usual scenario of large-scale structure formation in the galactic distribution.

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