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The winds of hot massive first stars*

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ABSTRACT

We study dynamical aspects of the circumstellar environment around massive zero-metallicity first stars. We apply our NLTE wind models showing that the hydrogen-helium stellar wind from stationary massive first generation (Population III) stars (driven either by the line (bound-bound) or continuum (bound-free and free-free) transitions) is unlikely. The possibility of expulsion of chemically homogeneous wind and the role of minor isotopes are discussed. We estimate the importance of hydrogen and helium lines in shutting off the initial accretion onto first stars and its influence on the initial mass function of first stars.

Key words. stars: mass-loss – stars: winds, outflows – stars: early-type – ISM: general

1. Introduction

Big Bang nucleosynthesis has left our universe completely metal-free (e.g. Coc et al. 2004). Thus, in the early universe a population of stars existed composed of hydrogen and helium only. Numerical simulations show that the physical properties and the evolution of these first stars (Population III stars) were very different from the stellar evolution and properties of Population I and II stars. Simulations of first star formation (cf. Bromm et al. 1999; Nakamura & Umemura 2002) show that due to the less efficient cooling the first stars were probably much more massive than present stars. First stars with masses of the order 100 $M_{\odot}$ might have been formed. However, there are indications that the initial mass function of first stars was bimodal (Nakamura & Umemura 2002; Omukai & Yoshii 2003), and thus solar mass first stars may have been formed as well.

There are no available observations of first stars. Although the recently discovered extremely low metallicity star HE 0107–5240 (Christlieb et al. 2002) was claimed to be a first star (Shigeyama et al. 2003), it is difficult to explain the present surface chemical composition of this star (especially that of carbon and nitrogen) on the basis of its initial pure hydrogen and helium composition. For example, Shigeyama et al. (2003) explain the CN composition by surface enrichment due to central nucleosynthesis, however there is a question of whether a significant amount of CN elements may occur on the surface for this stellar type according to evolutionary calculations of Marigo et al. (2001). It is more likely that this star was formed from the material which was already enriched by the first stars (Bromm & Larson 2004) or by subsequent stellar populations.

Consequently, it is necessary to limit ourselves only to indirect observation of the first stars. Probably the most reliable indirect observation comes from the polarisation measurement of cosmic microwave background radiation. If the first stars ionized the matter in the universe significantly, we should observe its imprint on the cosmic microwave background due to the light scattering on free electrons. Recent cosmic microwave background polarisation measurements showed that the universe was reionized 180×10^6 years after the Big Bang (Kogut et al. 2003). Detailed numerical analysis shows that this effect can be attributed to the generation of massive zero-metallicity stars (Cen 2003; Wyithe & Loeb 2003; Sokasian et al. 2003). Moreover, the level of the sky infrared background radiation can also be explained by the generation of massive first-generation stars (Magliocchetti et al. 2003).

The detailed theoretical study of physical properties of the first generation stars is a challenging task. The study of its stellar winds is especially appealing, since winds might have a significant impact on the first star evolution. Moreover, the study of outflows of the first stars may be important for the estimate of the duration of the era of supermassive star formation. The possibility of supermassive star formation depends critically on the metal abundance in the interstellar medium. The presence of a relatively small amount of metals might inhibit subsequent formation of supermassive stars (see Bromm & Larson 2004, for a review). Note, for example, that there are indications that the initial formation of supermassive stars might have been inhibited by metals expelled due to supernova explosions and that direct black hole formation by implosion is necessary for the

* Appendices A, B and Figs. 2, 3, 5 and 6 are only available in electronic form at http://www.edpsciences.org

explanation of the duration of the massive star era (Ricotti & Ostriker 2003). Thus, the interstellar medium had to remain metal free for a significant amount of time if the stellar wind did not enrich it with nuclearly-processed material. This shows how important the study of winds from first generation stars potentially could be.

The outflows from first stars have not been systematically studied up to now. A first step in this direction was done by Kudritzki (2002), who calculated wind parameters suitable for massive extremely-low metallicity stars. As was discussed by Kudritzki and also subsequently supported by detailed numerical modelling by Krtička et al. (2003), some of these stellar winds may suffer from multicomponent effects (see Krtička & Kubát 2001, for a detailed modelling of multicomponent effects in the line-driven stellar winds). However, to our knowledge the line-driven stellar winds of zero-metallicity stars have not been discussed so far. To fill this gap we present the detailed discussion of pure H-He line-driven winds.

2. Theoretical limits for line-driven winds

To launch line-driven stellar wind, the radiative force should exceed the gravitational force at some point. Thus, we start with a discussion of this condition and its application to simple situations.

2.1. Minimum radiative force

The radiative acceleration due to the absorption or scattering of radiation is given by (Mihalas 1978)

$$g^{\rm rad} = \frac{4\pi}{c\rho}\int_0^\infty \chi_\nu H_\nu \, {\rm d}\nu, \tag{1}$$

where ρ is the mass density, χ_ν is the absorption coefficient, H_ν is the radiative flux, and ν is the frequency. For the calculation of the radiative force in the optically thin environment, the radiative flux $H_c(\nu)$ emerging from the stellar atmosphere can be directly inserted into Eq. (1). However, this is not the case of the stellar wind since the radiative flux H_ν is influenced by the absorption and emission of the radiation in the sorrounding wind environment in such cases. Thus, the self-shadowing in the given transition has to be accounted for, preferably by the solution of the radiative transfer equation. In the case of a rapidly accelerating stellar wind a convenient approximation of the radiative transfer equation solution is given by the Sobolev approximation (see Sobolev 1947).

From Eq. (1) we obtain the limit below which classical line-driven wind is not possible. In particular, neglecting continuum absorption, for a given set of lines the radiative force is maximum if lines are not self-shadowed and if lines are optically thin, i.e. if the optical depths $\tau < 1$ in lines (Gayley 1995). Thus, for given occupation numbers the line acceleration (i.e. line force per unit of mass) cannot be larger than

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

where now $H_c(\nu_{ij})$ is the frequency-dependent flux emerging from the star at the stellar radius $R_\star$, $\left(1-\mu_c^2\right) = R_\star^2/r^2$ is a correction due to the dilution of radiation, ν_{ij} and $g_i f_{ij}$ are the frequency and the oscillator strength of a given transition $i \leftrightarrow j$, n_i, n_j are the number densities, and g_i, g_j are the statistical weights of corresponding levels.

Note that $g^{\rm rad,\,max}$ is related to Gayley's parameter $\bar{Q}$ (Gayley 1995; Puls et al. 2000), namely

$$g^{\rm rad,\,max} = g_{\rm e}^{\rm rad}\bar{Q}, \tag{3}$$

where $g_{\rm e}^{\rm rad}$ is the radiative acceleration on free electrons,

$$g_{\rm e}^{\rm rad} = \frac{\sigma_{\rm e} L}{4\pi c r^2}, \tag{4}$$

where L is the stellar luminosity,

$$\sigma_{\rm e} = \frac{n_{\rm e} s_{\rm e}}{\rho}, \tag{5}$$

$s_{\rm e}$ is the Thomson scattering cross-section, and $n_{\rm e}$ is the electron density. The line-driven wind is possible only if the total radiative force is greater than gravity at some point in the stellar atmosphere or circumstellar envelope. Thus, the necessary condition for line-driven wind reads (neglecting the gas-pressure)

$$g^{\rm rad,\,max} + g_{\rm e}^{\rm rad} = \left(\bar{Q}+1\right) g_{\rm e}^{\rm rad} > g, \tag{6}$$

where $g = GM/r^2$ is the gravitational acceleration. Using Eq. (2) for maximal line acceleration and $1-\mu_c^2 = R_\star^2/r^2$ we can obtain a condition for the lowest limit of line-driven wind as

$$\Gamma + \frac{4\pi^2 e^2}{\rho m_{\rm e} c^2 GM} R_*^2 \sum_{\rm lines} H_c(\nu_{ij}) g_i f_{ij}\left(\frac{n_i}{g_i}-\frac{n_j}{g_j}\right) > 1, \tag{7}$$

where M is stellar mass and

$$\Gamma = \frac{\sigma_{\rm e} L}{4\pi c GM}. \tag{8}$$

Using the Gayley's parameter, which for our case reads

$$\bar{Q} = \frac{\pi e^2}{m_{\rm e} c s_{\rm e} n_{\rm e}} \sum_{\rm lines} \frac{H_c(\nu_{ij})}{H_{\rm t}(R_*)} g_i f_{ij}\left(\frac{n_i}{g_i}-\frac{n_j}{g_j}\right), \tag{9}$$

where $H_{\rm t}(R_*) = L/(4\pi R_*)^2$ is the total flux at the stellar surface R_*, the condition (6) may be rewritten as

$$\bar{Q} > \frac{1}{\Gamma} - 1. \tag{10}$$

Let us first assume that the stellar surface flux $H_c(\nu_{ij})$ is constant for a given transition $i \to j$ throughout the wind, i.e. that the frequency dependence of $H_c(\nu_{ij})$ due to the Doppler shift can be neglected. In such a case the only quantities in Eq. (7) that depend on radius are the fractions n_i/ρ, n_j/ρ. Thus, for a given star Eq. (7) gives a lower limit for n_i/ρ below which the line-driven wind is not possible. Equation (7) is a necessary condition to launch the stellar wind.

