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On mass-loaded accretion during high mass star formation

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Abstract

Analytical formulae of the dependence of the velocity and density on the radius during spherical accretion with both mass and momentum inputs, as well as the rate of mass inflow are presented. Some features of gas inflow near the star are discussed, and details of mass loading are presented and calculated as caused by hydrodynamical ablation and conductivity. It looks like that in one example velocities of inflow are in the range from 10-20 km/s (free fall) to 40-50 km/s and the densities are in the range from $2 \cdot 10^8$ (free fall) to $6 \cdot 10^6$ cm^{-3} at 10^{17} cm when mass-loading accretion is taken place during formation of $10M_\odot$ mass star.

Keywords: *ISM: star formation via mass-loading accretion flows*

1. Introduction

Massive stars (with masses M$\geq 8M_\odot$) are more interesting in terms of their environmental impact, as compared to the formation of low-mass stars described in detail in Bodenheimer (2011),Stahler & Palla (2005). Being powerful sources of hydrogen-ionizing L_c radiation and stellar wind, the formation of massive stars have a significant impact on the vicinity of the molecular cloud, the source of matter for such stars, and bring a large amount of mass, momentum and energy into the interstellar medium.

Comparing the estimate of time to reach MS (main sequence) (that is a Kelvin-Helmholz time) to the time it takes for the protostar to collect matter (accretion time), Dyson (1994) noted that massive stars should continue to gain mass, i.e., accrete, already reaching the MS, the nuclear reactions mode, that can serve as energy sources, since this time is clearly shorter. For example, for $10M_\odot$ one may got 5-10 megayears for accretion times and only $\sim$ 400 kiloyears for Kelvin-Helmholz time.

As a result, the protostar (with a reservation of about the beginning of nuclear reactions) remains immersed in a gas-dust shell-cocoon, which is very sensitive to the onset of hard radiation and the stellar wind, analyzed in detail in Kahn (1974).

Further the density distribution at this accretion phase is given by the obvious formula

$$\rho(r) = \dot{M}/(4\pi \cdot r^2 v) = (\dot{M} r^{-3/2})/(4\pi(2GM_*)^{1/2}), \tag{1}$$

together with free fall velocity,

$$v(r) = \sqrt{\frac{2GM_*}{r}} \tag{2}$$

This formula determines the behavior of the main gas-dynamic parameters at the accretion stage (Fig. 1). Here $\dot{M}$ is the mass accretion rate, M_* is the protostar mass and other quantities have their usual meanings.

When the protostar reaches the MS (and radiative equilibrium), but still continues to gain mass, the star (protostar) loses mass (via stellar wind) and ionizes the surrounding gas (by means of the stellar photon radiation), and the so-called ultra-compact HII region (UCHII) is formed Kahn (1974).

The present article is devoted to the features of mass accumulation by a protostar, by means of mass-loaded flows, described first in Hartquist et al. (1986) in relation to WR nebulae, and, in the formation of massive stars, in Dyson (1994).

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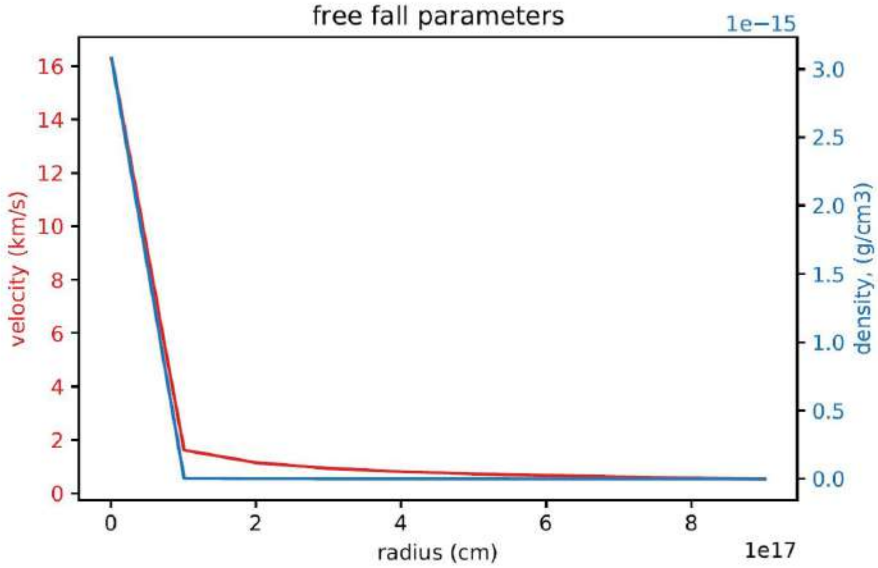

