Theoretical models of high redshift quasars and AGN

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Model description

We investigate the formation and evolution of black holes via cosmological realizations of the merger hierarchy of dark matter halos from early times to the present in a ΛCDM cosmology. The main features of the by now fairly standard SMBH evolution models that are used to interpret the data have been discussed in detail elsewhere[2–4]. We briefly outline some of the key features here. In this work, two "seed" formation models are considered : those deriving from population-III star remnants (Pop III), and from direct collapse models (D.C.). The main difference between these two models lies in the mass function of seeds. Pop III seeds are light weight (few hundred solar masses) and form abundantly and early (roughly one per comoving cubic Mpc at $z \simeq 20$). D.C. seeds are more massive ($10^4 - 10^6$ solar masses), but rarer (a peak density of 0.1 per comoving cubic Mpc at $z \simeq 12$). We summarize below the relevant and standard assumptions that go into our modeling of SMBH growth.

Essentially in this scheme central SMBHs hosted in galaxies accumulate mass via accretion episodes that are triggered by galaxy mergers. Accretion proceeds in one of two modes: self-regulated or un-regulated. For each SMBH in our models we know its mass at the time when the merger starts ($M_{\rm in}$), and we set the final mass through the self-regulated or unregulated prescription. These two models differ by the amount of mass a SMBH accretes during a given accretion phase. In the context of the currently supported paradigm for structure formation, growth of structure in the Universe occurs hierarchically and via copious merging activity. Our models rely on the following assumptions:

• SMBHs in galaxies undergoing a major merger (i.e., having a mass ratio >1:10) accrete mass and become active.

• In the self-regulated model, each SMBH accretes an amount of mass, corresponding to 90% of the mass predicted by the local $M_{\rm BH} - \sigma$ relation[5],

$$M_{\rm fin} = M_{\rm in} + 0.9 \times 1.3 \times 10^8 \left(\frac{\sigma}{200\,{\rm km\,s^{-1}}}\right)^{4.24} M_\odot; \qquad (1)$$

the 90% normalization was chosen to take into account the contribution of mergers, without largely exceeding the mass given by the $M_{\rm BH} - \sigma$ relation for SMBHs at $z = 0$. Here σ is the velocity dispersion of the host after the merger. We adopt $\sigma = V_c/\sqrt{3}$, where V_c is the virial velocity of the host dark matter halo[6,7]. A SMBH is assumed to stop accreting once it reaches the value given by the $M_{\rm BH} - \sigma$ relation.

•In the unregulated mode ($\times 2$) we simply set $M_{\rm fin} = 2 \times M_{\rm in}$, that is, we double the mass during each accretion episode.

• The rate at which mass is accreted scales with the Eddington rate ($f_{\rm Edd}$) for the SMBH, where $f_{\rm Edd}$ is the accretion rate in units of the Eddington rate. We adopt $f_{\rm Edd} = 0.3$ for D.C. models and $f_{\rm Edd} = 1$ for Pop III models in order to reproduce the mass density at $z = 0$. As Pop III seeds are lighter, they need to accrete more mass over the course of their cosmic history to become supermassive.

• The lifetime of an AGN depends on how much mass it accretes during each episode. Given the initial mass of a SMBH, $M_{\rm in}$, and the amount of mass it accretes, we can calculate its final mass, $M_{\rm fin}$, at the end of the active phase (Equation 4). For a given Eddington fraction, $f_{\rm Edd}$, the mass of the SMBH grows with time as:

$$M_{\rm fin} = M_{\rm in} \exp\left(f_{\rm Edd}\frac{1-\epsilon}{\epsilon}\frac{t}{t_{\rm Edd}}\right) \qquad (2)$$

where ϵ is the radiative efficiency ($\epsilon \simeq 0.1$), $t_{\rm Edd} = M_{\rm BH}c^2/L_{\rm Edd} = \frac{\sigma_T\, c}{4\pi\, G\, m_p} \simeq 0.45$ Gyr (c is the speed of light, σ_T is the Thomson cross section, m_p is the proton mass). Given $M_{\rm in}$ and $M_{\rm fin}$, then a SMBH is active for a time $t_{\rm AGN} = \frac{t_{\rm Edd}}{f_{\rm Edd}}\frac{\epsilon}{1-\epsilon}\ln(M_{\rm fin}/M_{\rm in})$. Note that the unregulated prescription (a SMBH mass doubles at each accretion episode) corresponds to assuming that all SMBHs shine as AGN for the same time at a fixed accretion rate (e.g., 100 Myr for an accretion rate $f_{\rm Edd} = 0.3$).

In summary, we study and compare two self-regulated models (Pop III, $f_{\rm Edd} = 1$; D.C., $f_{\rm Edd} = 0.3$) and two unregulated models (Pop III, $f_{\rm Edd} = 1$, $\times 2$; D.C., $f_{\rm Edd} = 0.3$, $\times 2$). We calculate number counts imposing selection criteria that match the observations we have analyzed. The limiting luminosity is 4.2×10^{41} erg s^{-1} for the stacked sample, i.e., if all the galaxies are emitting at this limit then we should detect them in the stack. For a single source, the more appropriate limit is this value multiplied by the number of sources in the stack, which is equivalent to a single source contributing all the signal. In that case, the luminosity limit is 3.1×10^{43} erg s^{-1} and the flux limit is 4.95×10^{-17} erg cm^{-2} s^{-1}. In that case, the source will be individually detected. We therefore select all accreting black holes in the theoretical sample at $z > 6$ that meet this flux criterion. From the Eddington ratio we calculate the bolometric luminosity and then apply a K-correction of 25 to derive the X-ray flux at the appropriate redshift. To ease comparisons with future, deeper, datasets we include also number counts with a flux limit 10^{-17} erg cm^{-2} s^{-1}

References

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