Another formulation of this may be obtained from the requirement that the work done by the radiative force (per unit mass) is greater than the absolute value of gravitational potential. In the case of wind driven purely by optically thin lines this condition can be easily obtained by the integration of Eq. (6) from $r = R_*$ to infinity if the wind ionization and excitation state is constant (in this case fraction n_i/ρ is constant for homogeneous winds)

$$\frac{\Gamma GM}{R_*}+\frac{4\pi^2 e^2}{\rho m_\mathrm{e} c^2}R_*\sum_\mathrm{lines}H_c(\nu_{ij})g_i f_{ij}\left(\frac{n_i}{g_i}-\frac{n_j}{g_j}\right)>\frac{GM}{R_*}\cdot \tag{11}$$

This is an identical condition to Eq. (7) and thus Eq. (7) is also an energy condition to launch the stellar wind driven purely by optically thin lines. However, real line-driven stellar winds are accelerated not only by optically thin lines but by the mixture of optically thin and optically thick lines. Thus, the simple condition (11) cannot be used in this case. Moreover, some of the lines that accelerate the stellar wind may be optically thick in the photosphere. In such a case, the stellar flux H_c depends on the wind velocity (and thus also on the radius) due to the Doppler effect and condition (11) cannot be applied.

2.2. Application to hydrogen

The necessary condition for the existence of line-driven winds (7) is especially simple in the case of the radiative force only due to the hydrogen lines. This is a rough approximation even in the case of stars with zero metallicity for which the radiative force due to the helium lines also may be important. However, condition (7) provides an estimate of occupation numbers for which the line-driven winds of stars at zero metallicity may exist. Adding other hydrogen-like ions is straightforward.

The oscillator strengths for hydrogen are given by the well-known Kramers formula, which neglecting Gaunt factors reads (Mihalas 1978, Eq. (4.78) therein)

$$g_i f_{ij}=\frac{64}{3\pi\sqrt{3}}\left(\frac{1}{i^2}-\frac{1}{j^2}\right)^{-3}\frac{1}{i^3 j^3}\cdot \tag{12}$$

For the resonance lines it may be assumed that

$$\frac{n_1}{g_1}-\frac{n_j}{g_j}\approx\frac{n_1}{g_1}, \tag{13}$$

which means neglecting the stimulated emission in all resonance transitions. Moreover, the contribution of other than resonance lines to the radiative force in many cases can be neglected.

Thus, in the case of hydrogen, we can obtain from Eq. (7) relatively simple condition for the existence of a line-driven wind in the form of

$$\Gamma+\frac{128\pi e^2}{3\sqrt{3}\rho m_\mathrm{e} c^2 GM}R_*^2\sum_j H_c(\nu_{1j})\left(1-\frac{1}{j^2}\right)^{-3}\frac{n_1}{j^3}>1. \tag{14}$$

The main contribution to the sum in condition (14) is to the resonance lines and the lowest relative occupation number of the hydrogen ground level $N_{\mathrm{H\,I},1}$ for which the hydrogen-driven wind is possible is given by

$$N_{\mathrm{H\,I},1}^{\min}=\left[\sum_j H_c(\nu_{1j})\left(j-\frac{1}{j}\right)^{-3}\right]^{-1}\times\frac{3\sqrt{3}m_\mathrm{e} m_\mathrm{H} c^2 GM}{128\pi e^2 X R_*^2}(1-\Gamma), \tag{15}$$

where m_H is hydrogen atom mass, $X=n_\mathrm{H} m_\mathrm{H}/\rho$ is the relative hydrogen abundance, n_H is hydrogen number density and $N_{\mathrm{H\,I},1}^{\min}=n_{\mathrm{H\,I},1}^{\min}/n_\mathrm{H}$ (where $n_{\mathrm{H\,I},1}^{\min}$ is the minimum number density of ground state neutral hydrogen necessary to launch the stellar wind). For stars close to the Eddington limit ($\Gamma\rightarrow 1$) the minimum relative number density $N_{\mathrm{H\,I},1}$ to launch the hydrogen line-driven wind is lower.

2.3. Application to helium

He II is the most important helium ion for radiative driving since helium is ionized in the stellar winds of hot stars. Thus, the radiative force due to helium can be calculated in a very similar way to that due to H I. Similarly to the case of H I, the resonance lines are the only important He II lines for radiative driving (assuming that helium is singly ionized ionized). Thus, we can write for He II (similarly as for H I)

$$\frac{n_i}{g_i}-\frac{n_j}{g_j}\approx\begin{cases}\frac{n_i}{2}, & i=1,\\ 0, & i>1.\end{cases} \tag{16}$$

The condition of existence of wind driven by the absorption in He II lines is (see Eq. (14))

$$\Gamma+\frac{128\pi e^2 R_*^2}{3\sqrt{3}\rho m_\mathrm{e} c^2 GM}n_{\mathrm{He\,II},1}\sum_j H_c(\nu_{1j})\left(1-\frac{1}{j^2}\right)^{-3}\frac{1}{j^3}>1, \tag{17}$$

and the lowest relative occupation number $N_{\mathrm{He\,II},1}$ for which the helium-driven wind is possible is

$$N_{\mathrm{He\,II},1}^{\min}=\left[\sum_j H_c(\nu_{1j})\left(j-\frac{1}{j}\right)^{-3}\right]^{-1}\times\frac{3\sqrt{3}m_\mathrm{e} m_\mathrm{He} c^2 GM}{128\pi e^2 Y R_*^2}(1-\Gamma), \tag{18}$$

where m_He is helium atom mass, $Y=n_\mathrm{He} m_\mathrm{He}/\rho$ is the relative helium abundance, n_He is helium number density and $N_{\mathrm{He\,II},1}^{\min}=n_{\mathrm{He\,II},1}^{\min}/n_\mathrm{He}$. The sums in Eqs. (17) and (18) converge due to the asymptotic behaviour of hydrogen-like oscillator strengths, $g_i f_{ij}\sim 1/j^3$ (see Eq. (12)).

In many cases the stellar wind is accelerated by lines which are optically thick in the photosphere and thus the stellar flux H_c for frequencies close to the photospheric line center depends strongly on frequency. Since the radiative flux at a given point is shifted due to the Doppler effect, the optically thin radiative force depends on velocity (and consequently also on radius). Even in such a case the conditions (15) and (18) can also be used to estimate the minimum conditions for line driven winds. However, the actual radiative flux $H_c[\nu(v_r)]$, which depends on wind velocity (and thus also on radius) should be inserted in these equations.

2.4. Stellar wind driven by optically thin lines

We have derived the necessary condition to launch the line-driven stellar wind. However, is this condition also sufficient? In other words, are the optically thin lines only able to drive stellar wind?

2.4.1. Constant ionization fraction

Let us first assume that the wind ionization and excitation state does not depend on wind density and on radius and that the stellar surface flux H_c does not significantly vary with frequency. In such a case the optically thin radiative acceleration (2) does not depend on wind density. Thus, also the wind momentum equation

$$v_r \frac{\mathrm{d}v_r}{\mathrm{d}r} = \frac{2a^2}{r} + \frac{a^2}{v_r}\frac{\mathrm{d}v_r}{\mathrm{d}r} - g + g^{\mathrm{thin}} + g_{\mathrm{e}}^{\mathrm{rad}}, \tag{19}$$

(where the optically thin radiative acceleration $g^{\mathrm{thin}} = g^{\mathrm{rad,\,max}}$, a is sound speed, and where we assumed isothermal flow) does not depend on wind density. It may seem that the optically thin line-force may launch the stellar wind with an arbitrary mass-loss rate. However, this is not true, since in such a case either for higher wind densities some of the lines would become optically thick or the photon tiring effect (Owocki & Gayley 1997) would impose constraints on the mass-loss rate.

2.4.2. Variable ionization fraction

In the case when the wind ionization and excitation state depends on wind density, the value of wind mass-loss rate can be derived from the hydrodynamic equations. The optically thin momentum Eq. (19) has a critical point for $v_r = a$. To obtain a smooth wind solution, the regularity condition

$$\frac{2a^2}{r} + g^{\mathrm{thin}} + g_{\mathrm{e}}^{\mathrm{rad}} = g \tag{20}$$

must be fulfilled at the critical point. Since wind ionization and excitation state depends on wind density now, the optically thin radiative acceleration also depends on wind density. Thus, the critical condition (20) depends implicitly on the wind density and using this equation the mass-loss rate of thin winds can be calculated. Note that in the common case when the gas pressure term is negligible, condition (6) will be fulfilled at the critical point. This again shows the importance of the condition (6).

However, this analysis does not tell us about the possibility to drive the wind material from the stellar gravitational potential well. This condition has to be tested using detailed numerical modelling. On the other hand, more wind properties can be revealed using a simple analysis. The stellar photosphere deep below the wind region is quasi-static. Thus, to obtain a smooth flow, the radiative force has to be smaller than the gravity in this region and the condition (6) has not to be fulfilled below the critical point. The change of wind ionization or excitation state then has to assure that the equality in Eq. (6) is fulfilled at the critical point. Finally, in the outer parts of the wind the inequality in condition (6) has to hold, i.e. the radiative force has to be greater than the gravity in the outer wind.

2.4.3. Frequency-dependent stellar flux

The frequency variable stellar flux gives probably the most attractive way to obtain consistent radiative force to drive an optically thin wind, i.e. radiative force that is lower than the gravitational force below the critical point and higher outwards. This is caused by the fact that some lines that accelerate the stellar wind may be optically thick in the photosphere and optically thin in the stellar wind. In such a case the stellar flux H_c strongly depends on frequency and, consequently, due to the Doppler effect, also on the wind velocity. The stellar wind near the star has low velocity and a given line is accelerated mainly by the weak flux from the line core. On the other hand, stellar wind with higher velocities is accelerated mainly by the stronger flux from the line wings and thus the line force of the outer wind may be higher than that of inner part of the wind close to the star. However, this is not as simple as it looks since higher flux may also cause higher excitation and ionization and consequently lower the radiative force. Clearly, detailed numerical calculations are necessary to test this possibility.

