**Blue Supergiant formation**

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Three competing concepts of massive star formation:

* Monolithic collapse in isolated cores
* Competitive accretion in a protocluster environment
* Stellar collisions and mergers in very dense systems

Primarily owing to the role of stellar mass and radiation pressure in controlling the dynamics

**Observable stages**

**IR dark clouds**

Are dense clouds seen in absorption against mid-IR background emission and are mostly filamentary structures that contain condensations of cold massive cores where massive stars seem to form.

Internal density maxima and temperature minima likely represent the ICs of high-mass star formation. High-mass starless cores probably contain low-mass and intermediate-mass accreting proto-stars, faint and hard to detect.

Recent mid-IR and millimetre-continuum observations show different evolutionary stages of massive star formation in adjacent cores. The origin of these structures derives from supersonic turbulence in giant molecular clouds, shock compression from convergent turbulent gas stream which can boost the magnetic field through flux freezing and the resulting clump will be stabilized through magnetic forces against gravitational collapse (subcritical compression).

If the magnetic field is not boosted, therefore the clump is not stabilised against gravitational collapse, then the clump is set up for collapse (supercritical compression) so quickly that that the set-up time is shorter than the free fall time.

**Hot molecular cores**

Large masses of warm and dense gases, large abundances of complex organic molecules evaporated off dust grains.

**Hypercompact and ultracompact HII regions**

Small but growing pockets of ionized gas have developed in this region that stay confined to the stellar vicinity. Hypercompact HII regions probably represent individual photoevaporating disks. Ultracompact HII regions probably represent disk-less stars photoionizing their own cocoons and massive envelopes.

**Compact and classical HII regions**

Their gas is ionized globally, often by several ionizing sources. It expands hydrodynamically as a whole and disrupts the parent molecular cloud, revealing both the embedded high-mass and lower mass stellar population for optical and near IR observations.

**Initial conditions**

Massive star formation occurs within dense, compact clumps in giant molecular clouds (H2 column densities are 1023- 1024 cm-2). Smaller mass clumps with lower peak H2 column densities do not form massive stars.

Methanol maser and OH maser emission is exclusively associated with high-mass star formation because methanol and OH masers are radiatively pumped and need intense far-IR source in their vicinity.

Gas and dust surveys have revealed dense, cold clumps with a molecular H density of 105 cm-3, gas temperature of 10-20K, and gas masses ranging from 100s-1000s of solar masses. Methanol maser surveys point towards hot molecular cores with internal heat sources and outflows as well as protoclusters.

**Endproducts**

**OB clusters**

Endproducts of massive star formation are either dense gravitationally bound OB star clusters or loose unbound OB associations. An example of Ob star clusters is the Orion nebula cluster (ONC).

**OB associations**

Examples include Scorpius OB2 and Orion OB1. The OB stars are spread over the whole face of the parent giant molecular cloud and are not densely packed at all. Distances between massive stars range from 1-10 pc. This appears to be a different mode of massive star formation, but OB associations often contain dense clusters too.

**Massive star formation: Basic theories**

**Sequence of events**

Starting from a giant pre-existing molecular cloud, the sequence of events is likely as follows:

1. Formation of cold dense molecular cores or filaments, induced by gravo-turbulent cloud fragmentation, meaning that supersonic turbulence rapidly produces localised compressed pockets of gas (some of which will remain gravitationally bound and provide ICs for collapse). [Compression phase]
2. Nonhomologous gravitational collapse of portions of the cores into optically thick, pressure supported prototile embryos with initial masses of 10-3 stellar mass. Nonhomologous collapse refers to fact that the relative distribution of material changes. [Collapse phase]
3. Accretion of material onto protostellar objects as they evolve towards the main sequence, for low mass objects the accretion stops long before H burning commences. The objects then slowly and quasi-hydrostatically contract to the main sequence phase. High mass objects eventually start burning H and develop radiation driven winds (stellar winds) as they continue to accrete and evolve up the main sequence to hotter and more luminous states. [accretion phase]
4. Disruption of the birth cloud as the first high-mass stars strongly influence their environment by their winds, outflows, and UV radiation, and eventually become supernovae. [disruption phase]

