The Growth of the Stellar Seeds of Supermassive Black Holes

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The collapse of baryons into extremely massive stars with masses >10^4 M⊙ in a small fraction of protogalaxies in the early universe is a promising scenario for the origin of supermassive black holes (BH). We determine the maximum masses such stars can attain by the accretion of primordial gas before they collapse to BHs. We find that the strong ionizing radiation emitted by these stars limits their masses to ~10^3 M⊙ (R_{acc}/10^{-3} M⊙ $yr^{-1})^{8/7}$, where R_{acc} is the rate at which a star gains mass. However, at extremely high accretion rates, usually found in numerical simulations of protogalactic collapse (R_{acc} >0.1 M⊙ yr^{-1}), the lifetime of the star instead limits its final mass to ~10^6 M⊙. We predict that unique observational signatures of rapidly accreting supermassive stars may be detected by future missions such as the James Webb Space Telescope.

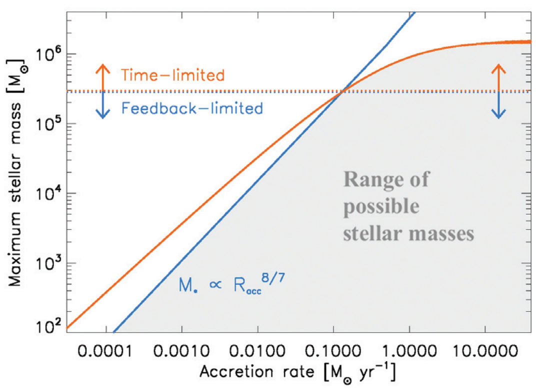

Fig. 1. The maximum mass to which a star can grow at a constant accretion rate R_{acc}. Above the maximum mass $M_* \propto R_{acc}^{8/7}$ (blue curve), radiative feedback shuts off accretion because ionizing radiation from the star transfers momentum to the gas and prevents it from reaching the stellar surface. However, for extremely high accretion rates R_{acc} > 0.1 M⊙ yr^{-1}, the maximum mass is set instead by the lifetime of the star (red curve), which is shortened due to the rapid rate at which nuclear fuel must be burned in order to support the star against its ever-increasing weight. As the red curve shows, this leads to a maximum stellar mass, at the highest accretion rates, of ~1.5 × 10^6 M⊙. The dotted horizontal line delineates the mass.

The origin of ~10^9 M⊙ black holes (BH) in massive galaxies at redshift z~7, less than a billion years after the Big Bang [1,2], is one of the great mysteries of cosmological structure formation. In the standard Lambda cold dark matter (ΔCDM) cosmological paradigm, early structure formation is hierarchical, with small dark-matter halos at early epochs evolving into ever more massive ones by accretion and mergers through cosmic time. Hence, it is generally held that supermassive black holes (SMBH) grow from much smaller seed BHs at high redshifts. The origin of these seeds, and how they reach such large masses by such early times, remains to be understood.

A promising scenario for the formation of SMBH seeds is the rapid collapse of primordial gas in protogalaxies into supermassive stars with masses >10^4 M⊙, which upon their deaths collapse to similarly massive BHs [3]. Such large initial masses may be necessary in order for the BHs to grow quickly enough to explain the presence of SMBHs in the very early universe [4]. Numerical simulations of this process [5–8] find that supermassive stars grow by accretion of gas at rates often exceeding ~0.1 M⊙yr^{-1}, orders of magnitude larger than is found for stars forming in the present-day universe.

We address a fundamental question: "What ultimately limits the growth of supermassive stars and thus sets the mass scale of seed BHs?" There are two processes that limit the mass to which such stars can grow, even at the highest accretion rates believed to take place in the early universe. The first of these is so-called radiative feedback from the star. Primordial stars, in particular, emit copious high-energy radiation that ionizes the gas surrounding them. When the high-energy photons from the star are absorbed, momentum is transferred to the gas and it receives a push away from the star. This is the process that we have found to be most effective at shutting off accretion [9]. In particular, by modeling how the dynamics of the accretion flow are altered by the radiation emitted from the growing star, we have found that the maximum mass M* that a primordial star can obtain by accreting gas at a constant rate R_{acc} is well approximated by M*~10^3 M⊙ (R_{acc}/10^{-3} M⊙ $yr^{-1})^{8/7}$. At higher accretion rates, the accretion flow is not stopped by the radiation from the star, and the star continues to grow; accretion at lower rates is not possible, as the radiation from the star prevents the gas from reaching the stellar surface. This maximum stellar mass is shown by the blue curve in Fig. 1. As the figure shows, the process of radiative feedback determines the final mass of stars that grow by accretion at rates R_{acc} <0.1 M⊙ yr^{-1}.