3. Numerical calculation of thin winds

For the numerical tests we used NLTE wind models described by Krtička & Kubát (2004). Our computer program allows us to solve hydrodynamic, simplified radiative transfer and statistical equilibrium equations in a radiatively driven stellar wind. However, we slightly changed the code. Since we do not know in advance whether a stellar wind is possible or not, the hydrodynamical variables, i.e. velocities, temperatures, and densities of all wind components (with the exception of the electron density) are kept fixed. This enables us to calculate the model occupation numbers and the radiative force regardless of the existence of the wind and, consequently, to test whether the wind exists.

The method itself was slightly improved with respect to the published one. We included accelerated lambda iterations (cf. Rybicki & Hummer 1992) and Ng acceleration (Ng 1974). These improvements will be described in detail in a separate paper (Krtička & Kubát, in preparation). To obtain a correct surface flux we accounted for the Doppler effect during the calculation of radiative transfer in lines, i.e. we shifted the stellar surface flux H_c according to the actual wind velocity (we accounted for the detailed profiles of photospheric lines, cf. Babel 1996). To assure a smooth transition between stellar atmosphere and wind, the model atmosphere fluxes are taken at the point where the density is equal to the boundary wind density.

First, we tested whether the radiative force is large enough to drive stellar wind in optically thin lines. Although this gives only the necessary condition for stellar wind and not the sufficient one (and thus further calculations are necessary to test whether the stellar wind is possible or not), this approach enables us to better understand more detailed models.

3.1. Minimum number density for line-driven winds

We performed two different tests of the possibility of a stellar wind of zero-metallicity stars driven by optically thin lines. First, we calculated the ionization structure of a possible extended stellar atmosphere and compared this ionization structure with minimum number densities to launch a line-driven wind obtained using Eqs. (15) and (18).

Table 1. Stellar (taken from Kudritzki 2002) and wind parameters used to calculate wind models.

	Stellar parameters				Model
$\log(L/L_\odot)$	$T_{\rm eff}$ [K]	$\log g$ CGS	R_* $[R_\odot]$	$T_{\rm wind}$ [K]	
7.03	60 000	3.95	30.38	49 000	T60
	50 000	3.63	43.76	39 000	T50
	40 000	3.25	68.32	29 000	T40
6.91	60 000	3.99	26.24	49 000	
	50 000	3.68	38.06	39 000	
	40 000	3.28	59.49	29 000	
6.76	60 000	4.04	22.29	49 000	
	50 000	3.73	32.10	39 000	
	40 000	3.34	50.12	29 000	
6.57	60 000	4.11	17.78	49 000	
	50 000	3.79	25.74	39 000	
	40 000	3.41	40.18	29 000	
6.42	60 000	4.16	15.07	49 000	
	50 000	3.85	21.71	39 000	
	40 000	3.46	33.93	29 000	
6.30	60 000	4.21	13.11	49 000	
	50 000	3.89	18.88	39 000	
	40 000	3.50	29.51	29 000	

For our detailed discussion we selected only those stars from the Kudritzki (2002) list that have the largest luminosity, i.e. those that are close to the Eddington limit. These stars have the largest radiative force due to the light scattering on free electrons in their atmospheres and thus also the highest chance of launching the stellar wind. Detailed models were calculated also for other stars from Kudritzki's list, however for these stars we describe the final results only. Parameters of all studied model stars are given in Table 1.

We compared the minimum number densities necessary to launch the stellar wind with actual number densities calculated by our NLTE code. Since we do not know in advance whether the radiative force is strong enough to drive a wind, the velocity structure of our models is given by an artificial velocity law

$$v(r) = 10^{-3}\sqrt{\frac{5}{3}\frac{kT_{\rm eff}}{m_{\rm H}}} + 4\times10^{7}\,{\rm cm\,s^{-1}}\,\frac{r-R_*}{R_*}. \qquad (21)$$

This velocity law corresponds to the Taylor expansion of the wind velocity around the sonic point. According to our experience with wind models of O stars this expression is valid in the wind region close to the star with $r \lesssim 1.2\,R_*$ within the accuracy of 20%. This is the region of rapid wind acceleration where the stellar wind attains velocities of the order of $100\,{\rm km\,s^{-1}}$. Note, however, that the obtained results do not significantly depend on the detailed form of the velocity law. The density structure is obtained from the equation of continuity. Wind temperature in these models was equal to $T_{\rm wind}$ and electron density was consistently calculated from hydrogen and helium ionization balance. For each of these stars with different effective temperatures three models with different values of mass-loss rates were calculated, namely $10^{-6}\,M_\odot\,{\rm year}^{-1}$, $10^{-7}\,M_\odot\,{\rm year}^{-1}$, $10^{-8}\,M_\odot\,{\rm year}^{-1}$.

Comparison of model number densities and minimum number densities necessary to launch the wind is given in

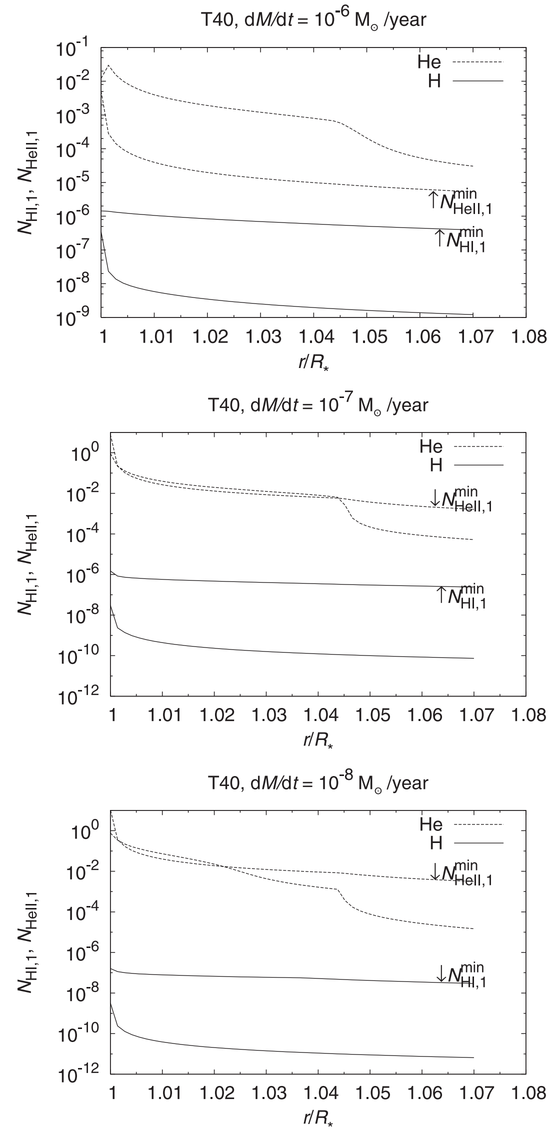

Fig. 1. Comparison of minimal occupation numbers $N^{\rm min}_{\rm H\,I,1}$, $N^{\rm min}_{\rm He\,II,1}$ required to launch the wind and actual occupation numbers $N_{\rm H\,I,1}$ and $N_{\rm He\,II,1}$ (shown by unlabeled curves) for model T40 and different mass-loss rates of $10^{-6}\,M_\odot\,{\rm year}^{-1}$, $10^{-7}\,M_\odot\,{\rm year}^{-1}$, and $10^{-8}\,M_\odot\,{\rm year}^{-1}$.

Figs. 1–3. Near the stellar surface number densities of ground levels of hydrogen-like ions are relatively high and they decrease with radius due to increasing ionization. The ionization is higher in the outer regions due to both lower density and higher radiative flux at frequencies outside the line core (due to the Doppler effect the line frequency shifts from the saturated core of photospheric line-profile, consequently larger flux absorbed in the lines increases populations of higher levels, for which the ionization rate is much higher than for lower levels). Minimum number densities also decrease. This is caused by increasing stellar flux as the wind lines move out from the centre of photospheric line due to the Doppler effect.

The relative number density of the ground level of H I is very low, mostly much lower than the minimum number density necessary to launch the stellar wind by H I lines. Thus, we conclude that H I *lines are not important for line-driven winds of first stars.* On the other hand, for specific regions of some

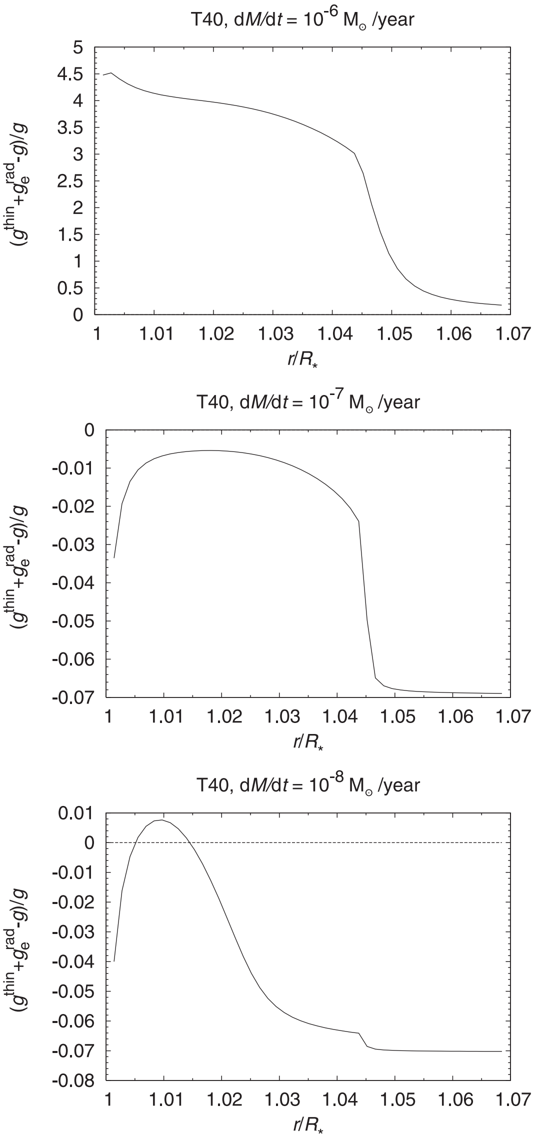

Fig. 4. The plot of the relative difference $\left(g^{\text{thin}} + g_{\text{e}}^{\text{rad}} - g\right)/g$ for model T40. Note that the points where this difference is zero match the points where the actual occupation number $N_{\text{He\,II},1}$ is equal to $N_{\text{He\,II},1}^{\text{min}}$ relatively well. Thus, the simple conditions Eqs. (15) and (18) for the minimum occupation number necessary to launch the stellar wind are able to predict relatively correctly the regions where the total radiative force is greater than gravity.

models the actual number density of ground level of He II is higher than the minimum number density necessary to launch the stellar wind. In these regions the total radiative force may be higher than the gravitational force and the sufficient condition for launching the stellar wind may be fulfilled there.

