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The formation of primordial stars

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Abstract. Much of the recent attention on primordial stars has focussed on the properties of massive objects, considered the natural outcome of first structure formation. While there are reasons to believe that massive stars were common, but not unique, in the early universe, the question of their actual formation is still not adequately understood. This review discusses the observational and theoretical evidence in favor of massive stars and shows how unique must have been the physical conditions in primordial clouds to yield such an unusual distribution of stellar mass. The results of numerical models of protostellar accretion of massive stars are presented. Unlike the case of ordinary stars, metal-free objects can accrete substantial amount of mass ($\gg$10 $M_\odot$) before the effects of radiation pressure act to retard, or even reverse the flow of the infalling gas. However, it is still difficult to predict the characteristic IMF or upper mass limit of the first stars, owing to the sensitivity of the evolution on the details of the accretion history.

Key words. Cosmology – first stars – stellar evolution: accretion

1. Introduction

Talking about the first stars that formed in the expanding universe after recombination is an excting topic. After years of highly speculative research and debate, it appears that we are about to discover the birthplaces and properties of these elusive objects.

Observationally, two results stand out. First, the detection of broad, black Lyman-α absorption troughs in the spectrum of high redshift QSOs ($z \sim$6), as predicted by Gunn & Peterson (1965), indicates that it is possible to probe the epoch when the universe was completely reionized by the first stellar populations (Becker et al. 2001). Second, the recent discovery made by WMAP of a moderate optical depth to electron scattering ($\tau_e = 0.17 \pm 0.04$) indicates that the beginning of reionization started earlier than anticipated, at redshifts $\sim$15–20 (Kogut et al. 2003). Thus, it seems that the first stars begun to form when the universe had an age of only $\sim 2 \times 10^8$ yr after the Big Bang. The cosmological implications of early reionization are important, and a full discussion can be found in the contribution by A. Ferrara in this volume.

On the theoretical side, recent numerical studies are disclosing the physical state of star forming regions (SFRs) within the first cosmic structures. In the framework of cold dark matter cosmology (ΛCDM),

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smaller objects tend to collapse earlier: a moderately rare object of $\sim 3\sigma$ overdensity collapses and virializes at about $z \sim 30$. However, only sufficiently massive objects can cool in a Hubble time and become luminous by forming stars. The minimum cooling mass at $z \sim 30$ is $M_{\rm min} \sim 10^6$ $M_\odot$, and is a decreasing function of redshift (Tegmark et al. 1997) After virialization, objects more massive than $M_{\rm min}$ can collapse gravitationally owing to the cooling provided by H_2 molecules (Palla et al. 1983) and fragment into high density clumps. The mass scale of these clumps is predicted to be rather high, of the order of $\sim 10^3$ $M_\odot$ (Abel et al. 2000)(Bromm et al. 2002).

What is, then, the fate of these SFRs? Will they give birth to a collection of stars distributed in mass as in present-day molecular clouds? Or, would the conditions be appropriate for an unusual initial mass function, possibly skewed towards massive objects? The question of the characteristic mass spectrum is obviously a central one.

2. Population III stars: why massive?

The view that the first stars were predominantly massive has pervaded the field for many years. Larson (1998) has summarised the evidence in favor of a top-heavy early IMF and argued for a universal, Salpeter-like IMF at high masses and a flattening at low masses with a characteristic mass that increases at lower metallicity (or higher redshifts). Additional, indirect support to the notion of an early generation of massive stars comes from the following considerations.

2.1. Observations

- The evidence for a minimum metallicity of galactic halo stars at $Z_{\rm min} > 10^{-4} Z_\odot$ (Beers 2000);
- a minimum metal abundance in high-redshift Ly-α clouds at about $Z_{\rm IGM} > 10^{-4} Z_\odot$ (Cowie & Songaila 1998);
- the detection of excess power on large angular scales by WMAP, interpreted as the signature of early reionization at $z \sim 15$–20 (Kogut et al. 2003).

On the other hand, the recent discovery by Christlieb et al. (2002) of a halo star with metallicity well below $Z_{\rm min}$ (by a factor of about 20, $[Fe/H] = -5.3$), has shaken the paradigm and shown that low-mass stars have indeed been able to form in an environment not too different from that of the pristine gas. This important discovery also casts some doubts about the reality of a minimum metallicity in high-redshifts Ly-α clouds which could simply reflect some selection bias, with lower metallicity systems waiting to be detected. Finally, although robust, the WMAP result has a low statistical significance and needs confirmation from independent observations.

