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Formation and evolution of massive black hole seeds at high redshift

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Abstract. I describe a simple analytical model to predict the amount of baryonic matter available in the center of dark matter halos at high redshift, to fuel the early formation and growth of the seeds of supermassive black holes. In this model black hole seed formation occurs in mini-halos with $T_{\rm vir} \sim 10^4$K before the Universe was significantly enriched by metals. If H_2 formation is inhibited, we find that such halos would naturally form central mass concentrations of the order of $10^5 M_\odot$ that we associate with the seed of supermassive black holes. Our model produces low-redshift black hole densities in good agreement with Soltan-type arguments, and predicts a flattening of the black hole density at redshift larger than $z \sim 6$. We also predict a relative dearth of SMBH in dwarf galaxies at $z = 0$.

Key words. accretion, accretion discs – black hole physics – galaxies: formation – cosmology: theory – instabilities – hydrodynamics

1. Introduction

Optically bright quasars with SMBH masses $M_{\rm bh} > 10^9 M_\odot$ are now detected out to redshifts $z > 6$ when the age of the Universe was less that 1Gyr (Fan et al. 2006), indicating that the average accretion rate onto the seed black hole during its early growth must have been at least $1 M_\odot$/yr. Such high accretion rates pose several challenging questions to theoretical models: (1) Is the black hole able to accept such high accretion rates? The difficulty here lies in the fact that low mass black hole seeds have a correspondingly small Eddington limit, thereby limiting their accretion rate to relatively low values, unless the accretion efficiency is very low ($\epsilon \lesssim 0.06$), which in turn requires the seed black hole not to be rapidly spinning (King & Pringle 2006). (2) Regardless of the ability of the hole to accept the incoming mass, can enough gas be channeled in the central regions of protogalaxies in order to fuel the black hole at the required high rate? The present contribution addresses this second aspect of the problem.

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2. A simple analytical model for black hole seed formation at high z

Here, I concentrate on a specific model for SMBH seed formation (Lodato & Natarajan 2006, 2007; Volonteri et al. 2008). According to such model, the formation of the seeds of SMBH occurs at a redshift $z \sim 10-15$, when the intergalactic medium had not yet been enriched by metals. The cooling properties of this gas are therefore relatively simple.

In particular, in the absence of H_2, the main coolant is atomic hydrogen, for which the cooling timescale becomes extremely long for temperatures smaller than 10^4 K, and we thus expect the gas to reach thermal equilibrium at a temperature $T_{\rm gas}$ of the order of 10^4K.

Consider a dark matter halo (modeled, for simplicity, as a truncated singular isothermal sphere) of mass M and circular velocity $V_{\rm h}$ and assume that the halo contains a gas mass $M_{\rm gas} = m_{\rm d}M$, where $m_{\rm d} \approx 0.05$, whose angular momentum is $J_{\rm gas} = j_{\rm d}J$, where $j_{\rm d} \sim m_{\rm d}$. The angular momentum of the dark matter halo J is expressed in terms of its spin parameter $\lambda = J|E|^{1/2}/GM^{5/2}$, where E is its total energy.

If the virial temperature of the halo $T_{\rm vir} \propto V_{\rm h}^2$ is larger than the gas temperature $T_{\rm gas}$, the gas collapses and forms a rotationally supported disc, with circular velocity $V_{\rm h}$. For low values of the spin parameter λ the resulting disc can be compact and dense. During the infall of gas onto the disc, its density rises until the disc becomes unstable to gravitational instabilities when $Q = c_{\rm s}\kappa/\pi G\Sigma \sim 1$, where $c_{\rm s}$ is the sound speed of the gas, κ is the epicyclic frequency and Σ is the surface density. The development of the instability, in the form of a large scale spiral structure, is able to efficiently redistribute angular momentum and allow accretion. Further infall of gas does not cause the density to rise much further, but rather it promotes an increasingly high accretion rate into the center. This process goes on until infall is over and the disc has attained a surface density low enough to be marginally gravitationally stable with $Q = \bar{Q}$, where $\bar{Q}$ is a number of order unity. It is then possible to calculate what fraction of the infalling mass needs to be transported into the center to make the disc marginally stable (Lodato & Natarajan 2006):

$$M_{\rm BH} = m_{\rm d}M\left[1 - \sqrt{\frac{8\lambda}{m_{\rm d}\bar{Q}}\left(\frac{j_{\rm d}}{m_{\rm d}}\right)\left(\frac{T_{\rm gas}}{T_{\rm vir}}\right)^{1/2}}\right] \quad (1)$$

where I have suggestively called $M_{\rm BH}$ the accreted mass, since this is the total mass available for the formation of the BH seed. Eq. (1) links in a simple way the expected mass of the seed black hole to the dark matter halo properties (such as its mass and spin parameters), that can be derived from cosmological N-body simulations (Bullock et al. 2001), and to a number of well constrained gas dynamical parameters, such as the gas temperature (which, for atomic hydrogen cooling is of the order of 5 10^3 – 10^4 K), and the marginal stability value of Q, which is of the order of unity.