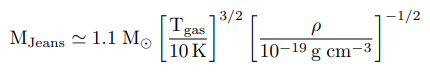
**Compression phase**

First step towards high-mass star formation is either a starless core (around 100 Mʘ) or a starless clump (around 1000 Mʘ) of molecular gas in a giant molecular cloud. These cores are theorised to be molecular condensations in a turbulence supported quasi-equilibrium that form single or gravitationally bound multiple massive protostars (Mc-Kee & Tan (2003)). Turbulent and pressurized clouds permit sufficient material to be available in the cores of giant molecular clouds for high-mass star formation. Mechanical energy must be injected into the clump to maintain the quasi-equilibrium between turbulence and gravity. The energy is either injected from the within the cores from the kinetic energy of the outflows and accretion shocks, or it comes from the outside and cascades down to smaller scale sizes. Magnetic fields likely play an important role in molecular cloud dynamics. A study of the evolution of clumps and cores formed as turbulent density fluctuations in nearby isothermal molecular clouds for both magnetic and non-magnetic cases with driven turbulence. The study found that the cores in the non-magnetic cases are unlikely to reach a hydrostatic state (necessary for monolithic collapse).

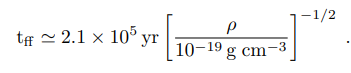
The magnetically subcritical clouds don not produce magnetostatic clumps, but rather a few marginally bound clumps that are subsequently dispersed. Ambipolar diffusion could have increased the clumps likelihood to become bound and subsequently to collapse. Clouds with a weaker magnetic field a few cores form and collapse on a timescale slightly larger than the cloud’s free-fall timescale. In their most supercritical simulation, fewer clumps, and cores form than in their non-magnetic counterpart and these cores re-expand because they are not Jeans unstable. Not all cores observed in molecular clouds will form stars, magnetic fields may help reduce the star formation efficiency by reducing core formation rather than by delaying the collapse of individual cores.

**Collapse phase**

Gravity plays the dominant role in star formation, in order to form a star gravity must overcome pressure, magnetic forces, internal turbulence and rotation. In the case of gravity versus gas pressure, one defines the Jeans mass which is the smallest mass for which gravity can become dominant:



Turbulence as a repulsive force will exceed gas pressure if motions are supersonic, but supersonic turbulence dies out unless continually replenished on a dynamical scale. Once gravity dominates pressure and magnetic forces in an optically thin gas capable of radiating compressional heat, it remains dominant and the gas collapses on a free-fall timescale:



The densest parts collapse the fastest and the Jeans mass decreases during collapse. The gas collapses nonhomologous until the densest parts become optically thick which allows the gas to heat up adiabatically and to increase in pressure dramatically. Centrifugal forces increase during gravitational collapse owing to conservation of angular momentum. As a result, flattened structures and accretion disks are expected phenomena of gravitational collapse.

**The Accretion phase**

**Formation of a hydrostatic core**

Non homologous collapse of a slowly rotating fragment of molecular material explains the formation of low-mass stars. The collapse is stopped in the central regions when the object becomes optically thick. There is a second, inside out collapse in the centre for Tgas= 2000K when molecular H dissociates. When the second core is optically thick and thermally ionized, pressure forces are able to balance gravity on a dynamical timescale. When it forms, the second hydrostatic core contains more than a Jupiter mass and has a radius on the order of 3-5 solar radii.

As long as material continues to flow onto the quasi-hydrostatic core it will grow in mass. It simultaneously contracts on the Kelvin-Helmholtz timescale toward H burning densities and temperatures. The problems of star formation can be separated into four distinct parts:

1. The evolution of the central core
2. The details of transporting materials from the disk onto the core
3. Transporting material inward within the disk
4. Accretion onto the disk

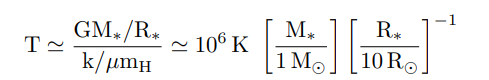
Fundamental differences between low-mass and high-mass star formation can be attributed to differences in the above processes and to significant differences in the timescales involved and the local radiative environment.

