The Environmental Impact of Supermassive Black Holes

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Abstract. The supermassive black holes observed at the centers of almost all present-day galaxies, had a profound impact on their environment. I highlight the principle of self-regulation, by which supermassive black holes grow until they release sufficient energy to unbind the gas that feeds them from their host galaxy. This principle explains several observed facts, including the correlation between the mass of a central black hole and the depth of the gravitational potential well of its host galaxy, and the abundance and clustering properties of bright quasars in the redshift interval of $z \sim 2$–6. At lower redshifts, quasars might have limited the maximum mass of galaxies through the suppression of cooling flows in X-ray clusters. The seeds of supermassive black holes were likely planted in dwarf galaxies at redshifts $z > 10$, through the collapse of massive or supermassive stars. The minimum seed mass can be identified observationally through the detection of gravitational waves from black hole binaries by Advanced LIGO or LISA. Aside from shaping their host galaxies, quasar outflows filled the intergalactic medium with magnetic fields and heavy elements. Beyond the reach of these outflows, the brightest quasars at $z > 6$ have ionized exceedingly large volumes of gas (tens of comoving Mpc) prior to global reionization, and must have suppressed the faint end of the galaxy luminosity function in these volumes before the same occurred through the rest of the universe.

1 The Principle of Self-Regulation

The fossil record in the present-day universe indicates that every bulged galaxy hosts a supermassive black hole (BH) at its center [1]. These BHs are dormant or faint most of the time, but occasionally flash in a short burst of radiation that lasts for a small fraction of the Hubble time. The short duty cycle accounts for the fact that bright quasars are much less abundant than their host galaxies, but it begs the more fundamental question: why is the quasar activity so brief? A natural explanation is that quasars are suicidal, namely the energy output from the BHs regulates their own growth.

Supermassive BHs make up a small fraction, $< 10^{-3}$, of the total mass in their host galaxies, and so their direct dynamical impact is limited to the central star distribution where their gravitational influence dominates. Dynamical friction on the background stars keeps the BH close to the center. Random fluctuations in the distribution of stars induces a Brownian motion of the BH. This motion can be described by the same Langevin equation that captures the motion of a massive dust particle as it responds to random kicks from the much lighter molecules of air around it [2]. The characteristic speed by which the BH wanders around the
center is small, \( \sim (m_\star/M_{\text{BH}})^{1/2} \sigma_\star \), where \( m_\star \) and \( M_{\text{BH}} \) are the masses of a single star and the BH, respectively, and \( \sigma_\star \) is the stellar velocity dispersion. Since the random force fluctuates on a dynamical time, the BH wanders across a region that is smaller by a factor of \( \sim (m_\star/M_{\text{BH}})^{1/2} \) than the region traversed by the stars inducing the fluctuating force on it.

The dynamical insignificance of the BH on the global galactic scale is misleading. The gravitational binding energy per rest-mass energy of galaxies is of order \( \sim (\sigma_\star/c)^2 < 10^{-6} \). Since BH are relativistic objects, the gravitational binding energy of material that feeds them amounts to a substantial fraction of its rest mass energy. Even if the BH mass occupies a fraction as small as \( \sim 10^{-4} \) of the baryonic mass in a galaxy, and only a percent of the accreted rest-mass energy leaks into the gaseous environment of the BH, this slight leakage can unbind the entire gas reservoir of the host galaxy! This order-of-magnitude estimate explains why quasars are short lived. As soon as the central BH accretes large quantities of gas so as to significantly increase its mass, it releases large amounts of energy that would suppress further accretion onto it. In short, the BH growth is self-regulated.

The principle of self-regulation naturally leads to a correlation between the final BH mass, \( M_{\text{bh}} \), and the depth of the gravitational potential well to which the surrounding gas is confined, \( \sim \sigma_\star^2 \). Indeed such a correlation is observed in the present-day universe [3]. The observed power-law relation between \( M_{\text{bh}} \) and \( \sigma_\star \) can be generalized to a correlation between the BH mass and the circular velocity of the host halo, \( v_c \) [4], which in turn can be related to the halo mass, \( M_{\text{halo}} \), and redshift, \( z \) [16].

