The Early Assembly of Supermassive Black Holes

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Abstract. I will review the main current channels for supermassive black hole seed formation, with particular focus on the mass estimates. These estimates, based on theoretical models and numerical simulations, remain quite uncertain, but there has been a trend toward lower values in recent works. New merger tree calculations are needed to understand if this is worrisome to account for bright quasars at \( z > 6 \). Certainly, we cannot relax the requirement of very efficient growth at early stages.

1. Introduction

The formation mechanism for supermassive black holes (SMBHs) in galactic nuclei remains unknown. Variations on most of the formation channels identified by Begelman & Rees (1978) — which include instabilities in clusters of stars or stellar remnants, and the collapse of supermassive stars or massive discs — are still under consideration today (Umemura et al. 1993; Freitag et al. 2006; Shibata & Shapiro 2002; Lodato & Natarajan 2006). A more recent idea holds that supermassive black holes result from sustained accretion onto, or mergers of, the remnants of Population III (PoPIII, i.e. metal-free) stars (Volonteri et al. 2003), at least some of which seem likely to be massive, short-lived progenitors of stellar mass black holes (Carr et al. 1984; Abel et al. 2002; Heger et al. 2003; Tumlinson et al. 2004).

The formation of supermassive black holes requires the inflow of \( > 10^6 M_\odot \) of gas from galactic scales into a region much smaller than a parsec. The presence of bright (\( \sim 10^{47} \text{ erg s}^{-1} \)) quasars at \( z > 6 \) (Fan et al. 2001) suggests that, at least in those cases, this inflow must have started at an earlier epoch and proceeded at sufficiently high rate to have allowed the assemblage of black holes of \( 10^9 M_\odot \), in less than a Gyr. However, the mass distribution of the seeds is also important. For example, stellar mass black holes would have never been able to grow into the brightest quasars at \( z \sim 6 − 7 \), even with an Eddington accretion luminosity. In general, the mass function of SMBH seeds has to be such that we can reproduce the luminosity function of quasars at any redshift and the occupation fraction of SMBHs in today quiescent galaxies.

In this talk, I will review the most popular routes to formation of SMBH seeds, with a particular focus on the most recent estimate for their masses. This routes are: remnants of the first generation of stars § 2 and direct collapse of gas in protogalaxies, § 3 and § 4. As this latter is concerned, I will focus on the path that from the gas collapse leads to a black hole seed, through the formation of a transient object called a “quasistar”, § 3, when the gas is still pristine. On the other hand in a more advanced stage of a (proto)-galaxy, when the gas has been already pre-enriched of metals, the gas
collapse may result in the formation of a central star cluster, with an intermediate mass black hole at its centre § 4.

![Figure 1](image)

Figure 1. *Left panel:* From Volonteri (2010). The mass function distribution for quasistars (blue), nuclear cluster (green) and PoPH (red) channels. See details in Volonteri (2010). *Right panel:* A personal update of the left panel. It is not meant to indicate a distribution, but just an updated (lower) range of masses.

### 2. Seeds from first generation of Stars

In this scenario the working hypothesis is that black holes *precede* the formation of galaxies. They are formed by the first generation of stars. In my opinion, the positive feature of this channel is that we are familiar with stellar born black holes. The less appealing feature is that they need to find their way to get to the centre of protogalaxies, and this path is full of difficulties. However, I will not discuss this last point nor I will review the difficulties in actually forming these stars. I will rather assume that they form and review the most recent estimates for their remnant black holes, seeds for future supermassive black holes. For this Section, I refer the reader to the excellent review by Haiman (2012).