**Evolution of Accreting cores**

Accretion onto the protostar will affect the core’s outer (atmosphere) regions and the overall spectral appearance. It is not easy to estimate the size of the region thermally affected by the accretion flow onto the protostar, because the radiation transfer in an optically thick plasma depends on details of the complex accretion geometry.

For low-mass stars it is generally accepted that material is transported onto the central core through an accretion disk. The net gain per unit time of gravitational potential energy of the accreted material is partially converted into rotational energy of the core and disk (around ¼) and partially converted into heat (around ¾) which is radiated away. Part of the gravitational energy is converted into heat in a series of disk accretion shocks, part of it is converted into heat within the disk by the same viscous process that transport angular momentum outward and allow the radial flow of material inward; and part of it is converted into heat in the accretion flow and shocks/relaxation zones on the protostellar surface.

The details of how is transported from the disk onto the core is still unclear. For low-mass stars it has been postulated that magnetically focused flows and/or accretion columns and/or X-winds are involved. 50% of the gravitational energy is converted into heat and radiated away within 1 solar radius of the core, so as either M\* or Ms-acc increases or as the core contracts the temperature and luminosity increase. The temperature of this gas is sufficiently high to produce x-rays and is given by:



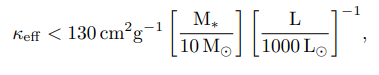
If the core and disk produce a wind or outflow, then the above argument is slightly modified in the case of speaking about a net mass accretion of Ms-acc – Ms-wind. A portion of the core’s rotational energy and angular momentum can be converted into kinetic energy and angular momentum of the wind. A necessary condition to accrete sufficient material to produce a massive star is thus:



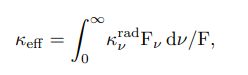
The accretion rate, Ms-acc onto an embryo object must exceed the outflow rate Ms-wind during a significant proportion of the formation process. Meaning that the acceleration owing to gravity must exceed the outward directed radiative acceleration of the accreting core. Gravity (GM\*/r2) at each radial point in an envelope increases linearly with core mass, the radiative acceleration of dusty material l (κL/4πr2c) is proportional to the core’s luminosity which increases as a high power of stellar mass, so a lower limit to the core’s luminosity is the ZAMS luminosity. To allow infall, a necessary condition is required:



With L= L\*+Lacc which translates into:



Where:



Kv rad is the frequency-dependant gram opacity (cm2g-1) of the material subject to radiative acceleration

is the radiative flux.

The protostar’s luminosity is given by the sum of it’s intrinsic luminosity, L\*and the luminosity, Lacc, emitted by the dissipation of kinetic energy of the material being accreted.

**Overcoming radiative acceleration**

How can the below equation (from above) be satisfied, i.e., accretional growth of an already existing stellar embryo can be enabled?



At least one of the following conditions must be met:

1. Keff must be sufficiently low, significantly lower than its ISM value for optical/UV radiation
2. The total luminosity, L must be reduced
3. Gravity (i.e the stellar mass, M\*,) must be increased

**Reducing Keff**

Keff can be significantly lower than its ISM value if the radiation field seen by the accreting material is that of a cold, embedded object. When embedded the protostellar radiation field is shifted away from the optical/UV (where the dust absorbs the photons) to the far-IR where the dust re-emits the absorbed energy. Keff can also be reduced if the average size of the dust grains increases or if most of the dust is destroyed.

Wolfire & Cassinelli (1987) concluded that very massive stars can only form if the dust has been significantly modified, Yorke & Krugel (1977) showed in a hydrodynamical simulation that spherically symmetric accretion must be non-steady for the high-mass case. They were able to produce stars of masses 17M­ʘ and 36Mʘ from cloud of masses 50Mʘ and 150Mʘ respectively, in a highly variable accretion flow.

