How heavy can a star get?

Introduction

The two most fundamental characteristics of any star are its mass and chemical composition, as they not only uniquely determine its physical state and structure, but also how its entire life is going to develop, from birth to death – which particular evolutionary processes such star have already experienced and which ones are still to become.

Contrarily to chemical composition, and except for favourable binary systems, the mass of a star cannot be readily obtained. This restriction complicates improving stellar models. We currently have a very good idea about how low-mass stars form and which the lowest mass limit particularly is. Unfortunately, the same topics for the top end of the stellar mass scale still remain controversial.

This essay is about such indefiniteness. It will begin with a succinct description of the standard star formation model for low-mass stars, followed by the analysis of the intrinsic difficulties that massive star formation poses. Next, potential constraints of metallicity and nucleosynthesis will be particularly discussed, finishing with the presentation of known stellar heavy-weight champions.

The formation of low-mass stars

All stars form from the accretional growth of material from a preexisting molecular cloud – those coldest and densest regions of the interstellar medium, basically comprised of molecular hydrogen – after some singular peak in density triggers the process. Once started, the embryo star continues to accrete material in a sort of highly nonuniform runaway process, until a new star is born.

Analytical models cannot give proper solutions for the complex star formation process, but state-of-the-art numerical simulations have aptly clarified the matter for the low-mass stellar range. Observation of star forming regions have properly corroborated predictions, and we pretty well know how stars form for masses going from *exactly* 0.072 solar masses – the lowest limit for a star to steadily sustain thermonuclear reactions – up to about a few solar masses[1] (Kroupa 2005).

If the mass of a molecular cloud is greater than the minimum mass required to initiate a spontaneous collapse – namely the *Jeans mass* – a gravitational contraction will

[1] Which also are the most abundant stars in the Universe. For every 1,000 stars weighing as much as the Sun, there is barely one star as heavy as 20 solar masses, and more massive stars are rarer still (Reid et al. 2002).

effectively begin after a triggering effect occurs[2]. The Jeans mass depends on both the temperature and density of the cloud, becoming lesser for either lower temperatures or higher densities.

Consequently, as the cloud contracts and density enlarges while temperature remains initially constant [3], different regions within the cloud will individually contain masses larger than the decreasing Jeans mass. Thus, the collapsing cloud will be actually fragmented into many smaller stellar cores, each one now collapsing locally.

Around each developing embryo stellar core, infalling material will still continue to be accreted almost in free-fall until the increase in density begins to trap the thermal energy and temperature also rises. Then, at different times depending on the mass of each embryo, the internal pressure at the cores will have enlarged enough as to balance gravity – namely reaching *hydrostatic equilibrium* – making them being renamed as *protostars*.

This sort of protostar litter of the same original cloud will finally derive in the profuse formation of sibling stars, technically known as a *stellar cluster*. The distribution of stellar masses within clusters seems to be fairly well described by a multiple power-law function, with different indexes for different mass intervals (Elmegreen 2004). According to Oey & Clarke (2005) such function would give an upper mass limit of about 120-200 solar masses.

The formation of massive stars

There is no standard star formation model for massive stars yet. Two causes concur for this deficiency. Compared to low-mass stars, the formation of massive ones is intrinsically a more complicated and chaotic process because of the additional physical effects involved; on the other hand, the detection and observational analysis of massive protostars being developed is a very difficult task to accomplish[4].

Observations do show that massive stars form in dense environments and in close proximity to other massive stars. According to Weidner and Kroupa (2006), there is a well-defined relation between the most massive star in a cluster and the cluster mass. In the core of a large forming cluster, all the various dynamical processes occurring (accretion, protostellar interactions, permanent condensation of matter into a smaller volume, etc) proceed faster as the density increases (Krumholz 2006).

Basically, two competing ideas have been suggested for the formation of massive stars. One is essentially a scaled-up version of the same process that forms low-mass stars – the final mass being determined by just the mass in the collapsing molecular core. In this model, the heaviest stars would be those reaching the natural limit where the pressure exerted by radiation prevents any further accretion (Kroupa 2005).

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[2] Although exactly when and why clouds undergo gravitational collapse is not yet well understood.
[3] Obviously, energy must be conserved as the cloud collapses, so that the gravitational potential energy becomes converted into thermal energy. However, until density does not become sufficiently large enough, this thermal energy can be radiated away in the infrared as blackbody radiation, and hence the temperature practically does not change.
[4] For reasons to be discussed later.

There is a well established theoretical limit for the maximum luminosity a given main sequence star can have – the *Eddington luminosity limit* – otherwise the excessive radiation pressure would prevent its hydrostatic equilibrium and mass loss must occur. This indirectly imposes a theoretical maximum value for the mass of stars, roughly estimated about 100-120 solar masses (Bromm 2006).

However, detailed simulations of the effect of radiation pressure on the infalling envelopes of massive protostars performed by Krumholz and colleagues (2005) have shown that radiation pressure does not stop accretion because radiation can still escape in some directions while infall continues in others. Constrains by radiation pressure may be even further reduced if accretion flows along favourable channels [5] (Banerjee, Pudritz & Anderson 2006).

Alternatively, a second idea proposes that the final mass of massive stars would be determined through environmental processes, such as *competitive accretion* or mergers in clusters. Numerical simulations buttress the viability of this latter mechanism (Bonnell & Bate 2006) nicely resumed by Bonnell, Vine, & Bate (2004) by stating that it is *'nurture, not nature'* the main cause of massive star formation.

The elucidation of which one is the right mechanism does not seem to be readily reached. Moreover, both ideas could even be concurrent, as latest simulations of cluster formation by Larson (2007) show that the most massive stars form near their centres by continuing accretion *and* also by mergers.