3.2. Maximum radiative force

The preceding simple analysis can be extended using the detailed calculation of the radiative force. For stars in Table 1 we have calculated the relative difference $\left(g^{\text{thin}} + g_{\text{e}}^{\text{rad}} - g\right)/g$ (i.e. the net acceleration in terms of gravitational acceleration) as a function of radius. The corresponding graphs are plotted in Figs. 4–6.

We came to the same conclusion as in the previous paragraph. The maximum possible radiative force is greater than the gravity in some regions of some models. However, the functional dependence of the difference $g^{\text{thin}} + g_{\text{e}}^{\text{rad}} - g$ in most cases does not have the correct radial dependence necessary to launch the stellar stellar wind, i.e. the total radiative force in these models is higher than the gravity near the star and lower than the gravity in the outer regions.

The optically thin radiative force is maximum for a given set of lines and clearly the actual radiative force will be lower due to the self-shadowing effect. Moreover, for many of the models the total radiative force is not greater than the gravity. Thus, we conclude that *winds of zero metallicity stars driven purely by the optically thin lines are unlikely.* However, these results will be tested by a more detailed models with the possibility that some lines are optically thick.

Inspecting Figs. 1–6 note that Eqs. (15) and (18) are able to reliably estimate the minimum occupation number necessary to launch a line-driven stellar wind because they correctly predict the location of the region where the optically thin radiative force is greater than gravity.

4. Wind with optically thick lines

Our final test for the existence of line-driven stellar wind of first stars should include the possibility that some lines are optically thick. Thus, we now study the more realistic case of the stellar wind driven partially by the optically thick lines. This is a much more complicated task than study of the wind driven purely by optically thin lines since now we cannot use any simple criterion to decide whether the wind is possible or not. We have to use detailed modelling. Moreover, the nonlinear character of wind equations (especially equations of statistical equilibrium) does not guarantee that the obtained solutions are unique. This is especially the case of zero metallicity stars when the wind may be driven just by one ionization state. Thus, for some ionization structures the wind may be possible and for some other not.

To make this problem more tractable we calculate the radiative force in the Sobolev approximation for the same models for which we studied the optically thin radiative force in Sect. 3. The radiative force in the Sobolev approximation is given by the sum of partial radiative forces due to the individual lines (Castor 1974; Abbott 1982)

$$g^{\text{rad}} = \frac{8\pi}{\rho c^2}\frac{v_r}{r}\sum_{\text{lines}}\nu_{ij}H_c\int_{\mu_c}^{1}\mu\left(1+\sigma\mu^2\right)\left(1-\mathrm{e}^{-\tau_\mu}\right)\,\mathrm{d}\mu, \tag{22}$$

where ρ is the wind density, v_r is the radial velocity, H_c is the stellar flux, $\mu_c = \sqrt{1 - R_*^2/r^2}$ is the direction cosine of the photospheric limb, R_* is stellar radius, $\sigma = \mathrm{d}\ln v_r/\mathrm{d}\ln r - 1$ and the Sobolev optical depth τ_μ is

$$\tau_\mu = \frac{\pi e^2}{m_{\text{e}}\nu_{ij}}\left(\frac{n_i}{g_i} - \frac{n_j}{g_j}\right)g_i f_{ij}\frac{r}{v_r\left(1+\sigma\mu^2\right)}. \tag{23}$$

If some of the lines are optically thick, then the actual radiative acceleration given in the Sobolev approximation Eq. (22) is lower than the maximum radiative acceleration (2). This is

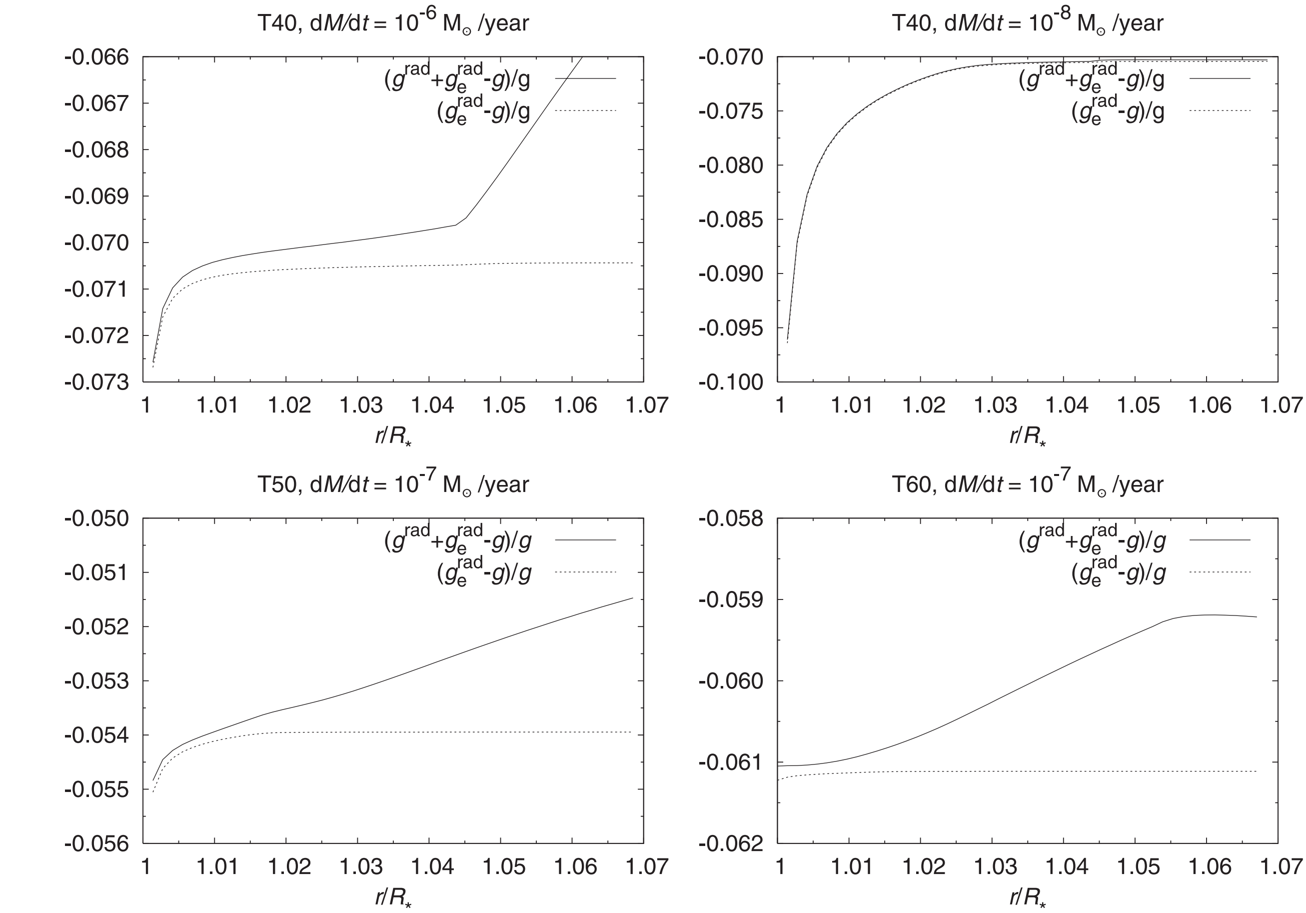

Fig. 7. The plot of the net radiative acceleration $g^{\mathrm{rad}} + g_{\mathrm{e}}^{\mathrm{rad}} - g$ and the net radiative acceleration acting on the whole gas due to free electrons only $g_{\mathrm{e}}^{\mathrm{rad}} - g$ relative to the gravitational acceleration g. The contribution of the radiative acceleration due to the line transitions g^{rad} calculated after Eq. (22) is much smaller than the gravity acceleration and is not able to drive a stellar wind.

caused by the effect of self-shadowing, i.e. that some part of the stellar flux which is supposed to accelerate the wind in a line was already absorbed by a given line in the region closer to the star. Thus, here we present only results for models for which optically thin radiative force can drive a stellar wind, since it is clear that there will not be any wind in the opposite case.

The radiative force calculated using Eq. (22) in the selected models is given in Fig. 7. Clearly, since most of the strongest lines are optically thick, the radiative force due to these lines is much lower than the optically thin radiative force. The more realistic radiative force given by Eq. (22) is generally by several orders of magnitude lower than the gravitational force. Thus it is unlikely that some change of wind density or velocity may give a significantly stronger radiative force that would drive a stellar wind. This is also supported by our models, because we were not able to find sufficiently large radiative force for any reasonable wind model. *We conclude that it is unlikely that stationary massive* H-He *stars have any* H-He *stellar wind driven by the line transitions.*

We have also calculated similar models for other stars from the Kudritzki (2002) list with lower masses and lower luminosities (with parameters given in Table 1). These stars are not as close to the Eddington limit as the stars discussed sofar. Consequently, the radiative force due to light scattering on free electrons is lower for these additional stars and the minimum radiative force necessary to launch the stellar wind is higher in this case (see Eqs. (15), (18)). Clearly, the possibility of launching the stellar wind is lower for stars that are not close to the Eddington limit.

