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Mass Loss from Massive Zero-Metallicity Stars

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Abstract. We show that the radiative force is not able to drive a stellar wind from non-rotating hot massive zero-metallicity stars. This means that stellar winds from stationary massive hot first generation stars are unlikely. We study the possibility of expulsion of chemically homogeneous winds and the role of minor isotopes.

1. Introduction

According to the present picture of the evolution of the Universe, Big Bang nucleosynthesis has left the Universe completely metal-free (e.g. Coc et al. 2004). Clearly, the very first stars formed were completely metal-free. Numerical simulations of the formation and evolution of first (Population III) stars show that they were very different from the evolution and properties of present stars (see Bromm 2006; Ekström et al. 2006; Omukai 2006). Simulations of first star formation show that due to the less efficient cooling of the primordial gas the first stars were probably much more massive than the present stars. First stars with masses of the order $100\,\mathrm{M}_\odot$ might exist. Although there is no available observational evidence for the existence of these stars up to now, it is very interesting and possibly also very useful to study the properties of these first stars.

Owing to their mass, massive first stars should be mostly very hot. Present hot stars have radiatively driven winds due to the line transitions of heavier elements like carbon, nitrogen, oxygen or iron (Lamers 2006; Vink 2006; Graefener & Hamann 2006). Thus, it is not clear whether hot massive pure hydrogen-helium stars could have line-driven winds. The purpose of our study is to test if hot massive first generation stars could have radiatively driven winds or not.

2. Theoretical limits for line-driven winds

The necessary condition to launch the line-driven stellar wind is relatively simple. At some point in the wind the total radiative acceleration due to both line transitions $g^{\mathrm{rad,\ lines}}$ and light scattering on free electrons $g^{\mathrm{rad,\,e}}$ should exceed the gravitational acceleration g,

$$g^{\mathrm{rad}} = g^{\mathrm{rad,\ lines}} + g^{\mathrm{rad}}_{\mathrm{e}} > g. \tag{1}$$

The total radiative force is given by

$$g^{\mathrm{rad}} = \frac{4\pi}{c\rho}\int_0^\infty \chi_\nu H_\nu \,\mathrm{d}\nu, \tag{2}$$

where ρ is the mass density, χ_ν is the absorption coefficient, H_ν is the radiative flux, and ν is the frequency. The radiative flux is generally obtained using complicated solution of the radiative transfer equation. The radiative force due to a given line at a given point is lowered due to the absorption of radiation between stellar surface and a given point in the same line. Thus, the maximum radiative force $g^{\mathrm{rad,\,max}}$ can be obtained assuming that the line is optically thin. In such a case the line radiative force is given by

$$g^{\mathrm{rad,\,max}} = \frac{4\pi^2 e^2}{\rho m_\mathrm{e} c^2}\left(1-\mu_c^2\right)\sum_{\mathrm{lines}} H_c(\nu_{ij}) g_i f_{ij}\left(\frac{n_i}{g_i}-\frac{n_j}{g_j}\right). \tag{3}$$

The maximum *line* radiative force is, however, higher than the actual one calculated assuming that some lines may be optically thick, i.e.

$$g^{\mathrm{rad,\,max}} \geq g^{\mathrm{rad,\ lines}}. \tag{4}$$

A more realistic form of the radiative force takes into account that some lines may be optically thick. The radiative force in the Sobolev approximation is

$$g^{\mathrm{rad,\ lines}} = \frac{8\pi}{\rho c^2}\frac{v_r}{r}\sum_{\mathrm{lines}} \nu_{ij} H_c \int_{\mu_c}^1 \mu\left(1+\sigma\mu^2\right)\left(1-e^{-\tau_\mu}\right)\,\mathrm{d}\mu, \tag{5}$$

where v_r is the radial velocity, $\mu_c = \sqrt{1-R_*^2/r^2}$, R_* is stellar radius, $\sigma = \mathrm{d}\ln v_r/\mathrm{d}\ln r - 1$, and the Sobolev optical depth τ_μ is

$$\tau_\mu = \frac{\pi e^2}{m_\mathrm{e}\nu_{ij}}\left(\frac{n_i}{g_i}-\frac{n_j}{g_j}\right) g_i f_{ij} \frac{r}{v_r\left(1+\sigma\mu^2\right)}. \tag{6}$$

Eqs. (3) and (1) enable to calculate minimum occupation number n_i of a given level necessary to launch a stellar wind due to a given transition only.

