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The effect of photoevaporation on the first stars

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Abstract. As the first stars accrete and grow to masses $\gtrsim$40 $M_\odot$, their EUV luminosities rapidly increase. The EUV ionizes and heats infalling gas and gas accreting through the circumstellar disk, and this feedback can terminate the accretion onto the star and fix its final mass. This contribution focuses on the halting of the accretion through the disk onto the star caused by the EUV-induced photoevaporation of the disk. We note that recent numerical simulations have found higher photoevaporation rates, and therefore lower mass first stars, than earlier semi-analytic estimates of the rates by Hollenbach et al (1994). We propose reasons for the difference, and suggest refinements on future numerical studies that may lead to somewhat higher masses for the first stars.

Key words. Stars: Population III – Stars: massive – Stars: formation – Stars: circumstellar matter– Cosmology: dark ages, reionization, first stars

1. Introduction

The mass of the first stars determines their fate and affects the subsequent evolution of the universe. Heger & Woosley (2002) review the fate of the first stars as a function of their mass. If their mass lies between $\sim$ 10 – 150 $M_\odot$, they undergo core collapse, supernova within a few Myr, and expel much of their mass and the first metals back into the interstellar medium for subsequent evolution into next generation stars. If their mass lies between $\sim$ 150 – 300 $M_\odot$, they undergo pair instability supernovae, with a resultant isotopic signature in the ejected gas that effects the relative abundances of odd and even nuclei (Heger & Woosley 2002). On the other hand, if they grow in mass to $\gtrsim$300 $M_\odot$, they would collapse into black holes and not return material back to the interstellar medium. Given our current universe, that does not appear to have happened!

However, the first condensations of dark matter and hydrogen and helium gas are predicted to produce $\gtrsim$1000 $M_\odot$ Jeans unstable gas cores at temperatures $\sim$ 300 K and hydrogen nuclei densities of $\sim 10^4$ cm^{-3} (Tan & McKee 2004, Yoshida et al 2006). What prevented most of these cores from completely collapsing and forming black holes? One answer to this question is that as the stars grow to masses $\gtrsim$40 $M_\odot$, the increasing EUV (extreme ultraviolet, $h\nu > 13.6$ eV) luminosities of these stars heat the surrounding gas to $T > 10^4$ K, reversing the infall or the accretion onto the star through the circumstellar disk, and therefore terminating accretion before the full $\sim$ 1000 $M_\odot$ core could be accreted onto the star (e.g., McKee & Tan 2008, Hosokawa et al 2011).

In this contribution I will review work on this feedback process in Section 2, discuss new higher rates for photoevaporation from accreting disks around the first stars in Section 3, and conclude with appeals for further numerical studies which may raise the predicted mass of the first stars.

2. EUV feedback on the growth of the first stars

I chose this topic in commemoration of Francesco Palla not only because of his published work on the first stars, but because in the period 2005-2007 he and I worked on the problem of the EUV photoevaporation of the accreting disks surrounding the first stars, and how this process could terminate accretion and determine the final mass of the star. At that time there were several theoretical calculations of the accretion rates $\dot{M}_{acc}$ onto the star/disk system (Abel et al 2002, Bromm & Loeb 2004, Tan & McKee 2004). They showed a somewhat declining rate with time, or with the growing mass of the central star. Assuming the accretion onto the star was fed by a gravitationally unstable disk, so that the accretion rate onto the disk roughly equaled the accretion rate onto the star, we compared $\dot{M}_{acc}$ with the EUV photoevaporation rate $\dot{M}_{evap}$ (Hollenbach, et al. 1994), which increased with time and stellar mass as the star got hotter and more luminous. Once these two rates were equal, photoevaporation would prevent further accretion onto the star. The unpublished result was that the mass of the first stars would be $M_* \sim 160\ \mathrm{M}_\odot$ (Bromm and Loeb 2004), 300 $\mathrm{M}_\odot$ (Abel et al 2002), or 500 $\mathrm{M}_\odot$ (Tan & McKee 2004), depending on the mass accretion rate evolution in the different models. However, our unpublished work only treated the photoevaporation of the disk around the star, and not the photoevaporation (or reversal of infall) of the material falling directly onto the star or disk.

McKee & Tan (2008), using analytical techniques, did treat the reversal of the infall in the non-shadowed regions. In effect, this lowered the accretion rate onto the star, as it now was only the shadowed infall that fed the disk which then fed the star. This lowered the required EUV photoevaporation rate of the disk necessary to terminate the accretion onto the star. They found, for their preferred accretion history, a typical first star mass of $\sim 140\ \mathrm{M}_\odot$.

