A Strong Case for Supermassive Stars in the Early Universe

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Since the detection of supermassive black holes (SMBH) a decade ago, it has been a challenge to explain how they have reached masses greater than 10^9 solar masses (M⊙) less than a billion years after the Big Bang. Drawing on a growing body of theoretical and observational evidence, we argue that the "seed" black holes (BH) from which they grew must have had masses of at least ~ 10^5 -M⊙, consistent with their formation by direct collapse in primitive galaxies. Corroborating this, some of the most realistic large-scale cosmological simulations to date show that massive SMBH seeds could have formed much more often in the early universe than previously assumed. We conclude that these may have been the origin of most SMBHs in the centers of galaxies today and that they may soon be detected in upcoming deep surveys by the James Webb Space Telescope (JWST).

Over the past decade, observations have revealed that quasars powered by the accretion of gas onto SMBHs are assembled at very early times in cosmic history. The most distant quasar known, at a redshift z~7, has been recently inferred to harbor a SMBH with a mass of ~2×10^9 M⊙ [1]. How such a BH grew to such masses less than 800 million years after the Big Bang remains a mystery. There are two main competing theories for the origin of SMBHs [2]. The first posits that an initial ~100-M⊙ "seed" BH formed from the collapse of primordial (or Pop III) stars that formed in primordial gas ~200 million years after the Big Bang. The second posits that a much more massive, ~10^5-M⊙ seed BH formed during the catastrophic collapse of gas at the centers of primitive galaxies ~500 million years after the Big Bang. Once formed, these seeds are thought to rapidly accrete gas and grow into the SMBHs that power the z~7 quasars.

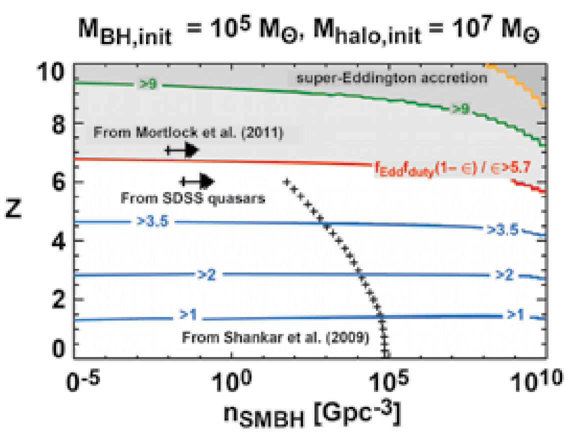

Fig. 1. The rate and radiative efficiency of accretion onto various BH seeds needed to produce SMBHs with masses >10^9 M⊙ with a space density >n_{SMBH} (horizontal axes) by redshift z (vertical axes) for two different scenarios for the initial BH seeds: 10^5 M⊙ BH formed in 10^7 M⊙ dark matter halos (top) and 10^2 M⊙ Pop III progenitors formed at earlier times in 10^5 M⊙ halos (bottom). The yellow, green and red contours correspond to radiative efficiencies ε = 0.07, 0.1, and 0.15, for the case of constant accretion at the Eddington rate; the three shaded regions show the cases in which super-Eddington growth is required, for these three radiative efficiencies. Also shown are the space densities of SMBHs with masses >10^9 M⊙ inferred from observations. These data are most easily explained if the seeds of the highest-redshift SMBHs formed from SMSs, instead of from Pop III seeds. This provides indirect evidence for the existence of SMSs in the early universe.

In both of these models, the BHs must accrete gas at or above the Eddington limit (the accretion rate at which pressure from the radiation in the accretion disk around the BH balances gravity) in order to grow quickly enough to explain the highest-redshift quasars. Not only this, but the radiative efficiency of the BH, defined as the fraction of the rest mass energy of accreted material that is converted to radiation in the accretion disk, must be low as well. Figure 1 shows the radiative efficiencies ε of the observed population of SMBHs with masses >10^9 -M⊙ that permit the formation of these behemoths in the two dominant BH seed theories (top and bottom panels). For Pop III seeds (bottom panel) Fig. 1 shows that the maximum allowed ε is ~0.07, while for massive SMBH seeds (top panel) the maximum ε is higher, ~0.1. These limits strongly favor the massive BH model as the most viable because ε for high-redshift SMBHs is generally inferred to be >0.1 [3]. In some cases, ε is thought to be as high as 0.3–0.4, which would imply accretion at rates exceeding the Eddington limit. In any case, however, the observational constraints are most easily satisfied by massive SMBH seeds because they can grow more quickly than less massive BHs.