The arguments outlined above do not take into account the possibility that a strong gravitational instability results in disc fragmentation, rather than accretion. Several numerical investigations have addressed the issue of identifying the conditions under which a gravitationally unstable gaseous disc undergoes fragmentation (Gammie 2001; Rice et al. 2005). It is now well understood that fragmentation does occur if the cooling time in the disc is smaller the dynamical time Ω^{-1}. For our primordial gas, the main coolant at temperatures below 10^4K is molecular hydrogen. If H_2 formation is suppressed (for example, by the presence of a strong UV flux), we should then expect fragmentation to be inhibited. The issue of H_2 formation in the presence of an ionizing UV background has become the subject of intense investigations (Wise & Abel 2007; O'Shea & Norman 2008). It appears that while H_2 formation can still happen even in the presence of a strong background, this is confined to the innermost regions of the halo, and the small molecular fraction is not enough to cool the gas below 10^3 K and to induce fragmentation (O'Shea & Norman 2008).

Even if the cooling timescale is long, the disc might still fragment if the torque required to redistribute the excess baryonic mass becomes too large to be sustained by the disc. Detailed numerical models (Rice et al. 2005) have shown that the maximum torque that can be delivered by a quasi-steady self-regulated disc is of the order of $\alpha_{\rm c} \approx 0.06$ (using the standard α parameter for the disc viscosity). In the context of the present model, it can be shown that fragmentation occurs when the virial temperature exceeds a critical value $T_{\rm max}$, given by (see Lodato & Natarajan 2007 for details):

$$\frac{T_{\rm max}}{T_{\rm gas}} > \left(\frac{4\alpha_{\rm c}}{m_{\rm d}}\frac{1}{1 + M_{\rm BH}/m_{\rm d}M}\right)^{2/3} \quad (2)$$

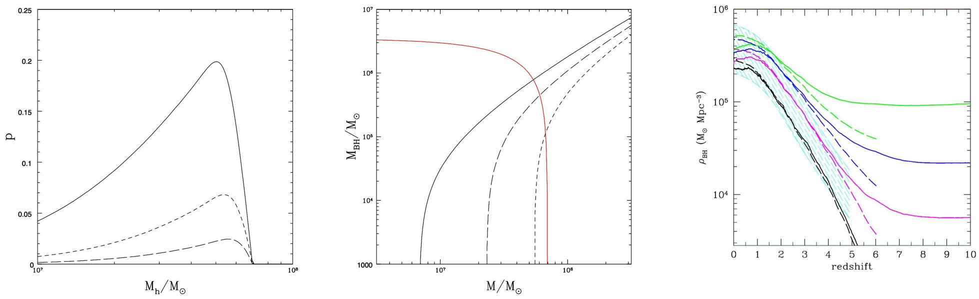

Fig. 1. Left: Probability of hosting a seed black hole at $z = 15$ as a function of halo mass for $\bar{Q} = 3$ (solid line), $\bar{Q} = 2$ (short-dashed line), and $\bar{Q} = 1.5$ (long-dashed line). Middle: Relationship between dark matter halo mass M and expected black hole seed mass $M_{\rm BH}$ based on Eq. (1), for $z = 15$, $\bar{Q} = 2$ and $T_{\rm gas} = 5000$K. The three curves refer to $\lambda = 0.01$ (solid line), $\lambda = 0.015$ (long-dashed line) and $\lambda = 0.02$ (short-dashed line). The red curve indicates the halo mass above which fragmentation is expected. Right: black hole density as a function of redshift for $\bar{Q} = 3$ (green solid line), $\bar{Q} = 2$ (blue solid line) and $\bar{Q} = 1.5$ (purple line). The black line indicates the expected density for low mass black hole seeds formed as remnant of Pop-III stars.

3. Properties of the black hole population at high and low redshift

The model outlined above allows us to predict the properties of the black hole population at high redshift, starting from the expected properties of the dark matter halos within which they formed, such as their mass function (Sheth & Tormen 1999) and the distribution of dark matter spins (Bullock et al. 2001).

The left panel of Fig. 1 shows the total probability for a dark matter halo at $z = 15$ of hosting a black hole seed as a function of halo mass. The three lines refer to three different choices for the marginal stability value $\bar{Q}$. The solid line refers to $\bar{Q} = 3$, corresponding to the (probably unrealistic) case where the gravitational instability is very efficient and develops already for relatively hot discs. The short-dashed and long-dashed lines refer to $\bar{Q} = 2$ and $\bar{Q} = 1.5$, respectively. It can then be seen that for such realistic values the total probability of hosting a black hole is of the order of a few percent. The typical halo mass inside which a seed black hole forms is of the order of $10^7 - 10^8 M_\odot$.