The second process that limits the growth of supermassive stars is their limited lifetime, which can be shorter than a million years, much shorter than the ~10-billion-year lifetime of most stars formed in the present-day universe. When the star exhausts its nuclear fuel its core collapses to a BH, which quickly swallows the entire star [10]. For a star to become supermassive it must therefore grow very quickly before

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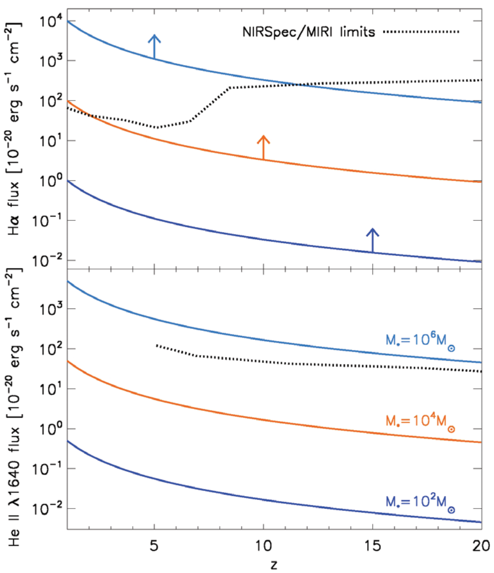

Fig. 2. The flux in Hα (top panel) and He II λ1640 (bottom panel) from rapidly accreting primordial stars, as a function of redshift z, for stellar masses of 10^2 (dark blue), 10^4 (red), and 10^6 M⊙ (light blue). The dotted black lines show flux limits for detection of these lines with the Near-Infrared Spectrograph (NIRSpec) and the Mid-Infrared Instrument (MIRI) on the JWST. NIRSpec operates at wavelengths of ≅1–5 µm, while MIRI covers the range from ≅5–28 µm. The Hα fluxes shown here are lower limits, as indicated by the arrows. While detection of Hα from stars with masses of >10^4 M⊙ may be possible out to redshifts z >10, only accreting primordial stars with masses of at least ~10^5 M⊙ are likely to be detectable in He II λ1640.

its time runs out. However, the faster the star grows, the more quickly it must burn its nuclear fuel in order to support its ever-increasing weight–the result being that the faster a star grows the shorter is its lifetime [11]. We find that this process results in a maximum possible stellar mass of ~1.5 x 10^6 M⊙ which is asymptotically approached at the highest accretion rates [9], as shown by the red curve in Fig. 1. As shown in the figure, this process sets the maximum mass of stars that grow by accretion at rates R_{acc} >0.1 M⊙yr^{-1}. As accretion rates in this range are found in cosmological simulations of the collapse of primordial protogalaxies, our findings suggest that there is nothing preventing the stellar seeds of supermassive black holes from forming with masses approaching ~10^6 M⊙.

Given that supermassive stars may indeed have been the seeds of SMBHs in the early universe, it is an important question whether or not these objects could be detected and identified observationally. In Fig. 2 we show the flux emitted from rapidly accreting primordial stars as a function of redshift z for three representative stellar masses: 10^2, 10^4, and 10^6 M⊙. In this figure we also show the flux limits for deep infrared surveys to be carried out by the James Webb Space Telescope (JWST) [12]. While the most luminous emission line predicted for primordial stars is the Lyman α line of atomic hydrogen [13], we find that this line is scattered so readily in the accretion flow that it cannot escape to be observed. Instead, this emission is likely reprocessed largely into Hα line emission from atomic hydrogen, which does escape and could be detected; shown in the top panel of Fig. 2 are lower limits for the flux in this line. In the bottom panel, we show the flux in the 1640 Angstrom emission line of ionized helium, which is predicted to be very strong from primordial stars. Together, the detection of Hα and He II 1640, along with the non-detection of Lyman α, are unique observational signatures of rapidly accreting supermassive primordial stars. As the figure shows, these signatures could be detected by the JWST from stars with masses of at least ~10^5 M⊙. This opens up the exciting possibility that in the coming years missions such as the JWST may reveal the nature of the earliest seeds of SMBHs.

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