Hosokawa, et al. (2011, 2016) presented the first detailed numerical hydrodynamical studies of the EUV feedback process on the first stars. The standard case in Hosokawa, et al. (2011) gave a characteristic mass $M_* \simeq 43\ \mathrm{M}_\odot$ for the first stars. This lower mass than previous work was caused by two effects: (i) an enhanced reversal of infall onto the star/disk system even in the shadowed regions, and (ii) an increase by a factor ~ 3 in the EUV photoevaporation rate from the accreting disk compared to the Hollenbach, et al. (1994) rates. The remainder of this contribution discusses the latter effect.

3. Discussion of EUV photoevaporation of circumstellar disks

The enhanced photoevaporation rate found by Hosokawa, et al. (2011) was further analyzed and discussed by Tanaka, et al. (2013). Tanaka, et al. (2013) did not treat the hydrodynamics, but focussed on a numerical study of the diffuse and direct components of the EUV radiation field and an analytic estimate of the EUV photoevaporation rate created by these components. Hollenbach, et al. (1994) had found that the direct radiation field from the star impinging on the neutral disk surface was heavily attenuated by the time the photons reached a cylindrical radius $r \sim r_g$, where

$$r_g \equiv \frac{GM_*}{c^2} \simeq 10^{16} \left(\frac{M_*}{100\ \mathrm{M}_\odot}\right)\left(\frac{10^4\ \mathrm{K}}{T}\right)\ \mathrm{cm}. \quad (1)$$

The parameter r_g is the "gravitational radius" where the thermal speed of the gas in the EUV heated disk atmosphere at temperature $T \sim 3 \times 10^4$ K is equal to the gravitational escape speed from the system. Inside this radius, the hot ionized gas was bound by the stellar gravity; outside this radius the hot surface gas photoevaporated. Here, c is the sound speed, and the neutral disk surface is assumed flat, either in the form of a thin disk in the equatorial plane or a radial surface emanating from the star at some angle (a wedge-shaped neutral disk). We will discuss later "flared disks", where the disk neutral surface curves upwards ($z \propto r^a$, where

$a > 1$). Hollenbach, et al. (1994) found that for $r < r_g$ the combination of direct and diffuse field maintained a base electron or proton density

$$n_{eb} = n_0 \left(\frac{\phi_i}{10^{49}\ \mathrm{s}^{-1}} \right)^{1/2} \left(\frac{r}{10^{15}\ \mathrm{cm}} \right)^{-3/2}, \qquad (2)$$

where ϕ_i is the EUV ionizing photon luminosity and n_0 is a normalization density (Hollenbach, et al. 1994 found $n_0 = 1.8 \times 10^7$ cm^{-3}). The base density n_{eb} is the density at the ionization front (IF) boundary marking the boundary of the hot EUV ionized HII envelope with the cooler neutral disk surface. However, because of attenuation of the direct flux and because of a diminishing diffuse field, for $r > r_g$ the base density dropped steeply. The result was that most of the photoevaporative mass loss came mostly from $r \sim r_g$.

However, Tanaka, et al. (2013) and Hosokawa, et al. (2011) found in their numerical simulations that the direct flux was not significantly attenuated out to the disk outer radius r_d, which was of order $10^{16} - 10^{17}$ cm in their computations, or about $10 r_g$. As a result, they found that the base density $n_{eb} \propto r^{-3/2}$ all the way out to r_d. In this case the evaporative mass loss rate goes as $\dot{M}_{evap} \propto n_{eb} c r^2 \propto r^{1/2}$ for $r > r_g$. Therefore, the mass loss rate was dominated by mass loss from the outer disk radius r_d, and since $r_d \sim 10 r_g$, the mass loss was about $10^{1/2} \sim 3$ times that in Hollenbach, et al. (1994).

For a flat disk surface as defined above (assumed by both Hollenbach, et al. 1994 and Tanaka, et al. 2013), the difference in the penetration of the direct flux from the star can be attributed to two causes: (i) the normalization n_0 of the base density, and (ii) the assumed inner disk radius r_i where the direct flux enters the attenuating hot disk atmosphere. Following the EUV photons as they skim along the disk surface, just above the ionization front, the Stromgren condition can be written

$$\phi_i = \int_{r_i}^{r_s} \alpha_B n_{eb}^2 4\pi r^2 dr, \qquad (3)$$

where α_B is the case B recombination coefficient that assumes that all diffuse EUV photons are absorbed locally. This case is not completely fulfilled along the disk surface, but any escaping diffuse photons would only make the effective recombination coefficient larger and r_s smaller. That is, we are attempting to determine the maximum distance r_s that EUV can penetrate before significant attenuation. Here, r_i is the radius where the stellar photons enter the dense ($n_e \sim n_{eb}$) ionized gas near the IF. Substituting Eq. (2) for n_{eb} into Eq. (3)

$$r_s = r_i \exp\left(- \frac{10^4}{4\pi \alpha_B n_0^2} \right), \qquad (4)$$

where α_B and n_0 are in cgs units. Note that since $n_{eb} \propto \phi_i^{1/2}$, the result for r_s is independent of ϕ_i. This is somewhat counterintuitive, since one might think that increased ϕ_i would drive further penetration and thus increase r_s. However, the increased ϕ_i increases the base density, which then increases the attenuation and leads to an r_s independent of ϕ_i.