Figure 1. Distribution of velocity and density along the radius, according to free-fall dependencies for spherically symmetric accretion, $M_* = 10M_\odot, \dot{M} \approx 10^{22} g/s \approx 10^{-3} M_\odot/yr$

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2. Mass-loading accretion and the formation of massive stars

We will divide this process of additional mass gain into two types - the first one is the one through clumps of the molecular cloud (clumps) via photoionization, and the second one - through the same clumps, but already via the stellar wind, and the mass injection rate will vary.

When a molecular cloud is compressed, followed by the formation of a star, flows with continuously added gas along the way are possible. The source of this gas can be condensations, having 3-4 orders of magnitude higher density than usual, for example, in this case, in the region of star formation. It is also possible that the influence of the stellar wind is insignificant, which is typical for not very massive stars. We should be interested in a period with an intense wind, on the order of $\sim 10^{-6} M_\odot$, when UCHII is formed under the influence of both hard radiation and a sufficiently powerful wind. In this case, the wind flow itself can be considered isothermal, since the loaded mass is excited and immediately radiate, and the emission measure is proportional to the square of the density. As a result, a uniform temperature of the order of 10000 K is established in the region of intense HII emission. The hard radiation of a protostar is responsible for the ionization because thermonuclear reactions are already taking place, the radiation energy propagates to the outer layers and is radiated through the photosphere into the environment, in the first approximation, as an absolutely black body with an effective temperature inherent in massive O, B stars. In the case of mass-loaded flows, taking into account stationarity and isothermality, the gas-dynamic equations of conservation of mass and momentum should be written as:

$$\frac{d}{dr}(\rho v r^2) = S r^2, \tag{3}$$

$$\frac{1}{r^2}\frac{d}{dr}(\rho v^2 r^2) = -S v_c - \frac{dP}{dr} - \frac{GM_* \rho}{r^2}, \tag{4}$$

and instead of conservation of energy, we use the relationship between pressure and density in an isothermal process:

$$P = \rho c^2. \tag{5}$$

The first term on the right in (4) takes into account the momentum of the gas portions that have entered the flow from moving clumps, and the minus sign is the direction towards the wind. Our goal is to show that an arbitrary combination of the observed parameters of fast winds leads to the establishment of protostar parameters that do not contradict the observations. Because

$$\frac{1}{r^2}\frac{d}{dr}(\rho v^2 r^2) = S v + \rho v \frac{dv}{dr} = -S v_c - \frac{dP}{dr} - \frac{(GM_* \cdot \rho)}{r^2}, \tag{6}$$

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then after some algebric transformations we bring the system to the form:

$$\frac{dv}{dr}(v^2 - c^2) = -\frac{S}{\rho}(v^2 + c^2 + vv_c) + \frac{(2uc^2)}{r} - \frac{(GM_* v)}{r^2}, \tag{7}$$

$$\frac{d\rho}{dr} = -\frac{\rho}{v}\frac{dv}{dr} - \frac{2\rho}{r} + \frac{S}{v}. \tag{8}$$