\[
M_{\text{bh}}(M_{\text{halo}}, z) = \text{const} \times v_c^5
\]

\[
= \epsilon_0 M_{\text{halo}} \left( \frac{M_{\text{halo}}}{10^{12} M_\odot} \right)^{\frac{5}{2}} \left( \frac{\zeta(z)}{1+2z} \right)^{\frac{5}{2}}
\]

where \( \epsilon_0 \approx 10^{-5.7} \) is a constant, \( \zeta(z) \) is close to unity and defined as \( \zeta \equiv [((\Omega_m/\Omega_m^0)(\Delta_c/18\pi^2)), \Omega_m^0 \equiv [1+(\Omega_\Lambda/\Omega_m)(1+z)^{-3}]^{-1}, \Delta_c = 18\pi^2 + 82d - 39d^2, \) and \( d = \Omega_m - 1 \) (see equations 22–25 in Ref. [5] for the relation between \( v_c \) and \( M_{\text{halo}} \)). If quasars shine near their Eddington limit as suggested by observations of low and high-redshift quasars [6,7], then the above value of \( \epsilon_0 \) implies that a fraction of \( \sim 5–10\% \) of the energy released by the quasar over a galactic dynamical time needs to be captured in the surrounding galactic gas in order for the BH growth to be self-regulated [16].

With this interpretation, the \( M_{\text{bh}}-\sigma_\star \) relation reflects the limit introduced to the BH mass by self-regulation; deviations from this relation are inevitable during episodes of BH growth or as a result of mergers of galaxies that have no cold gas in them. A physical scatter around this upper envelope could also result from variations in the efficiency by which the released BH energy couples to the surrounding gas.

Various prescriptions for self-regulation were sketched by Silk & Rees [12]. These involve either energy or momentum-driven winds, where the latter type is a factor of \( \sim v_c/c \) less efficient [13,14,15]. Wyithe & Loeb [16] demonstrated...
that a particularly simple prescription for an energy-driven wind can reproduce the luminosity function of quasars out to highest measured redshift, $z \sim 6$ (see Figs. 1 and 2), as well as the observed clustering properties of quasars at $z \sim 3$ [17] (see Fig. 3). The prescription postulates that: (i) self-regulation leads to the growth of $M_{bh}$ up the redshift-independent limit as a function of $v_c$ in Eq. (1), for all galaxies throughout their evolution; and (ii) the growth of $M_{bh}$ to the limiting mass in Eq. (1) occurs through halo merger episodes during which the BH shines at its Eddington luminosity (with the median quasar spectrum) over the dynamical time of its host galaxy, $t_{dyn}$. This model has only one adjustable parameter, namely the fraction of the released quasar energy that couples to the surrounding gas in the host galaxy. This parameter can be fixed based on the $M_{bh} - \sigma_*$ relation in the local universe [4]. It is remarkable that the combination of the above simple prescription and the standard $\Lambda$CDM cosmology for the evolution and merger rate of galaxy halos, lead to a satisfactory agreement with the rich data set on quasar evolution over cosmic history.
The cooling time of the heated gas is typically longer than its dynamical time and so the gas should expand into the galactic halo and escape the galaxy if its initial temperature exceeds the virial temperature of the galaxy. The quasar remains active during the dynamical time of the initial gas reservoir, \( \sim 10^7 \) years, and fades afterwards due to the dilution of this reservoir. Accretion is halted as soon as the quasar supplies the galactic gas with more than its binding energy. The BH growth may resume if the cold gas reservoir is replenished through a new merger.

**Fig. 2.** The comoving density of supermassive BHs per unit BH mass (from [13]). The grey region shows the estimate based on the observed velocity distribution function of galaxies in Ref. [18] and the \( M_{bh} - v_c \) relation in Eq. (1). The lower bound corresponds to the lower limit in density for the observed velocity function while the grey lines show the extrapolation to lower densities. We also show the mass function computed at \( z = 1, 3 \) and 6 from the Press-Schechter [19] halo mass function and Eq. (1), as well as the mass function at \( z \sim 2.35 \) and \( z \sim 3 \) implied by the observed density of quasars and a quasar lifetime of order the dynamical time of the host galactic disk, \( t_{dyn} \) (dot-dashed lines).