The influence of metallicity

Considering that radiation pressure is a fundamental process in limiting how heavy a star can get, then the metal content of the accreting gas should play an important role, as it partially determines the gas' *opacity* [6] – an index of its photon's absorption capacity. Metals do absorb radiation more efficiently than hydrogen and helium.

Unexpectedly, observations have shown that the same massive star limit exists for environments having as much differences in metallicity as a factor of three (Kroupa 2005). This exonerates metallicity as being responsible for limiting accretion to build-up massive stars, at least in the range of metallicities primarily found in our modern Universe.

The early Universe was a totally different scenario, as immense clouds were allowed to cool and thus collapsed and fragmented into dense clumps, each of them containing several hundred solar masses (Reed et al. 2005). Such clumps finally spawned the very first and extremely massive stars[7], as radiation pressure could hardly stop accretion due to the absolute absence of metals. According to Bromm (2006) up to 500 solar masses were created, although observational evidence is still far ahead to be obtained (Hogan 2007).

[5] That is, if infalling material actually accreting channeled along *magnetized filaments*.
[6] Also depending on the density and temperature of the gas.
[7] The so named *Population III* stars.

As soon as the first generation of huge stars went *'hypernovae'*, the presence of heavy elements began to gradually affect the transition from an early star formation mode dominated by massive stars, to the familiar mode dominated by low-mass stars (Bromm 2005). According to Tumlinson (2007), recent discoveries of peculiar abundances in the lowest metallicity stars constitute evidence that the stellar mass function changes smoothly with metallicity and/or time.

Nucleosynthetic reasons constraining massive star formation

The time it takes a protostar to evolve into a star – that is, to achieve the necessary temperature at its core to steadily burn hydrogen – strongly depends on its mass, as it becomes controlled by the rate at which the quasi-static protostar can thermally adjust to the collapse[8]. For a one solar mass star it takes about 40 million years, while for 60 solar masses is only about 1,000 times less (Carroll & Ostlie 2007).

However, while each protostar is following its own evolutionary track towards the goal of plain stellar status, all collapsing parts of the original molecular cloud are also undergoing a free-fall gravitational process (everywhere the same process as long as the original density remains uniform). The free-fall time for a typical density of a dense core of a giant molecular cloud is 400,000 years (Carroll & Ostlie 2007).

Therefore, high-mass stars start steadily burning hydrogen much earlier than the free-fall accreting phase would be finished. And even still earlier, deuterium burning and far more exothermic nuclear reactions – the CNO cycle – are started, although not yet at their equilibrium rates[9].

Because of the enormous sustained luminosity, radiation pressure begins to drive significant amounts of mass loss from the protostar – the heavier the protostar, the greater the mass loss – while also tending to disperse the remainder of the cloud. Paradoxically, not only massive stars accrete material during much less time compared to low-mass stars, but lose much more already accreted material as well (Larson 2007).

Observational evidence of massive stars

Massive stars should exist in stellar clusters fulfilling two restrictive features. Such clusters must be large enough (total mass typically greater than 10,000 solar masses) and young enough for the most massive stars to still be living (typically, younger than about 2-3 million year-old).

Observation of promissory clusters becomes difficult because (a) if not old enough, they still are partly covered by their natal molecular cloud, and (b) if not close enough, their stars can not be individually discerned. Even worse, massive stars are extremely few

[8] The *Kelvin-Helmholtz timescale*.
[9] Because of the much larger central temperatures of massive developing protostars, the strongly temperature-dependent CNO cycle quickly becomes the dominant process, thus establishing a steep temperature gradient in the cores which favours convective energy transportation (a condition that will remain even after the main sequence is reached).

and their luminosity does not peak at optical bands, which makes their detection a truly big challenge (Weidner & Kroupa 2004).

From the detailed analysis of the suitable Archer cluster by Figer (2005) no star heavier than about 130 solar masses was detected, despite theoretical predictions allowing much massive ones to exist there. Although it can be argued that the Archer cluster lies very close to the centre of our galaxy – thus increasing observational errors – almost exactly the same result was obtained from the study of the similarly young and massive cluster R136 located in the Large Magellanic Cloud (Weidner & Kroupa 2004).

So far, the most luminous star ever detected is LBV 1806-20, in a smallish cluster of very young and massive stars located some 45,000 light-years away on the far side of the Milky Way (MacRobert 2004). According to its discoverers, the star has a mass not less than 150 solar masses (Eikenberry et al. 2004), which makes it our current record-holder for massive stars – and in fair agreement with theoretical computations.

However, as already mentioned, massive stars are extremely rare and live for minute periods – astronomically referencing. Hence, it could be that we have not yet detected any heavier star than 150 solar masses, not because they do not exist, but because of an observational bias. Moreover, such stars are expected to transcend into black holes, thus leaving behind almost no traces. This final comment should place current observational evidence for the massive star upper limit in its right context – worthy, but still not conclusive.

Conclusions

Although the physics of star formation for masses up to about a few solar masses is well understood, there is no clear explanation for which the process actually is for heavier stars. Consequently, despite being a basic quantity, there is no accepted upper mass limit for stars. Some theoretical predictions place it around 100-120 solar masses.

In limiting the maximum stellar mass, metallicity seems not to be an important factor for the present reigning conditions, while nucleosynthesis clearly is.

Given the extreme rarity and fleetingness of very massive stars, worsened by unfavourable environment conditions, their observation in our present Universe is very hard, let alone at high redshifts. So far, the heaviest observed stars have been limited to near 150 solar masses, in good agreement with predictions.

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