Let us first neglect the term on the right in (7), which takes into account gravity, and exclude ρ by means of

$$\dot{M} \cdot 4\pi r^2 \rho v = const, \tag{9}$$

which in this case is written as

$$4\pi r^2 \rho v = \dot{M}_s + 4\pi \int_{r_0}^{r} S r'^2 dr', \tag{10}$$

where $\dot{M}_s$ is the mass loss rate of the central star,

$$\dot{M}_s = 4\pi r_0^2 \rho_0 v_\infty. \tag{11}$$

The values with the index 0 refer to the inner boundary of the cloud from the side of the star and v_∞ is the ultimate speed of the fast wind, and further we denote

$$4\pi \int_{r_0}^{r} S r'^2 dr' \equiv I(r). \tag{12}$$

After subsequent integration, we finally get:

$$v = \frac{v_s I(r) + v_\infty \dot{M}_s}{M_s + I(r)}, \tag{13}$$

and

$$\rho = \frac{[\dot{M}_s + I(r)]^2}{[4\pi r^2 (v_s I(r) + v_\infty \dot{M}_s)]}. \tag{14}$$

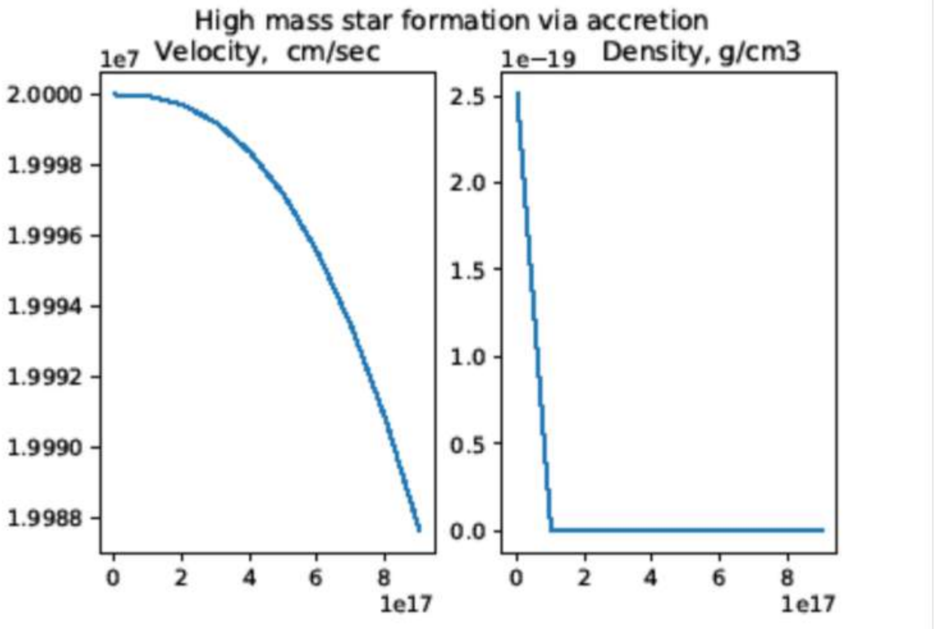

Figure 2. The distribution of velocity and density (13, 14) along the radius, when $M_* = 10M_\odot$, for spherical-simmetrical accretion with constant mass-loading rate about $\dot{M} \approx 10^{22} g/s \approx 10^{-3} M_\odot/yr$ when gravitation is not taken into account. Here we choose $S \sim 10^{-3} M_\odot/yr$.

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Gravity is not taken into account here, but the momentum introduced during the loaded mass from condensations is taken into account. They were first used in analytical theories of the planetary nebulae Yeghikyan (1999) and now are used in the description of formation of massive stars (Fig. 2).

It should be also mentioned the work of Johnson & Axford (1986), where the same equations are used to describe the galactic wind. Distribution (15, 16) for one set of parameters when mass-loading sources are constant, that is are not radius-dependent, is shown in Yeghikyan (2022).