Agreement between the predicted and observed correlation function of quasars (Fig. 3) is obtained only if the BH mass scales with redshift as in Eq. (1) and the quasar lifetime is of the order of the dynamical time of the host galactic disk [17].

\[
t_{dyn} = 10^7 \left[ \xi(z) \right]^{-1/2} \left( \frac{1 + z}{3} \right)^{-3/2} \text{yr.} \tag{2}
\]

The inflow of cold gas towards galaxy centers during the growth phase of the BH would naturally be accompanied by a burst of star formation. The fraction of gas that is not consumed by stars or ejected by supernovae, will continue to feed the BH. It is therefore not surprising that quasar and starburst activities
co-exist in Ultra Luminous Infrared Galaxies \cite{21}, and that all quasars show broad metal lines indicating a super-solar metallicity of the surrounding gas \cite{22}. Applying a similar self-regulation principle to the stars, leads to the expectation \cite{10,23} that the ratio between the mass of the BH and the mass in stars is independent of halo mass (as observed locally \cite{24}) but increases with redshift as \( \propto \xi(z)^{1/2}(1+z)^{3/2} \). A consistent trend has indeed been inferred in an observed sample of gravitationally-lensed quasars \cite{25}.

![Fig. 3. Predicted correlation function of quasars at various redshifts in comparison to the 2dF data \cite{20} (from \cite{17}). The dark lines show the correlation function predictions for quasars of various apparent B-band magnitudes. The 2dF limit is \( B \sim 20.85 \). The lower right panel shows data from entire 2dF sample in comparison to the theoretical prediction at the mean quasar redshift of \( \langle z \rangle = 1.5 \). The \( B = 20.85 \) prediction at this redshift is also shown by thick gray lines in the other panels to guide the eye. The predictions are based on the scaling \( M_{bh} \propto v_s^2 \) in Eq. \ref{eq:scaling}.](image-url)
The upper mass of galaxies may also be regulated by the energy output from quasar activity. This would account for the fact that cooling flows are suppressed in present-day X-ray clusters [26,27,28], and that massive BHs and stars in galactic bulges were already formed at $z \sim 2$. The quasars discovered by the Sloan Digital Sky Survey (SDSS) at $z \sim 6$ mark the early growth of the most massive BHs and galactic spheroids. The present-day abundance of galaxies capable of hosting BHs of mass $\sim 10^9 M_\odot$ (based on Eq. 1) already existed at $z \sim 6$ [29]. At some epoch, the quasar energy output may have led to the extinction of cold gas in these galaxies and the suppression of further star formation in them, leading to an apparent “anti-hierarchical” mode of galaxy formation where massive spheroids formed early and did not make new stars at late times. In the course of subsequent merger events, the cores of the most massive spheroids acquired an envelope of collisionless matter in the form of already-formed stars or dark matter [29], without the proportional accretion of cold gas into the central BH. The upper limit on the mass of the central BH and the mass of the spheroid is caused by the lack of cold gas and cooling flows in their X-ray halos. In the cores of cooling X-ray clusters, there is often an active central BH that supplies sufficient energy to compensate for the cooling of the gas [27,26,13]. The primary physical process by which this energy couples to the gas is still unknown.

2 Feedback on Large Intergalactic Scales

Aside from affecting their host galaxy, quasars disturb their large-scale cosmological environment. Powerful quasar outflows are observed in the form of radio jets [30] or broad-absorption-line winds [31]. The amount of energy carried by these outflows is largely unknown, but could be comparable to the radiative output from the same quasars. Furlanetto & Loeb [32] have calculated the intergalactic volume filled by such outflows as a function of cosmic time (see Fig. 4). This volume is likely to contain magnetic fields and metals, providing a natural source for the observed magnetization of the metal-rich gas in X-ray clusters [33] and in galaxies [34]. The injection of energy by quasar outflows may also explain the deficit of Lyα absorption in the vicinity of Lyman-break galaxies [35,36] and the required pre-heating in X-ray clusters [37,27].

Beyond the reach of their outflows, the brightest SDSS quasars at $z > 6$ are inferred to have ionized exceedingly large regions of gas (tens of comoving Mpc) around them prior to global reionization (see Fig. 5 and Refs. [38,43]). Thus, quasars must have suppressed the faint-end of the galaxy luminosity function in these regions before the same occurred throughout the universe. The recombination time is comparable to the Hubble time for the mean gas density at $z \sim 7$ and so ionized regions persist [39] on these large scales where inhomogeneities are small. The minimum galaxy mass is increased by at least an order of magnitude to a virial temperature of $\sim 10^5 K$ in these ionized regions [5]. It would be particularly interesting to examine whether the faint end ($\sigma_* < 30 \text{km s}^{-1}$) of
Fig. 4. The global influence of magnetized quasar outflows on the intergalactic medium (from [32]). Upper Panel: Predicted volume filling fraction of magnetized quasar bubbles $F(z)$, as a function of redshift. Lower Panel: Ratio of normalized magnetic energy density, $\bar{u}_B/\epsilon_{-1}$, to the fiducial thermal energy density of the intergalactic medium $u_{fid} = 3n(z)kT_{IGM}$, where $T_{IGM} = 10^4$ K, as a function of redshift (see [32] for more details). In each panel, the solid curves assume that the blast wave created by quasar outflows is nearly (80%) adiabatic, and that the minimum halo mass of galaxies, $M_{h,\text{min}}$, is determined by atomic cooling before reionization and by suppression due to galactic infall afterwards (top curve), $M_{h,\text{min}} = 10^9 M_\odot$ (middle curve), and $M_{h,\text{min}} = 10^{10} M_\odot$ (bottom curve). The dashed curve assumes a fully-radiative blast wave and fixes $M_{h,\text{min}}$ by the thresholds for atomic cooling and infall suppression. The vertical dotted line indicates the assumed redshift of complete reionization, $z_r = 7$.