3. Wind models

For numerical tests we used NLTE wind models of Krtička & Kubát (2004). Our code solves hydrodynamic, simplified radiative transfer and NLTE equations in a radiatively driven stellar wind and allows to predict the mass loss rate. For the present purpose we slightly changed the code. Since we do not know in advance whether a stellar wind is possible, the hydrodynamical variables, i.e. velocities, temperatures, and densities of all wind components (with the exception of the electron density) are kept fixed. This approach enables us to calculate the model occupation numbers and the radiative force regardless of the existence of the wind and, finally, to test whether the wind exists.

Surface flux H_c is taken from first stars

NLTE model atmospheres calculated by the code of Kubát (2003).

4. Calculated models

4.1. Wind test

To test the wind existence we performed three tests:

i We calculated minimum H I and He II ground level number density necessary to launch wind and compared it with the number density calculated from NLTE equations.

ii We calculated highest possible radiative acceleration (assuming optically thin lines, Eq. (3)) and compared it with the gravitational acceleration.

iii We calculated realistic radiative acceleration

(5) allowing for optically thick lines.

Clearly, the last test is the most strict one.

4.2. Model stars

We assumed the same first star parameters as Kudritzki (2002). Stellar masses are in the range of $100\,\mathrm{M}_\odot \leq M \leq 300\,\mathrm{M}_\odot$, the effective temperatures $40\,000\,\mathrm{K} \leq T_{\mathrm{eff}} \leq 60\,000\,\mathrm{K}$. Elemental abundances are given by the primordial nucleosynthesis (Coc et al. 2004). We assumed zero rotational velocity.

We tested three values of a possible mass loss rate, namely $10^{-6}\mathrm{M}_\odot\,\mathrm{year}^{-1}$, $10^{-7}\mathrm{M}_\odot\,\mathrm{year}^{-1}$, $10^{-8}\mathrm{M}_\odot\,\mathrm{year}^{-1}$.

4.3. An example: $\mathbf{M = 300\,M_\odot}$, $\mathbf{T_{eff} = 60\,kK}$

As an example we present our calculations for star with parameters $M = 300\,\mathrm{M}_\odot$, $T_{\mathrm{eff}} = 60\,000\,\mathrm{K}$ and test mass loss rate $\dot{M} = 10^{-7}\,\mathrm{M}_\odot\,\mathrm{year}^{-1}$.

Minimum occupation number We have compared the minimum occupation numbers necessary to launch the wind with that calculated from NLTE equations (Fig. 1). Apparently, the relative occupation number of H I ground level is too low to drive the stellar wind, while the relative occupation number of He II ground level may be close to the star high enough to overcome the gravity.

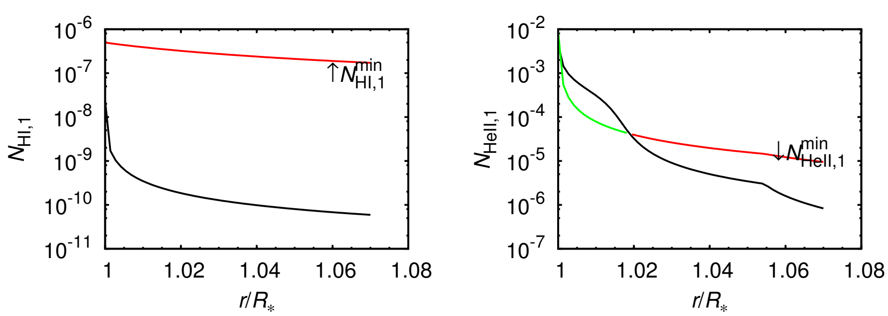

Figure 1. Comparison of minimum relative occupation numbers required to launch the wind and NLTE ones (unlabelled curves) for studied model star. *Left:* H I ground level *Right:* He II ground level.