With a uniform distribution of mass loading centers, $S(r) = S_0 = const$, and $v_s = 20km/s = const$, we have $I(r = r_m) = (4/3)S_0\pi r_m^3$, where $r_m^3 = 10^{18}$ cm is the maximum value of the radius from which accretion starts. With a power dependence of the form $S(r) = S_0(r_0/r)^\alpha, I(r) = 4\pi S_0(r^{3-\alpha} - r_0^{3-\alpha})/(3-\alpha)$.

Finally, in the general case, according to Pittard et al. (2004), one should distinguish the possibility of mass loading from cloud clumps (due to conductivity - S_c) and through hydrodynamic ablation - S_a), then the equations will be written in the form

$$\frac{d\rho}{dr} = -\frac{\rho}{v}\frac{dv}{dr} - \frac{2rho}{r} + \frac{(S_c + S_a)}{v} \tag{15}$$

$$\frac{dv}{dr} = \frac{v}{\rho(v^2 - c^2)}[S_a(v_c - v) - S_c(v + v_c)] - \frac{(GM_* v)}{((v^2 - c^2)r^2)} - \frac{(c^2(S_c + S_a))}{\rho(v^2 - c^2)} + \frac{(2uc^2)}{(r(v^2 - c^2))}. \tag{16}$$

Here, $S_c = S_{c0} \cdot (T/T_m)^{5/2} \cdot e^{(-r/r_m)}, S_a = S_{a0} \cdot (v/c)^{4/3} \cdot e^{(-r/r_m)}$ – expressions for terms describing mass loading Pittard et al. (2004). S_c is due to the conductivity of the electron gas formed during the interaction of a high-speed stellar wind with condensation in the cloud and causing photoevaporation with subsequent addition of the mass of the protostar. S_a, in turn, is the rate of mass input caused by hydrodynamic ablation (Bernoulli effect) in supersonic flow, and $S_a = S_{a0} \cdot (v/c)^{4/3}$ in subsonic flow, both mechanisms are described in Hartquist et al. (1986), Pittard et al. (2004). The solutions of the system of differential equations (15, 16), for one set of parameters are shown in Fig. 3, 4.

As can be seen, with these data, the density and initial velocity decrease with increasing radius, and the velocity at the protostar of about 100 km/s drops to several km/s only at a distance of about 10^{17} cm. The density decreases from 10^7 cm^{-3} to 70 cm^{-3} at a radius of the order of 10^{18} cm. However, these values were obtained at radius-independent mass-loading rates (Fig. 3).

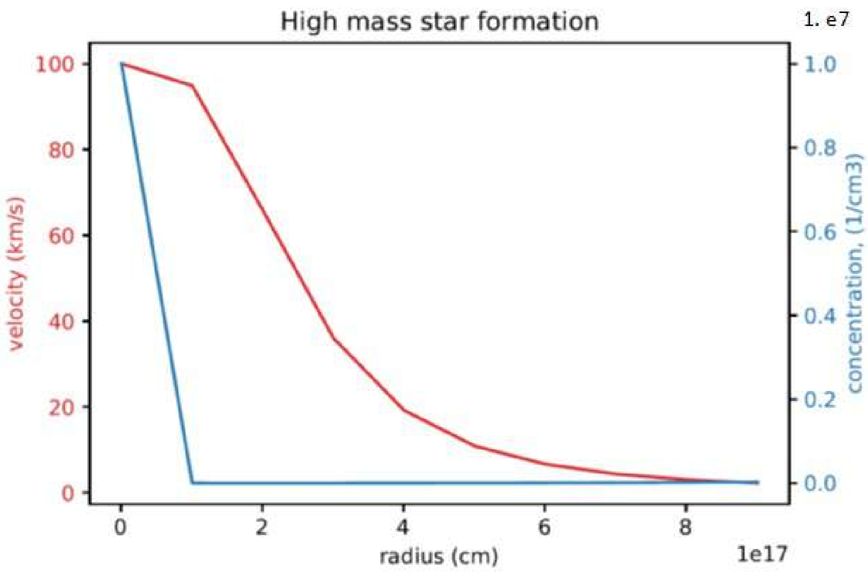

Figure 3. The distribution of velocity and density (concentration), solution of (15, 16), along the radius, when $M_* = 10M_\odot$, for spherical-simmetrical accretion with equal radius-independent mass-loading rates about $\dot{M} \approx 10^{22}g/s \approx 10^{-3}M_\odot/yr$ and $G \neq 0$.