#### 2.1. The “old” view

As the Universe expands in its early phases, progressively more massive structure leaves the Hubble flow and collapse under their own gravity. Baryons feel the local enhancement of the potential generated by these non-linear dark matter structures (called halos) and fall into their gravitational well. In the classical picture, the gas, while falling, is shock heated to the virial temperature: the temperature that corresponds to equipartition between the kinetic energy of the gas and its potential energy. This process leaves the gas in hydrostatic equilibrium, in a rather diffuse state. The picture changes when the gas is able to cool and release part of its thermal support. This first chance for the gas to cool in a non trivial number of objects is around $z \sim 25$ in halos of mass $10^{3-6} M_\odot$. There, the gas temperature is high enough that, in principle, molecular hydrogen cooling is efficient. In these halos, gas can progressively lose pressure support and sink further into the potential. In the central region temperature and densities increase. The
collapse may eventually be halted by ignition of nuclear reactions: the first non-linear baryonic structures may therefore be stars. This first generation of stars are called ‘Population III” (PoPIII in short) stars. The expectation is that, at least in a certain range of masses ($\sim 40 - 140M_\odot$ and $> 260M_\odot$), these stars will leave behind a black hole at the and of their life, after $\sim 1$ Myr (as we will see in a moment these are quite massive stars, emitting at their Eddington limit). But how big are these stars and their remnants? Let’s estimate an upper limit. These $10^{5-6}M_\odot$ halos at those redshifts are among the most massive ($\geq 3\sigma$ peaks). They form in the knots of the cosmic web and they are fed –in baryons– through the filaments at a rate

$$M_b = 3.3 \times 10^{-3} \left( \frac{(1+z)}{26} \right)^{2.5} \left( \frac{M_h}{10^6} \right)^{1.14} M_\odot \text{yr}^{-1},$$

(Neisten et al. 2010, Fakhouri et al. 2010). In the above equation, the halo mass is indicated with $M_h$ and I used a cosmic baryon fraction of $f_b = 0.17$. We can thus estimate an upper limit on the mass of the star by multiplying this rate for the age of the star $M_{\text{pop}} = M_b \times 1$ Myr $\approx 100 - 1000M_\odot$. Indeed early numerical works suggested that these gigantic clouds would not fragment further, forming unusually gigantic stars. Neglecting rotation, stars with masses outside the pair instability region would leave a black hole of comparable mass. A merger tree cosmological calculation is needed to compute the seed mass function. Under some hypothesis for the behaviour of baryons (see Volonteri 2010 for details), one obtain the mass distribution shown in Fig.1, left panel, red distribution.

2.2. The “new view”

Most recent work have instead indicated that the masses of the PoPIII stars and their remnants are generally lower. First, high resolution simulations have shown that the $\sim 10^6$ cloud tends to fragment into smaller clumps –especially in the presence of turbulence- forming binaries or small clusters. Second, these massive stars have some degree of rotation and are likely to lose mass during their life by vigorous winds. This in turn decreases further the star mass before it collapses into a black hole. Finally, residual bulk motions between the gas and dark matter at the moment of the halo formation can be of the order of the escape velocity (a few km s$^{-1}$). This can lead to a lower fraction of baryons being accreted or in a suppression of star formation at these redshifts. The overall consequence seems to be that the most common mass for the black hole from PoPIII stars is $\lesssim 100M_\odot$ and not more.

3. Direct formation of seeds in protogalaxies

This scenario has the attractive feature that black holes are born where we observe them today: galaxies and SMBHs were initially assembled at the same epoch ($z \sim 10$), by the same mechanism: local gravitational infall of baryonic mass that following the dark matter collapse feeds the hosting halo through the filaments of the cosmic web. This is in principle possible, since halos of $\sim 10^{8-9}M_\odot$ start to appear at this epoch and have virial temperatures $> 10^4$ K, so that atom hydrogen cooling is finally effective. This cooling can result in both “normal” star formation and assembly of a large masses of gas at the centre of the protogalaxies (in which proportions is still a matter of debate). This accumulation can drive the formation of a supermassive black hole seed. I will
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Figure 2. Schematic illustration of the quasistar structure that we consider in this paper. A seed black hole of mass $M_{BH}$ accretes gas from a massive, radiation pressure-supported envelope at a rate set by the conditions outside the Bondi radius. The luminosity liberated by the accretion process is transported convectively in the inner regions of the envelope, with a transition to a radiative zone once convection becomes inefficient. In this model version, we consider isolated, spherically symmetric models of quasistars, but the more physical situation would also include partial rotational support leading to flattening of the quasistar, and ongoing disc accretion at a fraction of a Solar mass per year.