5. Influence of continuum radiative force

Another force that can potentially accelerate the stellar wind of first stars is the radiative force due to bound-free and free-free transitions. Numerical calculations showed that the contribution of free-free transitions to the radiative force in the circumstellar environment is much lower than that of bound-free transitions. Thus, we discuss the bound-free transitions only, although the free-free transitions are also included in our models. The radiative acceleration has in this case the form (Mihalas 1978)

$$g^{\mathrm{rad,\,bf}} = \frac{4\pi}{c} \int_0^\infty \frac{\chi_\nu}{\rho} H_\nu \, \mathrm{d}\nu, \tag{24}$$

where χ_ν is the opacity due to the bound-free transitions,

$$\chi_\nu = \sum_i \left[n_i - n_k \left(\frac{n_i}{n_k} \right)^* \mathrm{e}^{-\frac{h\nu}{kT}} \right] \alpha_{ik}(\nu), \tag{25}$$

where the summation goes over all levels i for which bound-free transitions are accounted for and the asterisk refers to the LTE value.

Let us first briefly discuss the interesting possibility that the stellar wind is driven purely by the bound-free absorption. Combining Eqs. (24) and (25), the radiative acceleration is given by

$$g^{\text{rad}} = \frac{4\pi}{c}\sum_i \left[\frac{n_i}{\rho}\int_{\nu_i}^{\infty} \alpha_{ik}(\nu) H_\nu \,\mathrm{d}\nu - \frac{n_k}{\rho}\left(\frac{n_i}{n_k}\right)^* \int_{\nu_i}^{\infty} \alpha_{ik}(\nu) H_\nu \mathrm{e}^{-\frac{h\nu}{kT}} \,\mathrm{d}\nu\right]. \tag{26}$$

As already mentioned in Sect. 2.4, to obtain a smooth wind solution, the radiative force has to be smaller than the gravitational force in the stellar atmosphere below the critical point and larger than the gravitational force above the critical point. It is very difficult to achieve this in this case, since the radiative flux H_ν decreases rapidly with radius, especially in the case strong bound-free absorption is present. Moreover, the critical condition is not a sufficient one to drive the stellar wind, since it does not tell us whether the radiative force in the outer wind regions is strong enough to lift the wind material out from the stellar gravitational potential well. The decrease of the stellar flux with radius due to the bound-free absorption (see also the photon tiring effect, Owocki & Gayley 1997) can complicate this. Note that the situation with the line-driven wind is simpler, because the lines are usually illuminated by the unattenuated stellar flux due to the Doppler effect.

We included the radiative force due to the bound-free and free-free transitions Eq. (24) into our models. The numerical calculations (for stars with parameters given in Table 1) showed that the radiative force due to the bound-free and free-free transitions does not significantly contribute to the acceleration of the stellar wind of first stars because it is typically at least two orders of magnitude lower than the gravitational force.

Finally, we also calculated static spherically symmetric NLTE model H-He atmospheres (for the description of the code see Kubát 2003), where the radiative force was calculated without any simplification. All of the models with parameters from Table 1 are sub-Eddington i.e. the total radiative force is always lower than gravity. However, for the most luminous models the value of Γ reached 0.99.

6. Expulsion of individual elements by a wind

While first stars probably fail to drive H-He outflow, there is a possibility that hydrogen or helium are expelled separately, i.e. that there exists a pure hydrogen or helium wind. To show whether such outflow of chemically pristine elements is possible or not, we recalculated models with the same stellar parameters presented in Sect. 3 assuming that one element may form the wind while the other not and compared the radiative force in such a chemically homogenous wind with the gravitational force acting against such wind. To avoid charging of the star we assume that a corresponding number of electrons follow the escaping element, making the wind electrically neutral. We assume that such wind exists above the H-He photosphere.

Since these models are chemically homogenous, the electron density in such models is calculated only from the contribution of the element that remained in the wind (i.e. either hydrogen or helium). This difference is crucial for the final results, at least in the case of helium. If we assume that the helium gas consists of only the isotope ^{4}He, we may say that helium has two times less electrons per nucleon (proton or neutron) than hydrogen. Hence, the radiative force per unit of mass (i.e. the radiative acceleration) due to free electrons is lower in the case of helium. Consequently, although the number of free electrons *per atomic nucleus* is higher in pure He than in H-He models, the total radiative force is lower. Surprisingly, although helium lines significantly contribute to the radiative force in the H-He models, the possibility of pure He outflow is lower than that of H-He.

On the other hand, the situation in pure hydrogen models is also different. Hydrogen plasma has a higher number of free electrons per nucleon than H-He plasma. Consequently, H-He stars that are close to the Eddington limit may have slightly higher radiative force than gravity force for the same stellar parameters (mass, radius, luminosity) in a pure hydrogen wind, whereas the radiative force in hydrogen-helium atmosphere is (due to the contribution of the heavier helium atom) lower than gravitational force.

These considerations are supported by our numerical models. The total radiative force in helium models is lower than the gravitational force in all models considered (for stars with parameters given in Table 1). On the other hand, for model stars very close to the Eddington limit, the radiative force in purely hydrogen models may be greater than gravity, thus potentially enabling a hydrogen wind.

The condition for the existence of such a hydrogen wind is relatively simple. If the wind exists, radiative acceleration due to the free electrons in a pure hydrogen plasma is greater than the gravitational acceleration,

$$g^{\text{rad}}_{\text{e,H}} > g, \tag{27}$$

or using the Eddington parameter Γ_{H} in a pure hydrogen plasma (cf. Eq. (8))

$$\Gamma_{\text{H}} \equiv \frac{\sigma_{\text{e}}^{\text{H}} L}{4\pi c G M} > 1, \tag{28}$$

where

$$\sigma_{\text{e}}^{\text{H}} = \frac{n_{\text{e}}^{\text{H}} s_{\text{e}}}{\rho_{\text{H}}}, \tag{29}$$

s_{e} is the Thomson scattering cross-section and n_{e}^{H} is the electron number density in hydrogen plasma with the density ρ_{H}. Condition (28) can be rewritten in a more convenient form. Now we compare conditions in a pure hydrogen wind with that in a hydrogen-helium atmosphere. Using Eqs. (8) and (5) for the hydrogen-helium atmosphere, we can express the fraction $L/(4\pi c G M)$ in Eq. (28) using the Eddington parameter in the stellar atmosphere Γ and we obtain

$$\Gamma = \Gamma_{\text{H}} \frac{(\sigma_{\text{e}})_{\text{atmosphere}}}{\left(\sigma_{\text{e}}^{\text{H}}\right)_{\text{wind}}}, \tag{30}$$

which yields the condition ($\rho = \rho_{\rm H} + \rho_{\rm He}$ is the total density in the atmosphere)

$$\Gamma > \left(\frac{\rho_{\rm H}}{n_{\rm e}^{\rm H}}\right)_{\rm wind} \left(\frac{n_{\rm e}}{\rho_{\rm H} + \rho_{\rm He}}\right)_{\rm atmosphere}. \quad (31)$$

For a chemical composition given by primordial nucleosynthesis and assuming a fully ionized gas both in the atmosphere and in the wind we obtain simple condition

$$\Gamma \gtrsim 0.859. \quad (32)$$

Clearly, pure hydrogen-helium stars close to the Eddington limit (with $0.859 \lesssim \Gamma < 1$) may have a pure hydrogen wind, but not the H-He wind.

The only stars from our sample for which $\Gamma \gtrsim 0.859$ and which thus can have a pure hydrogen wind are the most massive stars with $M = 300\,M_\odot$ (for all considered values of effective temperature) and star with $M = 250\,M_\odot$ and $T_{\rm eff} = 40\,000$ K.

However, despite this behaviour of the radiative force in pure hydrogen models, pure hydrogen winds need not necesserily exist in all stars for which they are theoretically possible. Radiative force in these models is not due to the hydrogen line transitions, but mostly due to the free electrons. Thus, in order that a hydrogen wind exists, there should be some process able to separate hydrogen and helium atoms. The mass-loss rate of such a theoretical wind depends mainly on the rate of this separating process. The only possible process is the gravitational settling due to the different atomic masses (see Michaud 2005, for a recent review). However, the typical rate of such a process is very small, thus mass-loss rates of a pure hydrogen wind would be probably also very small (see also Appendix A). Moreover, any macroscopic motion in the stellar atmosphere may inhibit this gravitational settling. Thus, we conclude that *any possible pure hydrogen wind has either a very low mass-loss rate or is even missing.*

7. Other isotopes and elements

7.1. Contribution to the radiative force

Hydrogen and helium isotopes ${}^2_1$H and ${}^3_2$He were produced in a nonnegligible amount during the era of Big-Bang nucleosynthesis. The positions of their lines are slightly shifted with respect to those of ${}^1_1$H and ${}^4_2$He and thus they can potentially be exposed to a slightly higher flux than their much more abundant counterparts.

To test their importance we included ${}^2_1$H and ${}^3_2$He in our atomic list. We used essentially the same atomic data for the calculation of model atoms, however with modified energy levels due to the isotopic shift. The isotopic abundances were taken from the simulation of primordial nucleosynthesis by Coc et al. (2004), $N({}^2_1{\rm H})/N({}^1_1{\rm H}) = 2.6\times10^{-5}$, $N({}^3_2{\rm He})/N({}^1_1{\rm H}) = 1.04\times10^{-5}$, which are in relatively good agreement with the observed values.