Independent evidence for the formation of massive SMBH seeds by direct collapse comes from recent numerical simulations by independent research groups that suggest that these objects formed more frequently than previously assumed. It is generally thought that catastrophic gas collapse can only occur in protogalaxies immersed in very high molecule-dissociating UV backgrounds that suppress H_2 cooling until far more rapid atomic cooling begins [4,5]. It has been assumed in the past that these conditions are rarely met, since the stellar populations that would produce the large UV fluxes would also likely give rise to supernovae that would chemically enrich the primordial gas. However, recently the

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flux that is required to keep the protogalaxies molecule-free has been shown to be lower than previously expected [6,7]. In turn, as shown in Fig. 2, patches of the universe where primordial gas is subjected to such high UV fields have been found in the first large-scale cosmological simulations that model chemical enrichment by supernovae and the build-up of the molecule-dissociating radiation field self-consistently [8].

Semi-analytical models likewise suggest that massive SMBH seeds readily formed in the early universe [9,10]. As shown in Fig. 3, if the progenitors of these seeds were supermassive stars (SMS), there would be enough of them to be detected at redshifts $z > 6$ in deep-field surveys by the JWST for a variety of molecule-dissociating UV backgrounds. Indeed, enough SMSs may have formed at high redshifts to be the seeds of most of the SMBHs inferred to inhabit the centers of galaxies today [10].

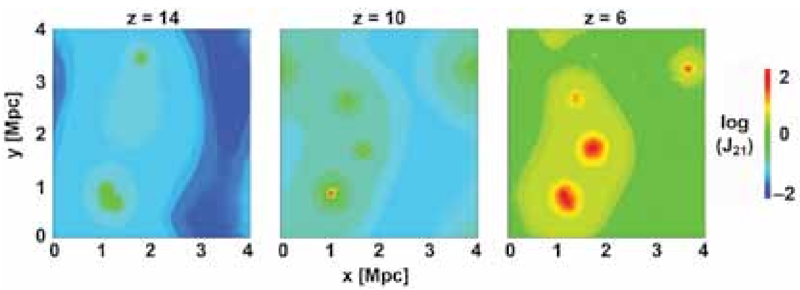

Fig. 2. The flux of molecule-dissociating radiation in units of J_{21} (10^{-21} erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}) generated by the stars formed in a (4 Mpc comoving)^3 cosmological simulation volume, at three redshifts: z = 14 (left), 10 (middle), and 6 (right). Massive SMBH seeds can form in regions that are not yet chemically enriched by supernova explosions and which are exposed to fluxes J_{21} > 30. Such regions are found to exist in recent cosmological simulations.

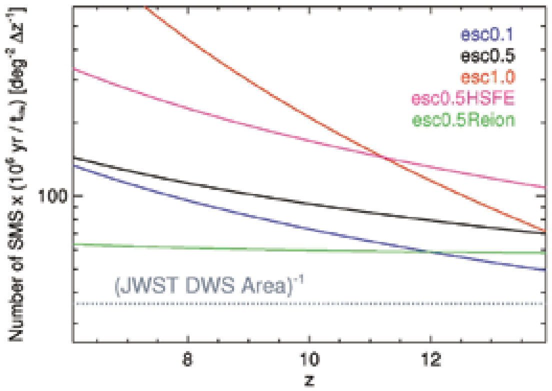

Fig. 3. The number of SMSs, as observed on the sky per square degree per redshift interval (Δz), as a function of redshift z. The number of SMSs is shown for five simulations in which different prescriptions have been used for star formation and radiative feedback. The dotted gray line shows the number of SMSs that must be present for at least one per redshift interval (Δz = 1) to appear in the field of view of the Deep-Wide Survey planned for the JWST. For all cases, the survey should be large enough to detect at least a few SMSs.

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