The middle panel of Fig. 1 shows the relation between dark matted halo and seed black hole mass defined by Eq. (1), for three different choices of the spin parameter: $\lambda = 0.01$ (solid line), $\lambda = 0.015$ (long-dashed line) and $\lambda = 0.02$ (short-dashed line). The red line indicates the fragmentation boundary: halos with mass above this threshold result in fragmentation rather than in the accumulation of baryonic matter in the center. It can then be seen that, for those halos which do host a seed black hole, the typical mass of the seed is of the order of $10^4 - 10^5 M_\odot$, with a sharp drop off in the mass function above $10^5 M_\odot$ due to fragmentation (see also Lodato & Natarajan 2007).

We have also considered the evolution of the properties of the black hole population from high redshift to $z = 0$ using the merger-tree approach of Volonteri et al. (2003). We initially populate dark matter halos at high redshift according to the seeding criteria outlined in the sections above and we then let the population evolve through the subsequent merger history of the halos, assuming that after the initial (rapid) seed formation phase, the black holes grow through a merger-driven AGN phase (see details in Volonteri et al. 2008).

The right panel of Fig. 1 shows the comoving black hole density as a function of redshift for our models (green: $\bar{Q} = 3$, blue: $\bar{Q} = 2$, purple $\bar{Q} = 1.5$) and for a model (black line) where the black hole seeds at high redshift are the relatively low mass remnants of the Pop-III stars. Most of the AGN-like growth of the black hole density occurs at $z < 6$ and it can be seen that

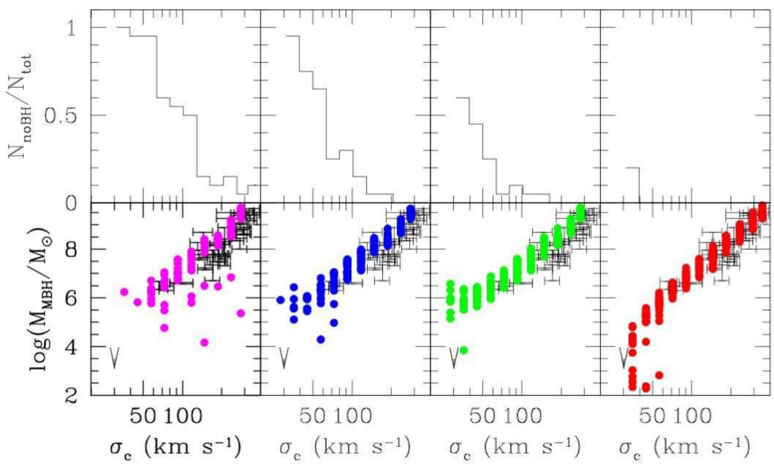

Fig. 2. Properties of the black hole population at $z = 0$. Upper panels: fraction of galaxies that do not host a supermassive black hole at $z = 0$. Lower panels: the $M - \sigma$ relation. The four models shown here are (from left to right): $\bar{Q}$ =3, 2 and 1.5, respectively, and a model based on low mass seeds, remnant of Pop-III stars.

all the models can reproduce relatively well the present day black hole density. The models start to differ at $z > 6$, when the density starts to reflect the original properties of the seed population. It is easily seen that while low mass seeds naturally tend to predict very small black hole densities at high z, our high mass seed models produce a flattening of the black hole density, corresponding to the initial density achieved through the rapid seed formation. The level at which the density flattens depends on the efficiency of the seed formation model and for reasonable values of the parameters is in the range of $10^4 M_{\odot}/\mathrm{Mpc}^3$. It is worth noting that similar values are also obtained in recent "BH population synthesis" models based on redshift dependent Soltan-like arguments (Merloni & Heinz 2008). Finally, Fig. 2 shows the present day $M-\sigma$ relation for the four models described above. The upper panels show, as a function of galaxy velocity dispersion, the number of halos at $z = 0$ that do not host a SMBH. It is then easily seen that (contrary to the low mass seed model) we predict that for galaxies with velocity dispersions smaller 50-100 km/sec the occupation fraction of SMBH should rapidly drop. This is simply a consequence of the fact that dwarf galaxies did not have any massive progenitor at high redshift, able to seed a black hole during the "seed formation era" at redshift $\sim$ 15. Note that also this prediction appears to be consistent with the decrease of the AGN fraction observed in the Virgo cluster (Gallo et al. 2008).

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