The luminosity function of dwarf galaxies shows any modulation on large-scales around rare massive BHs, such as M87.

To find the volume filling fraction of relic regions from $z \sim 6$, we consider a BH of mass $M_{bh} \sim 3 \times 10^9 M_\odot$. We can estimate the co-moving density of
BHs directly from the observed quasar luminosity function and our estimate of quasar lifetime. At $z \sim 6$, quasars powered by $M_{bh} \sim 3 \times 10^9 M_{\odot}$ BHs had a comoving density of $\sim 0.5 \text{Gpc}^{-3} \[16\]. However, the Hubble time exceeds $t_{\text{dyn}}$ by a factor of $\sim 2 \times 10^2$ (reflecting the square root of the overdensity in cores of galaxies), so that the comoving density of the bubbles created by the $z \sim 6$ BHs is $\sim 10^2 \text{Gpc}^{-3}$ (see Fig. 2). The density implies that the volume filling fraction of relic $z \sim 6$ regions is small, $< 10\%$, and that the nearest BH that had $M_{bh} \sim 3 \times 10^9 M_{\odot}$ at $z \sim 6$ (and could have been detected as an SDSS quasar then) should be at a distance $d_{bh} \sim (4\pi/3 \times 10^2)^{1/3} \text{Gpc} \sim 140 \text{Mpc}$ which is almost an order-of-magnitude larger than the distance of M87, a galaxy known to possess a BH of this mass \[44\].

What is the most massive BH that can be detected dynamically in a local galaxy redshift survey? SDSS probes a volume of $\sim 1 \text{Gpc}^3$ out to a distance $\sim 30$ times that of M87. At the peak of quasar activity at $z \sim 3$, the density of the brightest quasars implies that there should be $\sim 100$ BHs with masses of $3 \times 10^9 M_{\odot}$ per Gpc$^3$, the nearest of which will be at a distance $d_{bh} \sim 130 \text{Mpc}$, or $\sim 7$ times the distance to M87. The radius of gravitational influence of the BH scales as $M_{bh}/v^2 \propto M_{bh}^{3/5}$. We find that for the nearest $3 \times 10^9 M_{\odot}$ and $3 \times 10^{10} M_{\odot}$ BHs, the angular radius of influence should be similar. Thus, the dynamical signature of $\sim 3 \times 10^{10} M_{\odot}$ BHs on their stellar host should be detectable.

### 3 What seeded the growth of the supermassive black holes?

The BHs powering the bright SDSS quasars possess a mass of a few $\times 10^9 M_{\odot}$, and reside in galaxies with a velocity dispersion of $\sim 500 \text{km s}^{-1} \[45\]. A quasar radiating at its Eddington limiting luminosity, $L_E = 1.4 \times 10^{46} \text{erg s}^{-1}(M_{bh}/10^9 M_{\odot})$, with a radiative efficiency, $\epsilon_{\text{rad}} = L_E/Mc^2$ would grow exponentially in mass as a function of time $t$, $M_{bh} = M_{\text{seed}} \exp\{t/t_E\}$ on a time scale, $t_E = 4.1 \times 10^7 \text{yr} (\epsilon_{\text{rad}}/0.1)$. Thus, the required growth time in units of the Hubble time $t_{\text{hubble}} = 9 \times 10^8 \text{yr} (1+z)/7\]^{-3/2}$ is

$$t_{\text{growth}} = 0.7 \left( \frac{\epsilon_{\text{rad}}}{10\%} \right) \left( \frac{1+z}{7} \right)^{3/2} \ln \left( \frac{M_{bh}/10^9 M_{\odot}}{M_{\text{seed}}/100 M_{\odot}} \right). \tag{3}$$

The age of the universe at $z \sim 6$ provides just sufficient time to grow an SDSS BH with $M_{bh} \sim 10^9 M_{\odot}$ out of a stellar mass seed with $\epsilon_{\text{rad}} = 10\% \[10\]$. The growth time is shorter for smaller radiative efficiencies, as expected if the seed originates from the optically-thick collapse of a supermassive star (in which case $M_{\text{seed}}$ in the logarithmic factor is also larger).