In the opposite case, for the radius-dependent loading speed, we get the picture Fig. 4.

As you can see, with approximately the same density behavior, the speed almost everywhere remains about 40-50 km/s, while density (concentration) is around $6 \cdot 10^6$ cm^{-3} and then decrease, both at 10^{17} cm, which can be verified by observations and further refined by numerical models that take into account many various parameters. In this sense, the proposed analytical model should be regarded as preliminary.

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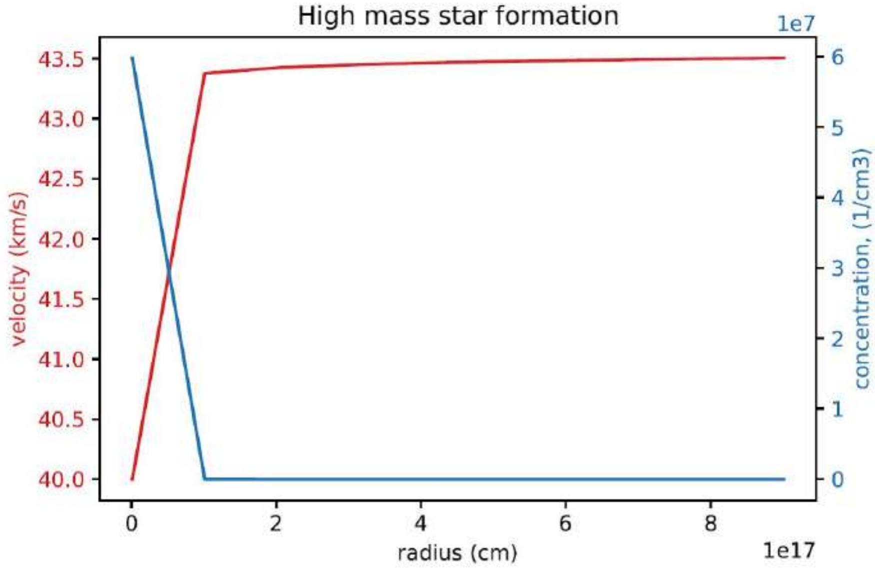

Figure 4. The distribution of velocity and density (concentration) along the radius, solution of (15, 16) for spherically symmetric accretion with loaded mass, $G \neq 0$, primary ($10^{-3} M_{\odot}$/yr) via ablation, and secondary $10^{-6} M_{\odot}$/yr) via conductivity, $M_* \approx 10 M_{\odot}, v_{\infty} = 2000$ km/s, $v_s = 20$ km/s. Initial conditions: $v = 100$ km/s, $n = 10^9$ cm^{-3} at $r_0 = 10^{15}$ cm.

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3. Conclusion

This article describes some details of the formation of massive stars, where the mass of protostars is gained by accretion and is carried out by loading through hydrodynamic ablation and electronic conduction. In the spherically symmetric case, the mass and angular momentum conservation equations are written, with the source terms given as functions depending on the radius. The gas-dynamic equations of gas flow with the loaded mass are analyzed, taking into account the momentum introduced by the loaded mass. In the simplest case of neglecting gravity, analytical formulas for the distribution of the velocity and density of matter in the vicinity of a protostar are obtained, in a more general case, when gravity is taken into account, the resulting system of differential equations is solved numerically. We emphasize that in this case, the sources of the accreted mass are cloud clumps, which are 3-4 orders of magnitude higher than density of the cloud, while the mechanisms for adding mass can be hydrodynamic ablation and electronic conduction, each, to the extent of its applicability. Numerical solutions of these equations can be verified by observations. Of course, the analytical description given in the article should be considered as preliminary, subject to refinement by means of numerical models.

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