The importance of other hydrogen and helium isotopes was tested using optically thin models discussed in Sect. 3. The calculated excitation and ionization states of ${}^2_1$H and ${}^3_2$He are very similar to those of ${}^1_1$H and ${}^4_2$He. Moreover, due to the relatively small isotopic shifts and due to the relatively broad photospheric lines the flux at the positions of lines of less abundant isotopes is similar to that of more abundant isotopes. The abundance of these isotopes is several orders of magnitude lower than the ordinary ones, which significantly diminishes the optically thin radiative force. Consequently, our models showed that the contribution of less abundant hydrogen and helium isotopes ${}^2_1$H and ${}^3_2$He to the radiative force is negligible.

Similarly, we have also tested the contribution of lithium to the total radiative force. We selected data on excitation and ionization of lithium ions from the Opacity Project database (Seaton 1987; Peach et al. 1988; Fernley et al. 1987). The primordial lithium abundance $N({}^7_3{\rm Li})/N({}^1_1{\rm H}) = 4.15\times10^{-10}$ was taken from Coc et al. (2004). Numerical calculation showed that due to the extremely low lithium abundance its contribution to the radiative force can be also neglected.

7.2. Expulsion of particular isotopes and abundance stratification

Slightly different radiative forces acting on different isotopes and different isotopic masses may cause radiative levitation of some isotopes and/or gravitation settling of others, the effect also referred to as light induced drift (Aret & Sapar 2002). Thus, atmospheres of first generation stars may be chemically stratified. However, the discussion of these issues is beyond the scope of the present paper which studies outflow from first generation stars. Although the radiation force due to the less abundant isotopes is very small and has only a marginal influence on the stellar atmospheres, it might be sufficient to expel these elements from the stellar surface into the interstellar medium.

However, numerical calculations showed that this is probably not the case. Considerations discussed in Sect. 6 for ordinary hydrogen and helium are valid also for deuterium and the ${}^3_2$He isotope. The radiative force acting on deuterium is too low to allow a pure deuterium wind. Moreover, the radiative force due to free electrons is lower in ${}^3_2$He wind due to a lower number of free electrons per nucleon compared to the H-He wind.

Similarly, numerical calculations showed that a pure lithium wind is also unlikely. Although the radiative force acting on lithium may be higher than the gravitational force in deeper layers of some models, in the outer regions it is always too low to drive the lithium wind.

8. Influence of line transitions on accretion physics

The initial mass function of first stars is not known (see Bromm & Larson 2004). One of the problems with the determination of the initial mass function of first stars is the process of termination of accretion onto a protostar. Dust grains are not present there, so the radiation pressure on dust grains operating in contemporary stars is not available there. Thus, other mechanisms may be important for metal-free stars (e.g. Omukai & Inutsuka 2002; Tan & McKee 2004).

We test whether line transitions due to hydrogen and helium are able to influence the accretion.

Thus, we selected a fixed velocity law which can be obtained from the solution of the momentum equation for isothermal ($T = T_{\rm wind}$) spherical accretion (Mihalas 1978)

$$\left(\upsilon_r - \frac{a^2}{\upsilon_r}\right)\frac{{\rm d}\upsilon_r}{{\rm d}r} = \frac{2a^2}{r} - g. \quad (33)$$

The boundary condition of Eq. (33) was artificially selected to be $\upsilon_r(100R_*) = \sqrt{\frac{5}{3}}a$ and the density structure was calculated from the continuity equation

$$4\pi\rho\upsilon_r r^2 = \dot{M} = {\rm const.}, \quad (34)$$

where $\dot{M}$ is the accretion rate. We selected three different values of accretion rates, namely $10^{-3}\,M_\odot\,{\rm year}^{-1}$, $10^{-5}\,M_\odot\,{\rm year}^{-1}$, $10^{-7}\,M_\odot\,{\rm year}^{-1}$. The highest value of the accretion rate roughly corresponds to the critical accretion rate above which a protostellar core reaches the Eddington limit and no supermassive star forms (Omukai & Palla 2003).

For the velocity and density structure mentioned above we solved statistical equilibrium equations for hydrogen and helium inflow. We neglected any influence of possible shock at the stellar surface and assumed that the protostar is in hydrostatic equilibrium. In such a case, for our numerical calculations we may use the same stellar parameters as we used for wind tests, namely the stellar parameters taken from Kudritzki (2002). Our numerical calculations showed that the sum of the radiative force in the Sobolev approximation calculated after Eq. (22) and the radiative force acting on free electrons together can exceed the gravitational force only in stars close to the Eddington limit and only for relatively small accretion rates (of the order of $10^{-5}\,M_\odot\,{\rm year}^{-1}$ and smaller).

The principal difference between a possible stellar wind and accretion flow is that important regions of accretion occur at much greater distances from the star than the acceleration region of the stellar wind. Since the ionizing stellar flux at greater distances is lower, the inflow (especially helium) is less ionized and the line radiative force due to He II becomes important relative to the gravity force.

Clearly, the importance of the radiative force increases for more massive stars closer to the Eddington limit. Thus, there is a possibility that for even more massive stars than those considered here the radiative force both due to line transitions and free electrons is able to overcome gravity and set the initial mass function of supermassive stars. However, these considerations have to be tested against more advanced accretion models.

9. Discussion of simplifying assumptions

9.1. Radiative transfer

There are several problems that can influence our final results, such as the simplified radiative transfer in lines. This can influence the calculated occupation numbers and hence also the radiative force. However, this is probably not the case, since the results obtained are relatively robust, i.e. in many cases even the optically thin radiative force is not sufficient to drive a stellar wind.

9.2. Level dissolution

There is another more subtle problem related to the neglect of the so-called level dissolution (Hummer & Mihalas 1988). It is the statistical treatment of the fact that the highest atomic levels cease to exist under the influence of surrounding particles. Usually this problem is treated approximately using the lowering of the ionization potential. However, it can be treated in a consistent way using the so-called occupation probability formalism (Hubeny et al. 1994; Kubát 1997). Possibly, neglect of level dissolution can influence the calculated radiative force, especially in the case of hydrogen. However, test calculations with different numbers of hydrogen and helium lines showed this is not the case. Although total number densities of individual ionization states may differ, number densities of lower excited levels (which are important for line driving) are nearly the same. Since there is a relatively low radiative flux in the wavelength regions of lines originating from higher excited levels, their contribution to the radiative force is negligible (see also Sect. 2.2). Thus, we conclude that the influence of level dissolution on our results is only marginal.

9.3. Pulsations

Since we assume stationary flow here, the effect of possible stellar pulsations is neglected. According to numerical simulations of Baraffe et al. (2001), primordial stars may actually lose mass via pulsational instability. However, such an effect is connected mostly with the stellar interior, so it is beyond the scope of the present paper.

10. Conclusions

10.1. Stars with chemical composition given by primordial nucleosynthesis

We have studied the dynamical aspects of a possible circumstellar envelope around massive first stars using our NLTE models. Although many of the studied stars are very close to the Eddington limit and the maximum possible radiative force (calculated assuming that all lines are optically thin) is high in some cases, stellar winds driven by line transitions are unlikely because the line radiative force is very small. The influence of other isotopes and elements produced during primordial nucleosynthesis was found to be marginal. The effect of the continuum radiative force is also negligible.

We have also tested whether first stars can expel individual elements, either the dominant ones (i.e. hydrogen and helium) or the trace ones (i.e. hydrogen and helium isotopes or lithium). Calculations showed that the only theoretically possible chemically homogeneous outflow is that of hydrogen (for stars very close to the Eddington limit with $\Gamma \gtrsim 0.859$), since other elements yield a small number of free electrons per nucleon (and the line-radiative force is always negligible). However, even the case of a pure hydrogen outflow is unlikely since the radiative force in such a wind would be predominantly due to the free electrons. Hence, another process which would be able to separate hydrogen and helium atoms in the atmosphere should exist (e.g. gravitational settling) to enable a pure hydrogen wind. Without such a process a pure hydrogen wind is not possible.

We have tested whether the radiative force due to line transitions is able to terminate the initial accretion onto first stars. We have found that this is only the case for stars relatively close to the Eddington limit and with relatively low accretion rates. Consequently, it is possible that for even more massive stars this process could influence the accretion physics and the initial mass function of first stars.

Our results do not imply that the first stars are completely without line driven winds during all of their life time. For example, cooler stars (which were not inlcuded in our present study) could have wind due to the hydrogen or helium lines. Moreover, if the accretion terminates, then as soon as a sufficient amount of heavier elements is synthesised in the stellar core and transported to the surface layers, the line-driven wind is initiated (Kudritzki 2002). If this happens at a sufficiently low metallicity, such a stellar wind would be multicomponent, allowing for element separation and frictional heating (Krtička et al. 2003).

10.2. General picture of the stellar wind of massive low-metallicity stars

From this study and previous ones (Kudritzki 2002; Krtička et al. 2003) a general picture of the properties of stellar wind of massive stars at low metallicities emerges.

i. Zero-metallicity stars with $\Gamma \lesssim 0.859$ likely do not have any stellar wind. If their atmospheres are relatively quiet (i.e. in the absence of violent pulsations or fast rotation) chemical peculiarity in their atmospheres may develop. On the other hand, zero-metallicity H-He stars with $\Gamma \gtrsim 0.859$ may have a pure hydrogen wind (probably very thin with mass-loss rates of about $10^{-14}\ M_\odot\,\mathrm{year}^{-1}$, see Appendix B), driven only by the light scattering on free electrons.
ii. With increasing metallicity a line-driven wind may develop. For extremely low metallicities such a stellar wind is likely to be purely metallic (see Babel 1996).
iii. For higher metallicities hydrogen and helium are also expelled from the atmosphere and multicomponent effects become important (Krtička et al. 2003). The multicomponent structure does not significantly influence the wind mass-loss rate, which may be approximated by formulae obtained for one-component flow by Kudritzki (2002).
iv. For higher metallicities, a line-driven wind similar to the stellar wind of present-day hot stars exists; its mass-loss rate was calculated by Kudritzki (2002).