The effective opacity of the accreting can also be reduced by density inhomogeneities resulting from the photon bubble instability. The radiation escapes readily through the gaps between the shocks that are driven by disturbances in the radiation flux

**Reduce the effective luminosity**

Nakano, Hasegawa & Norman (1995) and Jijina & Adams (1996) pointed out that, radiation pressure could blow away tenuous polar regions but not the massive disk, because we expect accretion to proceed through an accretion disk. Yorke & Bodenheimer (1999) and Yorke & Sonnhalter (2002) studied this effect quantitively and substantiated this claim through numerical simulations. They found that the radiation field quickly becomes anisotropic farther from the centre, whereas the central object may emit radiation isotopically. For a dust grain attempting to accrete onto an existing protostellar disk, the radiative flux close to the equatorial plane can be much smaller than the component parallel to the rotation axis, this is the so-called flashlight effect (beaming of radiation in the polar direction which occurs whenever a circumstellar disk forms.

Yorke & Bodenheimer (1999) estimated that the edge-on and pole-on bolometric fluxes can differ by more than a factor of 30after about one half of the mass of a 2Mʘ collapsing protostellar has accreted onto the protostar. The difference in radiative acceleration is much greater than this factor of >30, however, because the edge-on flux is dominated by the far-IR, which is far less effective at radiatively accelerating dusty gas than mid- and near-IR light seen pole-on. Yorke & Sonnhalter (2002) showed by calculating frequency-dependant radiation transfer that the flashlight effect is further enhanced by the central star’s optical and UV radiation blowing out material in the polar direction, which reduces back-scattering of radiation towards the disk. Photons emitted or scattered into these directions will not hinder accretion of material within the disk or material in the disk’s shadow regions.

The flashlight effect allows dusty material to come close to the central source via a circumstellar disk, the material to be accreted will eventually encounter optical and UV radiation from the central source. For this material to be accreted rather than blown out by radiation, the dust must be largely destroyed, or it must have coagulated into larger particles so that the opacity is dominated by the gaseous component.

No massive disk has yet been directly observed around a main sequence O type star, there is much indirect evidence that such disks exist, an argument that disks exist during the early phases of massive star formation is the observation of massive bipolar outflows. Such massive outflows are probably powered by disk accretion and, similar to low-mass counterparts, the flow energetics appear to scale with he luminosity of the source.

If the primary source of the massive star’s material is accretion from the surrounding molecular core, then a circumstellar disk should be a natural consequence of the star-formation process even in high-mass cases. However it is difficult to observe disks around massive stars due to the high far UV and extreme UV fluxes associated with high-mass stars beginning to evaporate the disks on timescales of around 105 year. This provide negative feedback for disk accretion which limits the build-up of more massive stellar objects and may even imply an upper mass limit for star formation

**Increasing gravity**

The gravitational acceleration is enhanced with respect to radiative acceleration when massive stars form within a dense cluster of not so brightly radiating objects. In this scenario, one requires a density-peaked cluster of low-mass objects embedded with a molecular cloud, with ρobjects>> ρgas. The effective gravity near the cluster’s centre is enhanced relative to an isolated molecular cloud without the cluster and relative to off-centre regions of the molecular cloud.

**Stellar and protostellar luminosity evolution**

Because the luminosity is so critical during accretion up to high stellar masses, one must also consider the luminosity evolution of accreting objects. Protostars do not evolve along premain-sequence tracks until they land on and remain at a unique spot on the main sequence where H burning starts. Rather, they reach the main sequence, the H burning stage, well before they have finished accreting mass. After that they continue growing in mass and evolve up the main sequence until they run out of material to accrete. An initially low-mass object that gains mass through accretion evolves substantially differently in the HR diagram than would a nonaccreting premain-sequence star of the same final mass.

What order of magnitude of mass accretion rate can be expected?