Maximum radiative force Comparison of maximum possible radiative acceleration with gravitational acceleration (Fig. 2) shows that the net acceleration (i.e. the difference between the radiative and gravitational acceleration) may be positive only close to the star. This means that the radiative acceleration may be larger than the gravitational acceleration only near the stellar surface.

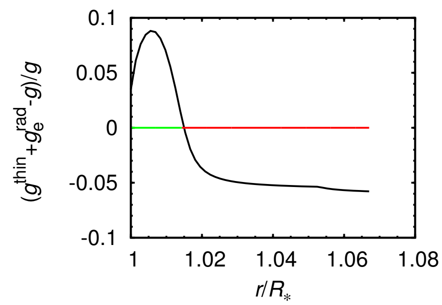

Figure 2. The plot of the relative difference $\left(g^{\rm thin}+g_{\rm e}^{\rm rad}-g\right)/g$.

Radiative force in the Sobolev approximation Finally, we calculated the radiative force (in the Sobolev approximation) allowing for optically thick lines. More realistic Sobolev radiative force is generally lower than that calculated assuming optically thin lines. Our calculations show that the net acceleration is always negative (see Fig. 3). This means that the stellar wind is unlikely in this case.

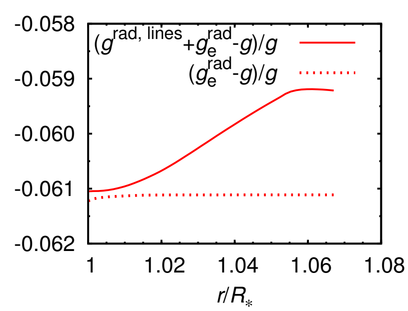

Figure 3. The plot of the net radiative acceleration $g^{\rm rad,\,lines}+g_{\rm e}^{\rm rad}-g$ and the net radiative acceleration acting on the whole gas due to free electrons only $g_{\rm e}^{\rm rad}-g$ relative to the gravitational acceleration g. The radiative acceleration due to the line transitions $g^{\rm rad,\,lines}$ calculated after Eq. (5) is much smaller than the gravity acceleration and is not able to drive a stellar wind.

4.4. Other stars

Calculations performed for other studied stars show similar results. Material around these stars is highly ionized, consequently the occupation numbers of ground levels of H I, He II are very low. Thus, the radiative force due to bound-bound transitions (lines) is very low. The radiative force due to bound-free and free-free transitions is also negligible. The only important radiative force is that due to free electrons. Consequently, H-He radiatively driven winds are unlikely.

4.5. Influence of other isotopes and elements

Isotopes ${}^{2}_{1}$H, ${}^{3}_{2}$He and Li were produced in a non-negligible amount during Big-Bang nucleosynthesis. To test their importance for radiative acceleration we included these isotopes and elements in our atomic list. However, our models showed that their contribution to the radiative force is negligible.

5. Expulsion of individual atoms

Although the radiative force is not able to drive stellar wind, it might be sufficient to expel individual elements from the stellar surface into the interstellar medium. To test this possibility, we compared the radiative force acting on individual elements with gravitational force. However, numerical calculations showed that this is probably not the case. For ${}^{2}_{1}$H, ${}^{3}_{2}$He, ${}^{4}_{2}$He and Li the radiative force is too low to expel these atoms from the stellar atmosphere.