Thus, in our opinion, the best choice for the evolutionary calculation now is to assume a zero mass-loss rate for zero and low metallicity stars mentioned in items i–ii and to use the Kudritzki (2002) prescription for other stars (or Vink et al. 2001, predictions for stars with lower masses).

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Online Material

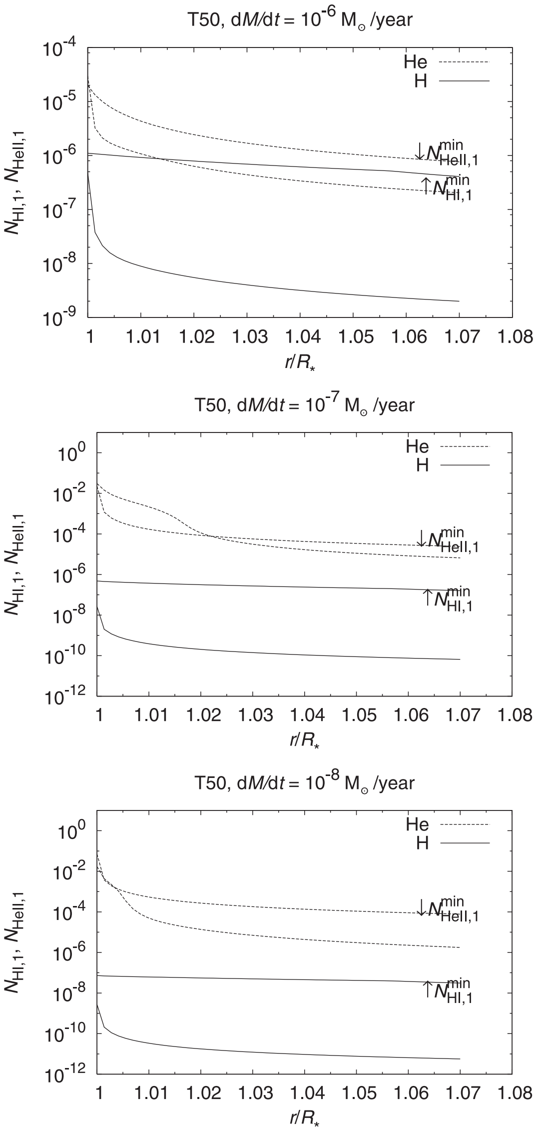
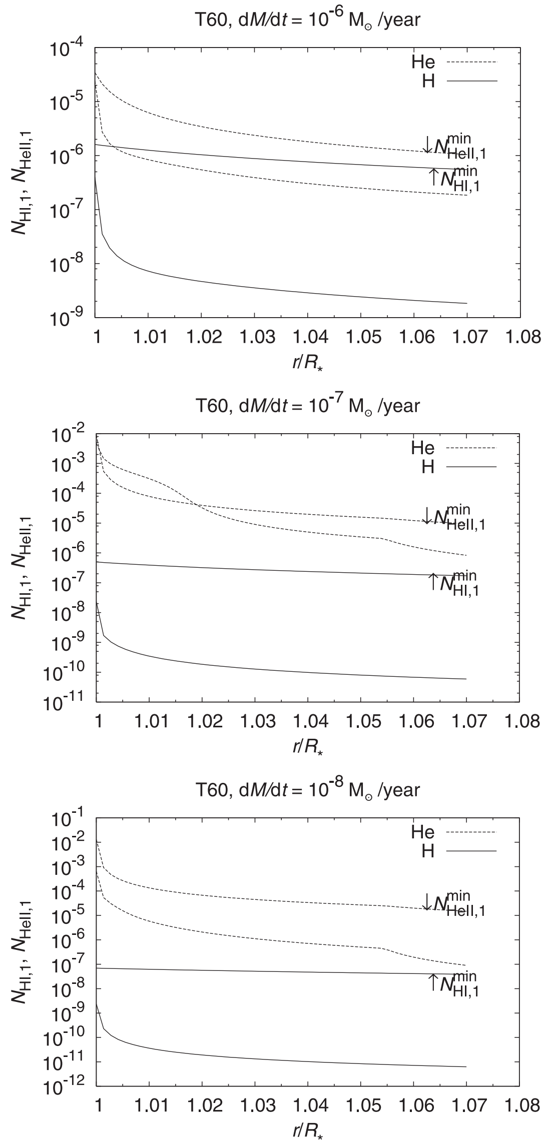


Fig. 2. The same as Fig. 1, however for model T50.



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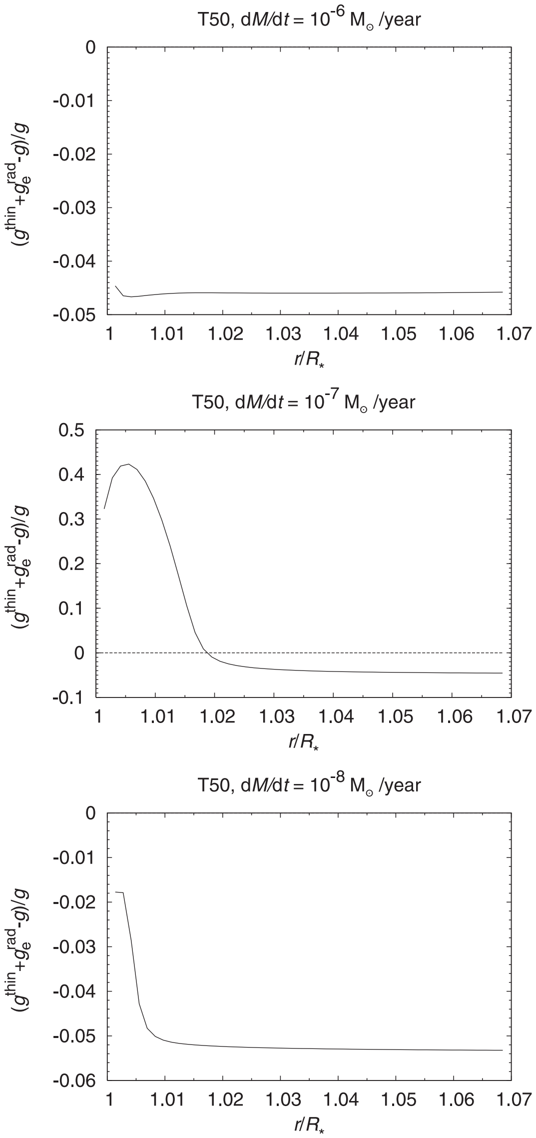

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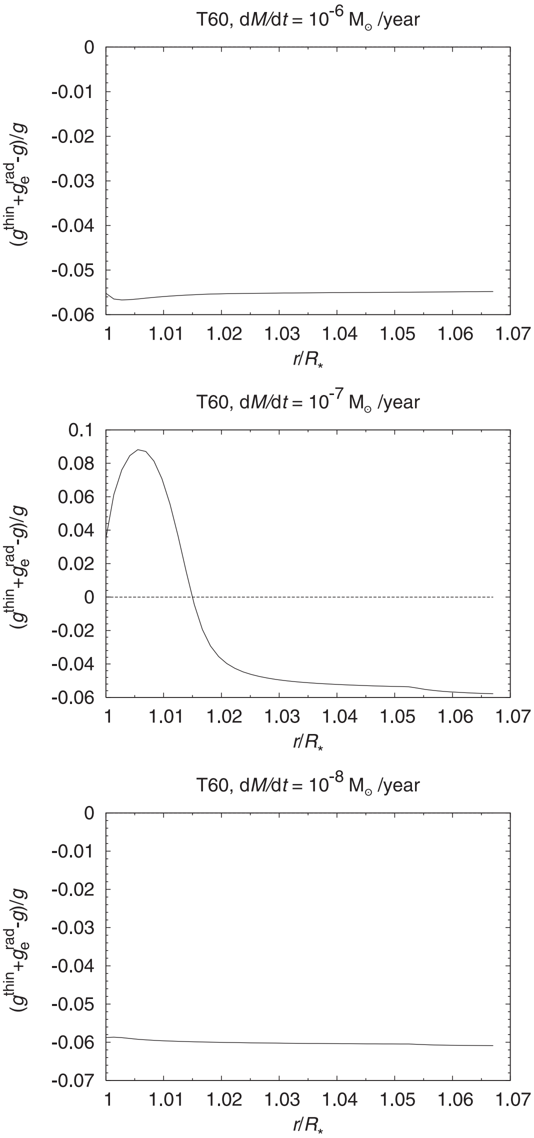

Fig. 6. The same as Fig. 4, however for model T60.

Appendix A: Gravitational settling time scale

We estimate the characteristic time-scale $\tau_{\rm D}$ for gravitational settling of helium in the atmospheres of first stars. This is given by (Kippenhahn & Weigert 1990, p. 59)

$$\tau_{\rm D} \approx \frac{S^2}{D}, \tag{A.1}$$

where S is the characteristic length for the density variation and the diffusion coefficient

$$D \approx \ell \sqrt{\frac{kT}{3m_{\rm H}}}. \tag{A.2}$$

The mean free path of helium in hydrogen plasma ℓ we estimate using the expression for Coulomb collision frequency (Burgers 1969). For typical parameters of the outer parts of the atmosphere ($S = 10^{11}$ cm, $n \approx 10^8\,{\rm cm}^{-3}$, $T \approx 30\,000$ K) we obtain a mean free path of $\ell \approx 10^4$ cm and corresponding characteristic diffusion time scale $\tau_{\rm D} \approx 10^4$ years, which shows that gravitational settling is possible in the outer parts of the atmosphere of first stars. On the other hand, in deeper atmospheric layers (where $S = 10^{11}$ cm, $n \approx 10^{13}\,{\rm cm}^{-3}$, $T \approx 50\,000$ K) we obtain a mean free path of $\ell \approx 1$ cm and a diffusion time scale $\tau_{\rm D} \approx 10^8$ years, which greatly exceeds the expected lifetime of massive first stars (Marigo et al. 2001), which is about 10^6 years. Clearly, in the deeper layers the gravitational settling of helium probably does not take place.