omitted here to discuss the specific mechanisms that have been proposed to facilitate the gas angular momentum loss and avoid excessive fragmentation. I will rather concentrate on the formation of the black hole seeds, assuming that gas can copiously reach the protogalactic centre. In this circumstances, Begelman (2010) shows that a non-thermally relaxed gigantic star forms, in which convection is not efficient. This causes that only the hydrogen initially in the core is consumed. At the exhaustion of the fuel, the core will collapse into a $\sim 100 M_\odot$ black hole. Differently form the PoPIII scenario, here very optically thick matter keeps falling onto the hole. The accretion luminosity is thus trapped, it inflates and finally stops the infalling gas into an hydrostatic massive envelope. We call a "quasistar," this accreting black hole embedded within a massive hydrostatic gaseous envelope. This structure has a size of $\sim 100$ AU and mass at least 100 times those of the embryo black hole (Begelman et al. 2006, 2008; Ball et al. 2011). While the black hole is accreting from the envelope, the envelope is accreting from the protogalactic disc (see Fig.2). For halos of $10^{9.6 - 9} M_\odot$ at $z \sim 10$ the average accretion rate at the virial radius is a few $M_\odot$ yr$^{-1}$ (see eq.1).

3.1. The “old” view

In our first work, (Begelman et al. 2008), we used analytic models and numerical stellar structure calculations to study the structure and evolution of quasistars. We imposed hydrostatic equilibrium everywhere, and we found which configurations are possible. Our first result is that a quasistar can exist only if the envelope mass is 10–20 times the black hole mass. The excluded area is the shaded region in Fig.3, and it is shown in the parameter space of masses: the envelope mass ($m_*$) and black hole mass ($m_{BH}$). This result has been confirmed by Ball et al. (2011). In the allowed region, a quasistar is a massive, radiation dominated star, where in most of the envelope the energy is transported convectively. Only a thin radiative layer ensures that the accretion luminosity is finally released into the interstellar medium. The other remarkable result is that the accretion rate onto the black hole adjusts so that the luminosity carried by the convective
Figure 3. From Begelman et al. (2008). Envelope mass versus black hole mass for static solutions at the minimum photospheric temperature. The dashed line is for the “toy” opacity model, the solid lines are for the numerical opacity. Static solutions are excluded in the lower shaded regions. Superimposed on the figure are the evolutionary tracks. The upper track is for an accretion rate onto the envelope of $\dot{M}_e = 1 \ M_\odot \ yr^{-1}$. The lower track is for $\dot{M}_e = 0.1 \ M_\odot \ yr^{-1}$.

The envelope equals the Eddington limit for the total mass, $m_e + m_{BH} \approx m_e$. This greatly exceeds the Eddington limit for the black hole mass alone, leading to rapid growth of the black hole. Since we know the accretion rate onto the black hole, we can trace evolutionary tracks for the quasistar, assuming an accretion rate for the envelope (see Fig.3). We find that black hole seeds with masses greater than $10^3 \ M_\odot$ could form via this mechanism in less than a few Myr. The same merger tree calculation mentioned for the PoPIII scenario leads to a mass distribution showed in blue in Fig.1, left panel. The peak is around $10^9 \ M_\odot$, with a higher mass tail.