2.2. Theoretical Expectations

- The lack of metals and dust grains makes the primordial gas a poor radiator. The typical temperatures of the H_2 clouds were much higher than in present-day molecular clouds, by a factor 10–100 (Omukai 2000);
- in the absence of metals, the peak of the predicted IMF in the opacity limited fragmentation theory is shifted to about 4-10 $M_\odot$ (Silk 1977). Hydrodynamical models of collapsing clouds find similar values (Nakamura & Umemura 2002);
- the existence of a critical metallicity of $Z \sim 10^{-5} - 10^{-4} Z_\odot$ below which molecular clouds cannot fragment into low-mass clouds (Bromm et al. 2001), (Schneider et al. 2002);
- evolution of massive zero-metal stars indicates that only objects in a rather narrow mass interval, ~ 140–260 $M_\odot$, can contribute to the enrichment of the intergalactic medium (Heger et al. 2003). These stars end their lives as pair-unstable supernovae that leave no remnants, but release all the synthe-

sized metals. Above and below this mass range, stars are predicted to form black holes, with all the metals locked-up in their interior.

In conclusion, there appear to be good reasons to postulate the existence of massive and/or very massive stars. But did they actually form? And how? If primordial stars formed via the same process that is thought to dominate now, by accretion of molecular gas, then the requirement on the magnitude of the mass accretion rate is straightforward: it must have been unusually large to prevent radiation pressure effects to stop the flow early on in the evolution. In present-day clouds, typical accretion rates vary between $\dot{M}_{\rm acc} \sim 10^{-6}-10^{-5}$ $M_\odot$ yr^{-1}. For the formation of massive objects, $\dot{M}_{\rm acc}$ should have been at least 100 times higher. How were these peculiar conditions achieved? Even if that were indeed possible, what is the upper limit of the protostellar mass formed by fast accretion? Before discussing the results of detailed models of protostellar evolution that try to address these questions, let us take a brief detour on the properties of massive stars and the IMF in more mundane conditions.

3. Primordial stars: a unique environment

As we have said repeatedly, the primordial IMF is expected to be quite different from that at solar metallicity, with massive stars taking the lion's share. We may then ask whether there is evidence for a basic variation of the IMF as a function of metallicity in nearby SFRs. Since primordial SFRs cannot be probed directly by observations, it is important to gain some insight on how massive stars are formed in standard clouds. Given the lack of space, we can only address these important issues in a schematic fashion.

First, the IMF in our Galaxy does not seem to vary significantly from local regions, such as Orion, to more chaotic environs, such as the very rich clusters in the galactic center (Kroupa 2002). Also, the low-mass end of the IMF of galactic globular clusters has a remarkably similar shape and characteristic mass independent of the cluster metallicity down to $[Fe/H] \sim -2.2$ (Paresce & De Marchi 2000). Finally, the slope of the low-mass IMF in the galactic bulge ($[Fe/H]$ $\sim$solar) and in NGC 7008 ($[Fe/H] = -2$), a globular cluster with little or no dynamical evolution, is very similar, suggesting a lack of dependence on metallicity (Zoccali et al. 2000).

Probing the mass functions in nearby extragalactic systems at different metallicities and dynamical stastes has yielded similar results. For example, the dark matter dominated ($L/M \sim 80$) and low-metallicity ($[Fe/H] \sim -2.2$) dwarf spheroidal galaxy, Ursa Minor, has a faint mass function indistinguishable from that of M92, a metal-poor globular cluster with no dark matter (Wyse et al. 2003). In addition, the discovery of a population of old stars in Leo A, the most metal-poor galaxy in the Local Group, shows that low-mass stars have been formed in abundance despite the low oxygen content of the gas (Schulte-Ladbeck et al. 2002).

From this cursory summary, we can conclude that there is no evidence at present for a substantial diffence in the IMF as a function of environment for low-metallicity stars down to $[Fe/H] \sim -2$. Extending this result to objects and conditions beyond the Local Group is now impossible, but certainly doable in a near future as the next generation of space and ground-based telescopes comes into operation.

As to the question on the mechanism for the formation of ordinary massive stars, it must be said that there is still no well established theory. Empirically, we know that they are almost always found in clusters/associations and not in isolation. Even in extreme conditions, such as those in the Galactic center or in superclusters (e.g., 30 Doradus in the LMC and the Antennae), the most massive objects are accompanied by an even larger retinue of lower mass stars. Although theory predicts that the typical mass accretion rate be higher in massive molecular clouds, the evidence for such high values of $\dot{M}_{\rm acc}$ is still scant, if not absent. Also, the problem of the flow reversal by radiation pressure at masses ∼10–20 $M_\odot$ has not been solved, although the presence of massive circumstellar disks may help in this respect. Thus, the formation of massive objects by direct accretion is hard to achieve (Yorke & Sonnhalter 2002). Alternatively, these objects may result from the dynamical interaction and coalescence of dense cores and previously formed low-mass stars within the crowded environment provided by the young, embedded cluster (Stahler et al. 2000), or by direct collisions of stars in the same environs (Bonnell et al. 1998).