This analysis enables us to estimate the mass-loss rate due to the pure hydrogen wind, which is

$$\dot{M}_{\rm H} \approx 4\pi R_*^2 S\, n m_{\rm H} \tau_{\rm D}^{-1}. \tag{A.3}$$

Note that since $D \sim 1/n$ the estimated mass-loss rate does not depend on the atmospheric number density n, thus for both atmospheric points mentioned above we obtain $\dot{M}_{\rm H} \approx 10^{-16}\ M_\odot\,{\rm year}^{-1}$. This value is close to a more exactly estimated upper limit of a hydrogen stellar wind derived in Appendix B.

Appendix B: Pure hydrogen wind driven by free electrons

The radiative acceleration due to the light scattering on free electrons may be higher than the gravitational acceleration in pure hydrogen plasma for stars with $\Gamma \gtrsim 0.859$ (see Eq. (32)). Thus, if the hydrogen layer builds up at the surface of such a star (e.g. due to gravitational settling) then a pure hydrogen wind may occur (cf. Malov 1974, for a description of a stellar wind driven by Thomson scattering). In a stationary state such a stellar wind may be described (assuming spherical symmetry) by hydrodynamical equations (Burgers 1969, see also Krtička & Kubát 2001)

$$\frac{{\rm d}}{{\rm d}r}\left(r^2\rho_{\rm H}\upsilon_{r\rm H}\right) = 0, \tag{B.1a}$$

$$\upsilon_{r\rm H}\frac{{\rm d}\upsilon_{r\rm H}}{{\rm d}r} = g^{\rm rad}_{\rm e,H} - g - \frac{1}{\rho_{\rm H}}\frac{{\rm d}}{{\rm d}r}\left(a_{\rm H}^2\rho_{\rm H}\right) - \frac{1}{\rho_{\rm H}}K_{{\rm H}\alpha}G(x_{{\rm H}\alpha}), \tag{B.1b}$$

where indexes H and α stand for hydrogen and alpha particles, $\upsilon_{r\rm H}$ and $\rho_{\rm H}$ are the radial velocity and the density of completely ionized pure hydrogen plasma, $a_{\rm H}^2 = 2kT/m_{\rm H}$ (we assume that hydrogen and helium temperares are equal), the frictional parameter

$$K_{{\rm H}\alpha} = n_{\rm H}n_\alpha k_{{\rm H}\alpha} = n_{\rm H}n_\alpha\frac{4\pi q_{\rm H}^2 q_\alpha^2}{kT}\ln\Lambda, \tag{B.2}$$

and where the Chandrasekhar function $G(x)$, defined in terms of the error function ${\rm erf}(x)$, is

$$G(x) = \frac{1}{2x^2}\left({\rm erf}(x) - \frac{2x}{\sqrt{\pi}}\exp\left(-x^2\right)\right), \tag{B.3}$$

and the argument of the Chandrasekhar function is

$$x_{{\rm H}\alpha} = \frac{\upsilon_{r\rm H}}{\alpha_{{\rm H}\alpha}}, \tag{B.4}$$

where we have assumed that helium is static in the atmosphere and

$$\alpha_{{\rm H}\alpha}^2 = \frac{2kT\,(m_{\rm H}+m_\alpha)}{m_{\rm H}m_\alpha}. \tag{B.5}$$

Inserting continuity equation Eq. (B.1a) into Eq. (B.1b) and using the definition of $\Gamma_{\rm H}$ (see Eq. (28)) we obtain the momentum equation in the form of

$$\left(\upsilon_{r\rm H} - \frac{a_{\rm H}^2}{\upsilon_{r\rm H}}\right)\frac{{\rm d}\upsilon_{r\rm H}}{{\rm d}r} = \frac{GM}{r^2}\left(\Gamma_{\rm H}-1\right) - \frac{{\rm d}a_{\rm H}^2}{{\rm d}r} + \frac{2a_{\rm H}^2}{r} - \frac{n_\alpha}{m_{\rm H}}k_{{\rm H}\alpha}G(x_{{\rm H}\alpha}). \tag{B.6}$$

This equation has a critical point for $\upsilon_{r\rm H} = a_{\rm H}$. To obtain a smooth solution at this critical point the critical condition

$$\frac{GM}{r^2}\left(\Gamma_{\rm H}-1\right) - \frac{{\rm d}a_{\rm H}^2}{{\rm d}r} + \frac{2a_{\rm H}^2}{r} - \frac{n_\alpha}{m_{\rm H}}k_{{\rm H}\alpha}G\left(\frac{a_{\rm H}}{\alpha_{{\rm H}\alpha}}\right) = 0 \tag{B.7}$$

should be fulfilled. Finally, the helium density in a static case is given by the equation of hydrostatic equilibrium in the form of

$$-\frac{GM}{r^2}\left(1-\Gamma_\alpha\right) - \frac{1}{\rho_\alpha}\frac{{\rm d}}{{\rm d}r}\left(a_\alpha^2\rho_\alpha\right) + \frac{n_{\rm H}}{m_\alpha}k_{{\rm H}\alpha}G(x_{{\rm H}\alpha}) = 0. \tag{B.8}$$

Equations (B.6)–(B.8) (together with the boundary condition that links hydrogen and helium density deep in the stellar atmosphere) can be used to calculate wind models of pure hydrogen flow. The mass-loss rate of such a wind can be obtained by the requirement that the critical condition (B.7) is fulfilled at the critical point.

We do not aim to solve equations for pure hydrogen wind here; we present only an estimate of upper limit of the mass-loss rate. To make its derivation more tractable, we neglect gas-pressure terms in Eqs. (B.6)–(B.8). The critical condition (B.7) then yields the helium density at the critical point as

$$n_\alpha^{\rm crit} \approx \frac{GM}{r_{\rm crit}^2}\left(\Gamma_{\rm H}-1\right)\frac{m_{\rm H}}{k_{{\rm H}\alpha}}\left[G\left(\frac{a_{\rm H}}{\alpha_{{\rm H}\alpha}}\right)\right]^{-1}. \tag{B.9}$$

Similarly, the gas pressure term in the helium hydrostatic equation Eq. (B.8) is always positive, thus the upper limit for hydrogen density at the critical point is

$$n_{\rm H}^{\rm crit} \lesssim \frac{GM}{r_{\rm crit}^2}\left(1-\Gamma_\alpha\right)\frac{m_\alpha}{k_{{\rm H}\alpha}}\left[G\left(\frac{a_{\rm H}}{\alpha_{{\rm H}\alpha}}\right)\right]^{-1}. \tag{B.10}$$

With this we can derive the upper limit for the hydrogen mass loss rate as

$$\dot{M}_{\rm H} \lesssim 4\pi\, n_{\rm H}^{\rm crit}\, \upsilon_{r\rm H}^{\rm crit}\, r_{\rm crit}^2 = \\ 4\pi a_{\rm H} GM\,(1-\Gamma_\alpha)\,\frac{m_{\rm H} m_\alpha}{k_{{\rm H}\alpha}}\left[G\left(\frac{a_{\rm H}}{\alpha_{{\rm H}\alpha}}\right)\right]^{-1}. \quad \text{(B.11)}$$

Assuming $q_\alpha = 2q_{\rm H}$ this can be rewritten as

$$\dot{M}_{\rm H} \lesssim 2\times10^{-14}\, M_\odot\,{\rm year}^{-1}\left(\frac{M}{100\,M_\odot}\right)\left(\frac{T}{10^4\,{\rm K}}\right)^{3/2}(1-\Gamma_\alpha)\,. \quad \text{(B.12)}$$

This shows that the mass-loss rate of a hypothetical pure hydrogen wind is very small.

The wind velocity of such a wind outside the stellar atmosphere can be easily obtained from Eq. (B.6) assuming a negligible frictional force ($G(x_{{\rm H}\alpha}) \ll 1$), since in such a case we obtain an equation for the Parker type stellar wind (assuming isothermal wind, see Mihalas 1978). Note however, that the wind terminal velocity is influenced either by the radiative heating and cooling processes (which influence the sound speed $a_{\rm H}$) or by hydrogen recombination, which decreases the radiative force on free electrons.

Note however that the real situation likely will be more complex than that presented here. First, Eqs. (B.1) were derived assuming Maxwellian distributions of velocities for all the components. While this may be true for hydrogen and helium, the velocity distribution of electrons may have two maxima (one corresponding to electrons that move together with hydrogen and one corresponding to electrons that stay in the atmosphere). Possibly, an electric polarisation field, which was neglected in Eqs. (B.1), may play a role. Finally, the process described here may not be stationary. It is not likely that the pure hydrogen mass-loss rate is by orders of magnitude higher than that presented here, hence the influence of pure hydrogen mass-loss on the evolution of first stars is only marginal.

For the calculation of the radiative force we have assumed that the stellar wind is optically thin for Thomson scattering, which seems to be a plausible approximation given the low mass-loss rate.

We propose that wind driven by scattering on free electrons may exist. Malov (1974) concluded that such wind can exist only in the case of a positive temperature gradient $\mathrm{d}T/\mathrm{d}r > 0$ at the wind critical point. His conclusion is based on the critical point condition (B.7), which indeed cannot be fulfiled if $\mathrm{d}T/\mathrm{d}r \leq 0$ and if we do not account for friction due to the helium atoms. Here, however, the friction due to the helium atoms enables us to fulfill the critical point condition and acts in a similar way as the positive temperature gradient in Malov's (1974) paper.