3.2. The “new” view

In a subsequent paper, we consider an important ingredient: the large radiative flux may exceed Eddington and drive a wind from the radiative layer, even in absence of metal pollution. This is schematically illustrated in Fig.2. Using approximated recipies for the wind strength, we find that quasistars suffer extremely high rates of mass loss from their envelope, in analogy to very massive stars such as $\eta$-Carinae. Only for envelope masses greater than $2.8 \times 10^5 (M_{BH}/100 \ M_\odot)^{9/11}$ is the envelope evaporation time-scale
Figure 4. From Dotan, Rossi & Shaviv (2010). A heuristic description of the new model for a quasistar. We find that these “quasistars” suffer extremely high rates of mass loss through winds from their envelopes, in analogy to very massive stars such as η-Carinae.

longer than the accretion time-scale of the black hole. This relation thus constitutes a “threshold growth line” above which quasistars can grow their internal black holes (see white region in Fig.3). Accretion rates can be 10 to 100 times the Eddington rate. The quasistars born in this “growth region” with $10^6$, $10^7$ and $10^8 M_\odot$ can grow black holes with masses between $10^3$ to $10^5 M_\odot$, before crossing the threshold growth line and dispersing their envelopes in less than $10^4$ yr.

These results put strong constraints on the dark matter halos in which massive SMBH seeds can form. As mentioned before, our scenario follows the picture put forth by Begelman (2010), whereby the progenitors of quasistars are super massive stars that formed as the consequence of the high infall rate of hydrogen-cooled gas at the centre of dark matter halos. The life-time of these stars is set by the thermonuclear timescale for burning their hydrogen core. At the Eddington limit, it is $\sim 2$ Myr, independent of mass. After that, the core may collapse into a black hole. Once the black hole starts accreting from the envelope, the feedback from the released luminosity sets up the structure we have been investigated.

Our results constrain the initial mass of the quasistar, and thus of the supermassive star, that can grow massive SMBH seeds. A quasistar with an initial mass of $\approx 10^6 M_\odot$ (or $\approx 10^7 M_\odot$) can form a BH of $\approx 10^3 M_\odot$ ($\approx 10^4 M_\odot$), as can be seen in Fig.3. This initial mass should be accumulated in less than $\sim 2$ Myr, which requires accretion rates greater than a few $M_\odot \text{yr}^{-1}$. Halos accrete matter through their virial radius at a rate given by eq.1. This is also an estimate for the accretion rate that feeds the quasistar, under the assumption that almost all gas can be funnelled towards the halo centre. Under this assumption, we can connect through eq.1 the accretion rate needed in order to form a quasistar of a certain mass and at a certain redshift, with the mass of the host halo. However, we should also assume an efficiency factor, since not all gas ($f_b \times M_h$) in the halo can be used to form a quasistar. Therefore, the minimum halo mass that can host a given quasistar with mass $m_*$ is
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Figure 5. From Dotan, Rossi & Shaviv (2010). Quasistar evolutionary tracks. The blue lines describe the evolution of quasistars which accrete from the pregalactic disc at a rate of \(10 M_\odot\) yr\(^{-1}\). The upper three ones, have an initial BH mass of \(100 M_\odot\), and initial envelope masses of \(10^6\), \(10^7\) and \(5 \times 10^7 M_\odot\), respectively. The quasistar with \(10^6 M_\odot\) spends \(1.5 \times 10^3\) yr in the accretion zone and a comparable time, \(6 \times 10^3\) yr, in the evaporation strip. The aforementioned time-scales for \(M_* = 10^7 M_\odot\) (and \(M_* = 6 \times 10^7 M_\odot\)) are \(1.3 \times 10^3\) yr (600 yr) and \(1.5 \times 10^3\) yr (500 yr) respectively (see Fig. ??). In all cases, the mass evolution of the envelope is governed by the wind loses. In the BH growth zone, the quasistars lose only \(\approx 25\%\) of their initial mass, while all of it is lost in the evaporation strip. The final BH masses are: \(750 M_\odot\), \(1.3 \times 10^4 M_\odot\) and \(10^5 M_\odot\). The lower blue line is for a quasistar formed in the evaporation strip with \(M_{BH,i} = 25 M_\odot\) and \(M_{*,i} = 5.7 \times 10^3 M_\odot\), while the red-line is for the same initial conditions but with \(M_{acc} = 300 M_\odot\) yr\(^{-1}\). In these last cases, the final BH mass is determined by accretion rates.