In summary, we know of no place in the Galaxy or in the nearby universe studied at sufficiently high spatial resolution where massive stars are exclusively formed *without* the presence of low-mass companions: this result amply justifies the title of the subsection.

4. The collapse of primordial protostars

We now return to the central point of this contribution: establishing the physical processes that determine the upper mass limit of the first stars. The two main differences between primordial and Population I accreting protostars are that the opacity of the infalling gas is significantly reduced owing to the lack of dust grains, and that the mass accretion rate is substantially larger because of the higher temperatures of the parent clouds. A higher $\dot{M}_{\rm acc}$ produces protostars with much larger radii and lower entropy at the same mass. To appreciate the difference, Fig. 1 shows the run of the radius as function of mass during the initial stages of the accretion process: PopIII objects are more extended than their Pop I analogues by a factor ∼10–100. In such a distended structure, the central temperature remains rather low and below the ignition value of nuclear reactions, while the surface is not hot enough to generate copious UV radiation.

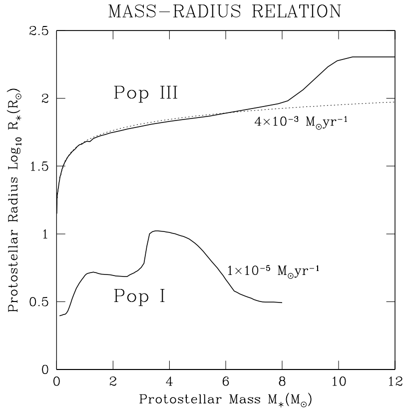

Fig. 1. Comparison between the protostellar radius of Pop I and Pop III protostars accreting at the indicated rates.

These properties imply a reduced effect of radiation pressure of the protostellar photons and a higher momentum of the inflow. Retardation of infall is much less efficient, and a higher maximum stellar mass is thus expected. Since the cosmological simulations of first structure formation find dense clouds of self-gravitating gas of mass $\sim 10^3$ $M_\odot$ in the inner regions of small halos (Abel et al. 2000), accretion is not limited by the amount of available gas. Thus, protostars can keep accreting unless an HII region or a powerful stellar wind does not develop and quenches the infall. To illustrate how a protostar is built by accretion, Fig. 2 shows the mass-radius relation computed at a fixed accretion rate of 4×10^{-3} $M_\odot$ yr^{-1} (Omukai & Palla 2001).

After an initial expansion of the radius for M_* <10 $M_\odot$, the protostar undergoes an extended phase of contraction up to M_* ∼60 $M_\odot$. As the interior luminosity approaches the Eddington luminosity, the protostellar radius rapidly expands, reaching a maximum around 100 $M_\odot$. However, changes in the ionization of

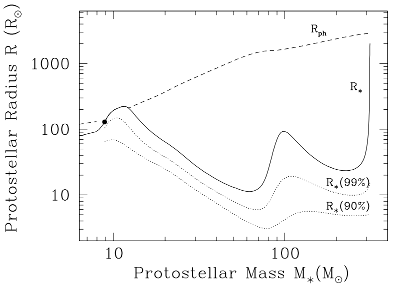

Fig. 2. Mass-radius relation for massive primordial protostars. The evolution of the core (*solid line*) and photospheric (*solid line*) as a function of mass. Note the dramatic swelling of the radius at $M_* \sim 300$ $\mathrm{M}_\odot$.

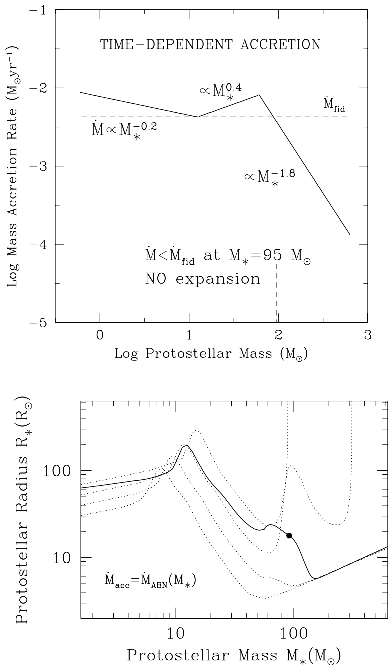

Fig. 3. Upper panel: time variation of $\dot{M}_{\rm acc}$ from Abel et al. (2000). The dashed line indicates the constant value used in Fig. 2. Lower panel: The evolution of the protostellar radius using the time dependent accretion rate displayed in the left panel. The filled circle marks the onset of H-burning during accretion. The thin dashed lines represent the evolution at constant, but different mass accretion rates. Note how the solutions differ at a critical mass of $\sim$100 $\mathrm{M}_\odot$ (Omukai & Palla 2003).