Tanaka, et al. (2013) found a density normalization factor, n_0, that was about 10% smaller than Hollenbach, et al. (1994). This small difference, however, because it occurs in the exponent squared (see Eq. 4), creates a factor of ~ 3 difference in r_s. For Hollenbach, et al. (1994) $r_s \simeq 110 r_i$, whereas for Tanaka, et al. (2013) $r_s \simeq 400 r_i$. This demonstrates that numerical codes must use very fine grids near the disk surface to achieve sufficient accuracy on the base density n_{eb} (or equivalently, the normalization parameter n_0) to ensure proper attenuation of the direct flux. This continues to be true beyond r_g, as the numerical studies of Font et al (2004) have shown that, because of the acceleration of the photoevaporative flow and its radial divergence, the density drops rapidly with z above the surface.

The second difference in the two groups is the estimate of r_i. The scale height H of the isothermal EUV ionized disk atmosphere rises as $H \propto r^{3/2}$ for $r < r_g$. Above the scale height, the ionized density n_{eb} drops rapidly with z. Hollenbach, et al. (1994) followed EUV photons that skimmed the disk surface at about a stellar radius r_* above the surface and found that the EUV photons effectively enter the disk atmosphere (that is, they penetrate below a scale height) when $H(r_i) \simeq r_*$. This occurs at

$r_i \simeq 0.4$ AU for $M_* = 100\ \mathrm{M}_\odot$ stars. However, due to practical considerations when constructing a numerical grid, Hosokawa, et al. (2011) assume a sink cell of $r_i \gtrsim 10$ AU and Tanaka, et al. (2013) use $r_i \gtrsim 2$ AU. Because of the neglect of EUV attenuation inside these artificial boundaries, they find a much larger r_s since it is proportional to r_i (see Eq. 4).

Combining these two factors of n_0 and r_i explains the different results of the two groups. Hollenbach, et al. (1994) obtains (see Eq. 4) $r_s \simeq 44$ AU, which is less than r_g. Therefore, the evaporative flow is driven by the much weaker diffuse field beyond r_g, and the dominant mass loss occurs around r_g. However, Hosokawa, et al. (2011) and Tanaka, et al. (2013) would obtain $r_s \gtrsim 4000$ and 800 AU, respectively. This lies beyond their assumed disk radius r_d, so that direct flux can continue to drive $n_{eb} \propto r^{-3/2}$ flow all the way to r_d, and produce higher photoevaporation rates.

4. Conclusion and discussion

In this contribution I have tried to explain the difference between the semi-analytic results of Hollenbach, et al. (1994) concerning the photoevaporation of disks by their central stars, and the new numerical results of Hosokawa, et al. (2011) and Tanaka, et al. (2013). The discrepancy appears to be caused by the numerical codes neglect of the attenuation of the EUV flux from the central star by the hot atmosphere of the inner ($r < 2 - 10$ AU) disk, and by small differences in the base electron density. To solve this problem correctly requires numerical simulations, and Hosokawa, et al. (2011) and Tanaka, et al. (2013) have done groundbreaking work in this area. However, better spatial resolution near the disk surface, and the inclusion of a smaller ($r_i < 0.4$ AU) central hole might reduce their photoevaporation rates. This will raise the predicted masses of the first stars, but by no more than a factor of $\sim$ 3. Another important effect, not considered by Hollenbach, et al. (1994) or Tanaka, et al. (2013), is that the neutral disk surface may be flared, curving upwards. This would raise r_i and increase the penetration of the EUV photons, possibly to $> r_g$, and may recover the rates and the predicted first star masses of Hosokawa, et al. (2011) and Tanaka, et al. (2013). Finally, Hosokawa et al (2016) consider a more complicated scenario than posited here in this contribution. If instabilities cause variable accretion onto the first stars, the stars can remain puffed up and relatively cool, thereby lowering EUV photoevaporation, and allowing more massive (up to 1000 $\mathrm{M}_\odot$) first stars to form.

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