AGN sub-populations important for black hole mass growth: a rule of thumb

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Abstract

For building the super-massive black hole population within a Hubble time, only sub-populations with more than $10^{52}$ erg/s/$\mathcal{L}$ objects on the sky are relevant, where $\mathcal{L}$ is the sample-averaged bolometric luminosity.

BUILDING MASS

To build a super-massive black hole with $M_\bullet = 10^8 M_\odot$ within the age of the Universe $\Delta t$ requires an average accretion luminosity of $\mathcal{L}_{\text{bol}} = 5 \times 10^{43}$ erg/s, assuming the usual luminosity efficiency conversions ($L_{\text{bol}} = \frac{\epsilon}{1-\epsilon} M \dot{c}^2$, $\epsilon = 10\%$). This is slightly above the common threshold for what is considered an active galactic nucleus (AGN), $L_X > 10^{42}$ erg/s, with the bolometric conversion $L_X (2-10\text{keV}) \approx L_{\text{bol}}/10$ (e.g., Marconi et al. 2004). Smaller black holes $M_\bullet = 10^4 M_\odot$ can be assembled with $\mathcal{L}_{\text{bol}} = 5 \times 10^{39}$ erg/s.

In considering the average luminosity, it is not necessary to assume a constant luminosity over $\Delta t$. Indeed, the accretion rate may be fluctuating over many orders of magnitude over long time-scales (e.g. Sartori et al. 2019), and most galaxies are not AGN. This means that if the black hole is active only in brief phases, the observed luminosities need to be higher to reach the same average luminosity.

BUILDING MASS DENSITY

In the local Universe, the mass density locked into black holes is estimated to be $\rho_\bullet \approx 5 \times 10^5 M_\odot/\text{Mpc}^3$ (e.g., Marconi et al. 2004). Which sub-populations of AGN contribute substantially (> 10%) to black hole growth history? Ten per cent ($50,000 M_\odot/\text{Mpc}^3$) corresponds to an average luminosity density over the age of the Universe $\Delta t$ of:

$$10\% \times \frac{\rho_\bullet}{\Delta t} \times \left(\frac{\epsilon}{1-\epsilon} c^2\right) = \frac{\mathcal{L} \times \varphi}{\mathcal{L}} = 2 \times 10^{40} \text{erg/s/Mpc}^3$$

For a substantial contribution (eq. 1), sources need to be luminous but also numerous. They need to be numerous to enable a high on-time (duty cycle) of the accretion process, otherwise the luminosity averaged over cosmic time is small. The expected number of AGN on the entire sky can be estimated by $N = V_c \times \mathcal{L}$, as the number density of AGN strongly declines above $z = 3$ (e.g., Georgakakis et al. 2015). This gives the rule of thumb that samples that contribute more than 10 percent of black hole growth need to have at least $10^{52}$ erg/s/$\mathcal{L}$ sources in the Universe.

EXAMPLES

Let’s first consider the most extreme AGN. For hot dust-obscured galaxies (DOGs, Tsai et al. 2015), $\mathcal{L} = 10^{48}$ erg/s. Therefore, $\mathcal{L} = 10^{-8}$ Mpc$^{-3}$, which means on the entire sky, at least $N = V_c \times \mathcal{L} = 10^4$ objects need to be seen for this population to be significant. However, only a few hundred objects were found, indicating that hot DOGs are not an important black hole mass growth phase. This can be either because hot DOGs are created too rarely, or because the phase is too brief.

Considering a more moderate luminosity, $\mathcal{L} = 10^{46}$ erg/s, such as for merger-induced red quasars (e.g., Urrutia et al. 2008), then $\mathcal{L} = 10^{-6}$ Mpc$^{-3}$, which means on the entire sky, at least $N = 10^6$ objects, or 24 objects per square degree, are required. However, only a few hundred objects have been found, suggesting that major merger phases are too rare to contribute substantially to black hole growth.

Finally, let us consider the redshift interval where substantial growth occurs. Figure 1 plots the accretion history inferred from the X-ray luminosity function of Buchner et al. (2015, slope-constant machine-learned space density.
Figure 1. Top panel: Black hole accretion history inferred from X-ray luminosity functions, including Compton-thick growth. Bottom panel: accumulated mass density over cosmic time. The gray error bars are local densities estimates are from Marconi et al. (2004) and Shankar et al. (2004). Most black hole growth occurs after the first and before the last 2 Gyrs.

model), and includes unobscured, mildly obscured and the most heavily obscured AGN population. The top panel illustrates that in the local Universe, the current accretion rate density is an order of magnitude lower than at its peak at cosmic noon, where it was $6 \times 10^{41}$ erg/s/Mpc$^3$/Gyr. For this reason, the growth accumulated (bottom panel) in the last 2 Gyrs (since $z < 0.3$) is small and amounts to less than 5 per cent. The growth in the first Gyr is also negligible.

CLOSING WORDS

While extreme and rare sub-populations may not contribute substantially to black hole growth, they are laboratories that expose extreme physical processes most clearly. However, when super-massive black hole mass assembly is considered, sub-populations with more than $10^{52}$ erg/s/L objects on the sky, and $L > 5 \times 10^{39}$ erg/s are required.

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