What was the mass of the initial BH seeds? Were they planted in early dwarf galaxies through the collapse of massive, metal free (Pop-III) stars (leading to $M_{\text{seed}}$ of hundreds of solar masses) or through the collapse of even more massive, i.e. supermassive, stars \[47\]? Bromm & Loeb \[48\] have shown through a hydrodynamical simulation (see Fig. 3) that supermassive stars were likely to
Fig. 5. Quasars serve as probes of the end of reionization. The measured size of the HII regions around SDSS quasars can be used to demonstrate that a significant fraction of the intergalactic hydrogen was neutral at $z \sim 6.3$ or else the inferred size of the quasar HII regions would have been much larger than observed (assuming typical quasar lifetimes). Also, quasars can be used to measure the redshift at which the intergalactic medium started to transmit Lyα photons. The upper panel illustrates how the line-of-sight towards a quasar intersects this transition redshift. The resulting Lyα transmission of the intrinsic quasar spectrum is shown schematically in the lower panel.

Form in early galaxies at $z \sim 10$ in which the virial temperature was close to the cooling threshold of atomic hydrogen, $\sim 10^4$K. The gas in these galaxies condensed into massive $\sim 10^8 M_\odot$ clumps (the progenitors of supermassive stars), rather than fragmenting into many small clumps (the progenitors of stars), as it does in environments that are much hotter than the cooling threshold. This formation channel requires that a galaxy be close to its cooling threshold and immersed in a UV background that dissociates molecular hydrogen in it. These
Fig. 6. SPH simulation of the collapse of an early dwarf galaxy with a virial temperature just above the cooling threshold of atomic hydrogen and no H\textsubscript{2} (from [48]). The image shows a snapshot of the gas density distribution at \( z \approx 10 \), indicating the formation of two compact objects near the center of the galaxy with masses of \( 2.2 \times 10^6 M_\odot \) and \( 3.1 \times 10^6 M_\odot \), respectively, and radii < 1 pc. Sub-fragmentation into lower mass clumps is inhibited as long as molecular hydrogen is dissociated by a background UV flux. These circumstances lead to the formation of supermassive stars [47] that inevitably collapse and trigger the birth of supermassive black holes [47,49]. The box size is 200 pc.

requirements should make this channel sufficiently rare, so as not to overproduce the cosmic mass density of supermassive BH.

The minimum seed BH mass can be identified observationally through the detection of gravitational waves from BH binaries with Advanced LIGO [51] or with LISA [50]. Most of the mHz binary coalescence events originate at \( z > 7 \) if the earliest galaxies included BHs that obey the \( M_{\text{BH}}-v_c \) relation in Eq. 1. The number of LISA sources per unit redshift per year should drop substantially after reionization, when the minimum mass of galaxies increased due to photoionization heating of the intergalactic medium. Studies of the highest redshift sources among the few hundred detectable events per year, will provide unique information about the physics and history of BH growth in galaxies [52].

The early BH progenitors can also be detected as unresolved point sources, using the future James Webb Space Telescope (JWST). Unfortunately, the spec-
trum of metal-free massive and supermassive stars is the same, since their surface temperature $\sim 10^5$K is independent of mass. Hence, an unresolved cluster of massive early stars would show the same spectrum as a supermassive star of the same total mass.

In closing, it is difficult to ignore the possible environmental impact of quasars on anthropic selection. One may wonder whether it is not a coincidence that our Milky-Way Galaxy has a relatively modest BH mass of only a few million solar masses in that the energy output from a much more massive (e.g. $\sim 10^9 M_{\odot}$) black hole would have disrupted the evolution of life on our planet. A proper calculation remains to be done (as in the context of nearby Gamma-Ray Bursts) in order to demonstrate any such link.

Acknowledgements. I thank the collaborators who inspired my work on this subject: Rennan Barkana, Volker Bromm, Steve Furlanetto, Zoltan Haiman, and Stuart Wyithe. This work was supported in part by NASA grant NAG 5-13292, and by NSF grants AST-0071019, AST-0204514.

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