the surface layers induce a secondary phase of contraction, followed by a final swelling due to radiation pressure when the stellar mass reaches about 300 $\mathrm{M}_\odot$. This expansion likely marks the end of the main accretion phase, thus setting an upper limit to the protostellar mass formed in these conditions.

In realistic collapse calculations deviations from a constant accretion rate are expected to occur. Thus, the results described above are more illustrative than quantative. The 3D simulations of Abel et al. (2000) allow to obtain an accurate description of the gas dynamics and hence of the accretion history. The upper panel of Fig. 3 displays the resulting variation of $\dot{M}_{\rm acc}$ that starts at very high values, remains well above 10^{-3} $\mathrm{M}_\odot$ yr^{-1} up to about 60 $\mathrm{M}_\odot$, and then falls rapidly for more massive stars. This behavior has important consequences on the determination of the maximum stellar mass.

The resulting time dependent protostellar evolution is shown in the lower panel of Fig. 3 (Omukai & Palla 2003). The initial phases of protostellar growth are qualitatively the same up to $\sim$60 $\mathrm{M}_\odot$, independent of the details of the evolution of $\dot{M}_{\rm acc}$. For more massive objects, the evolution follows two fundamentally different branches, depending on the instantaneous value of $\dot{M}_{\rm acc}$. The main results are:

- For high $\dot{M}_{\rm acc} > 10^{-3}$ $\mathrm{M}_\odot$ yr^{-1}, accretion can proceed up to $M_* < 100$ $\mathrm{M}_\odot$, independent of the accretion rate or the presence of a tiny abundance of metals.
- For $M_* > 100$ $\mathrm{M}_\odot$, there is a critical value of the mass accretion rate $\dot{M}_{\rm cr} \sim 4 \times 10^{-3}$ $\mathrm{M}_\odot$ yr^{-1}. If $\dot{M}_{\rm acc} < \dot{M}_{\rm cr}$, the accretion flow can continue unimpeded by radiation pressure effects. In this case, the upper limit to the stellar

mass can be $M_*^{\rm upp} \gg 100$ $M_\odot$, and is mainly limited by the available mass in the ambient cloud.
- For $\dot{M}_{\rm acc} > \dot{M}_{\rm cr}$, accretion is reversed by radiation pressure effects; the upper limit is then $M_*^{\rm upp} \simeq 100$ $M_\odot$ and is mainly determined by the specific time evolution of the mass accretion rate.
- The presence of trace amounts of metals ($Z/Z_\odot \sim 10^{-6} - 10^{-4}$) *increases* the value of $\dot{M}_{\rm cr}$, thus favoring prolonged accretion up to $Z/Z_\odot \sim 10^{-2}$.

5. Conclusions

Although it is likely that the primordial IMF extended to high- or very high-mass stars, their actual formation via accretion depends sensitively on the mass accretion rate and its time variation. Notwithstanding the role of other important processes that have been neglected in these models (disks, turbulence, magnetic fields), even the idealized case in which star formation is mainly determined by $\dot{M}_{\rm acc}$ leads to uncertain predictions on the outcome. Detailed numerical models have identified two possible pathways that yield discordant upper mass limits, $M_*^{\rm upp} \sim 100$ $M_\odot$ or $M_*^{\rm upp} \gg 300$ $M_\odot$.

In the former case, stars with mass $\sim$140–250 $M_\odot$ which are thought to be responsible for the early chemical enrichment of the intergalactic medium would hardly be formed. In the other case, the main question is what could possibly stop infall early on so as to avoid producing extremely massive stars which do not synthesize heavy elements. Unless the initial conditions of *real* primordial clouds are directly assessed, it is impossible to decide which one of the two branches is naturally followed by the forming stars. Thus, establishing theoretically the characteristic mass scale of the first stars is still premature and remains speculative. However, considering the rapid development of observational cosmology and numerical simulations, it is easy to predict that this situation will change soon.

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