\[
\frac{M_h}{M_\odot} \approx \max \left[ \frac{7 \times 10^8}{(1 + z)^{2.2}} \left( \frac{m_*}{10^6 M_\odot} \right)^{0.9}, 6 \times 10^8 \frac{m_*}{10^6 M_\odot} \right],
\]  

(2)

where we assumed in the second term that no more than 1% of the total amount of gas is used for the formation of the quasar. The first term comes directly from eq.1. Eq. 2 implies that at \(z = 10\), quasistars with \(M_* > 10^6 M_\odot\) can be found only in dark matter halos with \(M_h \gtrsim 10^9 M_\odot\). In particular, for \(z \gtrsim 10\) “massive” SMBH seeds of \(M_{BH} > 10^4 M_\odot\) need host halos with \(M_h \gtrsim 6 \times 10^9 M_\odot\).

These are very rare halos at \(z \sim 10\), therefore I anticipate that most of the seeds will be \(< 10^4 M_\odot\). However, some rare seeds may have born with \(10^4 - 10^5 M_\odot\) and
grow at the Eddington limit to $10^9 M_\odot$ by redshift 6 (the growth timescale is $\sim 0.5$ Gyr). A proper “merger tree” calculation should be done, in order to derive a mass function and assess if enough massive seeds can be formed through this channel.

![Figure 6. From Devecchi et al. (2011). Left panel: mass function of seed BHs formed via stellar dynamics in NCs. Right panel: Mean mass as a function of redshift $z$ for the same formation channel. Dotted lines denote the dispersion at $1-\sigma$ level.](image)

4. Nuclear Cluster

The previous scenarios were considering somewhat pristine gas. In the epoch of galaxy formation however, there may be halos that were pre-enriched of metals, when gas can start cooling and accumulate towards the centre. If the metallicity is $> 10^{-5} - 10^{-4}$ solar, the massive star à la Begelman (2010) may not form. Instead, gas may fragment a form a nuclear central cluster (NC) (Devecchi & Volonteri 2009). A compact star cluster can be subject to rapid segregation of the most massive stars in its core. If mass segregation occurs on a timescale shorter than the lifetime of massive stars, these latter will decouple dynamically from the rest of the cluster and start colliding in a runaway fashion. The mass spectrum evolves in such a way that a single very massive star (VMS) grows quickly (Portegies Zwart et al. 1999). Its growth is terminated once the reservoir of massive stars is exhausted, either via dynamical collisions (as they are all engulfed in the very massive star) or via stellar evolution. At low metallicity (below $\approx 10^{-3}$ solar), stellar mass loss is reduced compared to the solar metallicity case. A sufficiently massive star is then expected to end its life leaving behind a remnant BH of a few hundred up to a thousand solar masses.

We ran a number of simulations which aimed at tracing the formation of nuclear star clusters and their black hole seeds, in the framework of the current ΛCDM cosmogony (Devecchi et al. 2011). Our model tracks the chemical, radiative and mechanical feedback of stars on the baryonic component of the evolving halos. This procedure allows us to evaluate when and where the conditions for BH formation are met, and to trace the emergence of BH seeds arising from this channel, in a cosmological context.

Our result on the black hole seeds mass function in shown in Fig.4. The right panel gives the mean black hole seed mass as a function of reshift while the left panel gives the total (all redshift included) mass function. Most of the seeds have masses around a
few $100M_\odot$. This is a factor of ten lower than previous estimates that neglected mass loss from the massive stars, due to the presence of metals (see Fig.1, left panel, green distribution).

5. Summary and conclusions

The summary of my talk may be represented by Fig.1, right panel: the mass ranges expected for SMBH seeds are now lower. The consequences are still to be fully appreciated and worked out.

References