In order to produce a star of mass, M\* within 200,000yr an average accretion rate of 5x10-6Mʘ yr-1 [M\*/Mʘ] is necessary. Assuming this average accretion rate, we note that during the main accretion phase the luminosity of low-mass stars is dominated by accretion luminosity, whereas for high-mass stars the luminosity is initially determined by accretion but is eventually dominated by the intrinsic stellar luminosity. The actual accretion rate may vary strongly from this average value, the maximum sub-Eddington accretion rate possible onto a core H-burning star, assuming electron scattering and the effects of both the intrinsic stellar luminosity and accretion luminosity, can be inferred using the figure below:

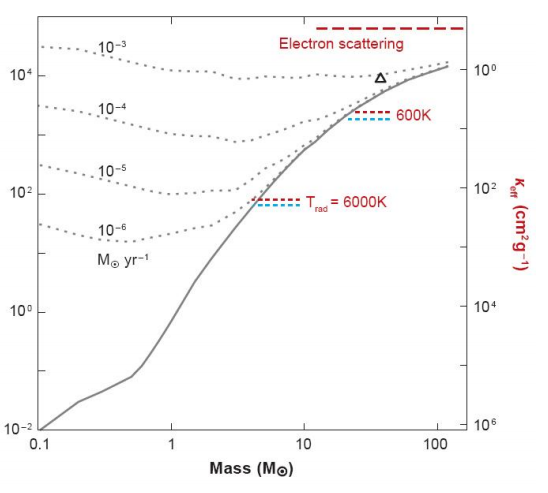


Figure 1: ZAMS luminosity to mass ratio (left scale) and corresponding critical effective opacity (right scale). The solid grey line depicts the ZAMS model. Dotted grey lines indicate the total luminosity (including accretion luminosity of stars accreting at the indicated constant rate. The triangle denotes the position of an O5V star. Dashed lines denote the opacities of dusty gas in the light of black body sources at the temperature indicated and the contribution form electron scattering in a fully ionized plasma.

The dotted curve corresponding to an accretion rate of 10-3 Mʘyr-1 lies below the value permitted by electron scattering, an accretion rate 10 times higher would lie above this value everywhere. Thus, accretion of ionized material onto a stellar core at a rate > 10-2 Mʘ yr-1 implies super\_Eddington accretion.

**Differences between high-mass and low-mass star formation**

To start with, radiative forces on gas and dust play little or no role in the build up of low-mass, solar type stars, whereas a substantial fraction of the luminosity of high-mass stars is emitted in ionizing radiation which introduces new effects such as the photoevaporation of the star’s accretion disk and protostellar envelope. This limits late accretion and the final stellar mass. In addition, the ionizing photons can photo evaporate the disks of the neighbouring lower mass stars. The non-ionizing far-UV radiation will influence the massive stars’ molecular cloud environment by dissociating H2 and CO molecules which requires photons of about eV. Even early-type B stars can produce these photons, but low-mass and intermediate-mass stars cannot. The radiative acceleration of dusty and gaseous matter also leads to radiation-driven bipolar winds, and ionizing radiation can escape through these wind-blown cavities (flashlight effect). However, the bipolar outflows from low-mass stars and generated by magneto-centrifugal forces.

The 2nd big difference is the fact that massive stars are practically born on the main sequence, whereas low-mass stars spend a considerable amount of their youth as contracting premain-sequence objects (30Myr for a solar-mass star). A massive star forming by accretional growth from an initially low-mass star with an accretion rate of 10-4 Mʘ yr-1 begins central H burning after about 9Mʘ have accumulated, 13Mʘ for an accretion rate of 10-3 Mʘ yr-1.

For low-mass stars, circumstellar disk evolution proceeds during the whole extended premain-sequence phase, whereas for massive stars the disk lifetime is very short (less than 1Myr)

Another difference is the role of competitive accretion in protoclusters which is far more important for high-mass stars than for low-mass stars. Low-mass stars can form directly by Jeans-type gravitational instability and turbulence-induced cloud fragmentation. High-mass stars must accrete large amounts of protocluster gas.

Massive stars have a much bigger influence on triggering new star formation in adjacent regions than low-mass stars through providing external pressure in the form of expanding HII regions, stellar winds, and supernovae explosions. They are capable of sustaining sequential and self-propagating star formation, a process that low-mass stars are incapable of. Massive star formation can trigger further massive star formation through runaway OB stars over large distances (Kpc), an important feature in sustaining large-scale nuclear starbursts. If massive star formation is massively triggered, the individual collapse of massive cores is outside-in, instead of inside-out. In other words, magnetic fields likely play a more passive role in massive star formation, whereas in low-mass stars they play a larger role.