The radiative acceleration acting on ${}^{1}_{1}$H is higher than the gravitational acceleration for stars close to the Eddington limit. While the Eddington parameter in H-He atmosphere

$$\Gamma_{\rm HHe} = \frac{1+2Y}{1+4Y}\frac{s_e L}{4\pi c m_{\rm H} G M} \tag{7}$$

(where $s_{\rm e}$ is Thomson scattering cross-section, M is stellar mass, L is luminosity and Y is He abundance (number densities ratio)) is lower than one, for stars with $\Gamma_{\rm HHe} \gtrsim 0.859$ the Eddington parameter in a pure hydrogen layer

$$\Gamma_{\rm H} = \frac{s_e L}{4\pi c m_{\rm H} G M} \tag{8}$$

is greater than one, thus possibly enabling a pure hydrogen wind.

The mass loss rate of such hypothetical pure hydrogen wind is probably given by gravitational settling time scale $\tau_{\rm D}$ (provided the atmosphere is quiet), $\dot{M}_{\rm H} \approx 4\pi R_*^2 S n m_{\rm H} \tau_{\rm D}^{-1}$, where S is the characteristic atmosphere length and n is particle number density. Inserting values typical for atmospheres of massive first stars gives mass loss rate about $\dot{M}_{\rm H} \approx 10^{-16} {\rm M}_\odot\,{\rm year}^{-1}$. A more detailed analysis (Krtička & Kubát 2005) gives mass loss rate of order $\dot{M}_{\rm H} \approx 10^{-14} {\rm M}_\odot\,{\rm year}^{-1}$.

6. Line-transitions and accretion

We tested whether the line radiative force is able to terminate the initial accretion onto first stars. We concluded that this is possible only for stars relatively close to the Eddington limit and with small accretion rates $\dot{M} \lesssim 10^{-5}\,{\rm M}_\odot\,{\rm year}^{-1}$. Consequently, it is possible that for some first stars the radiative force influences the accretion physics and the initial mass-function of first stars.

7. Conclusions: mass-loss rates for evolutionary models

i Very massive zero-metallicity stars with $\Gamma_{\rm HHe} \lesssim 0.859$ likely do not have any wind. If their atmospheres are quiet, chemical peculiarity may develop there. Stars with $\Gamma_{\mathrm{HHe}} \gtrsim 0.859$ may have a pure hydrogen wind (with $\dot{M} \sim 10^{-14} \mathrm{M}_{\odot}\,\mathrm{year}^{-1}$) driven by the light scattering on free electrons.

ii With increasing metallicity a purely metallic line-driven wind may develop.

iii For higher metallicities H and He are also expelled from the atmosphere and multicomponent effects are important (Krtička et al. 2003). However, these effects probably do not significantly influence the mass-loss rate.

iv For even higher metallicities a line-driven wind similar to the stellar wind of present-day hot stars exists.

In our opinion the best choice for the evolutionary calculations now is a zero mass-loss rate for extremely low-metallicity stars mentioned in items i–ii and use of the Kudritzki (2002) or Vink et al. (2001) prescription for other stars.

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Discussion

Langer: Rotating stellar models of low metallicity need to lose mass to relieve this angular momentum problems. How would it affect your results if the centrifugal force would be added to the momentum equation?

Krticka: Probably, another process is important for stars rotating close to the critical rotation rate (e.g. some mechanical wind). The effect of rotation itself (i.e. the centrifugal force) on wind dynamics is close to the star similar to the effect of electron scattering radiative force. However, the gravity darkening effect may be important. In this case the material could be less ionized at the equator and the radiative force could be higher (line radiative force).

de Koter: Your last slide shows that evolution theorists should adopt $\dot{M} = 0$ for Z = 0, but that they should switch to e.g. the Vink et al (2001) predictions when Z becomes larger. At what specific Z should they switch?

Krticka: We have not calculated this in detail yet. However, there is a paper by Krticka et al (2003), where we have calculated the value of Z for which the multicomponent effects become important. The value of Z at which Vink et al. (2001) predictions can be used is probably only slightly lower than that given by Krticka et al. (2003) paper.