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Hydrodynamic atmosphere models for hot stars

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Abstract. Nowadays, most non-LTE codes for the expanding atmospheres of hot stars consider model atoms of H, He, C, N, O, the iron group and other trace elements, including several millions of line transitions. Due to the frequency coupling in expanding atmospheres, it is not possible to apply sampling or re-ordering techniques to these complex opacity distributions. Instead, it is necessary to cover the whole relevant frequency range by a dense frequency grid and to calculate all individual line transitions at their proper frequency.

This detailed treatment of the radiation field offers the opportunity to calculate the radiative acceleration directly in the CMF radiation transport, i.e. effects like multiple line scattering or line blocking, and the transition from the optically thick part of the photosphere to the stellar wind are described in a realistic way. As shown by Gräfener, Koesterke, & Hamann (2002) for the case of WC stars, these models are able to produce a radiative acceleration which is lying significantly above the single scattering limit. Therefore, an extension of the present codes by a consistent treatment of the hydrodynamic equations is highly desirable for a profound understanding of radiatively accelerated winds.

In the present work we develop a method for the solution of the hydrodynamic equations, which utilizes the radiative force from the radiation transfer instead of the standard parametrization with force multipliers (Castor, Abbott, & Klein, 1975). The solution of these equations is fed back into the non-LTE code, and both codes are iterated until a fully consistent hydrodynamic atmosphere structure is achieved.

1. The radiative acceleration

In our CMF radiation transport, the opacity κ_ν and the Eddington flux H_ν are given on a fine grid over the whole relevant frequency range. This allows a direct integration of the radiative acceleration

$$a_{\mathrm{rad}} = \frac{1}{\rho}\frac{4\pi}{c}\int_0^\infty \kappa_\nu H_\nu \,\mathrm{d}\nu.$$

For a proper representation in the hydrodynamic equations it is further necessary to account for the dependence of a_{rad} on the velocity gradient v'. In contrast to Castor et al. (1975), who are using a nonlinear, globally parametrized form of the line force, we choose a linear approach for the v'-dependence. By this, we avoid numerical problems which arise from the fact that $a_{\rm rad}$ is prescribed by our atmosphere models in arbitrary form. Nevertheless, the characteristic properties of the hydrodynamic equations due to radiative-acoustic waves (see Abbott 1980) are retained.

In our approach $a_{\rm rad}$ is divided into a part due to optically thick spectral lines $\propto \frac{1}{\rho}\frac{\partial v}{\partial r}/r^2$ and a part due to optically thin lines and continua $\propto 1/r^2$. The size of both terms is determined by calculating $a_{\rm rad}$ for slightly varied velocity fields $v(r)$ in the radiation transport. As a result we obtain $a_{\rm rad}$ in the form

$$a_{\rm rad} = \frac{M_\star G\,\Gamma(\tau)}{r^2} + \frac{k(\tau)}{r^2}\left(\frac{1}{\rho}\frac{\partial v}{\partial r}\right)$$

with Γ and k being functions of the depth index in our model atmospheres.

2. The hydrodynamic equations

For given stellar parameters $M_\star$, $L_\star$ and $R_\star$ we intend to determine a stationary density and velocity structure $\rho(r)$ and $v(r)$ from the equations of hydrodynamics. Therefore we write down the equation of motion for a stationary velocity field $v(r)$ including $a_{\rm rad}$

$$v\frac{{\rm d}v}{{\rm d}r} = -\frac{M_\star G\,(1-\Gamma(\tau))}{r^2} - \frac{1}{\rho}\frac{{\rm d}p}{{\rm d}r} + \frac{k(\tau)}{r^2}\left(\frac{1}{\rho}\frac{{\rm d}v}{{\rm d}r}\right).$$

By the pressure term, this equation is coupled to the temperature $T(\tau)$ which is derived from the assumption of radiative equilibrium in our non-LTE atmosphere models. Because of this coupling, and because of the necessity to preserve the optical depth scale of the model atmosphere for subsequent iterations, it is requisite to choose the optical depth as integration variable. For simplicity we define ${\rm d}\tau = \rho\,{\rm d}r$ (i.e. in effect the ρ-dependence of the averaged absorption cross section is neglected).

Utilizing the sonic speed $a(\tau)$ in the pressure term, we obtain the following three equations: The equation of motion in the form

$$\frac{{\rm d}v}{{\rm d}\tau}\left[\left(1-\frac{a^2}{v^2}\right)\frac{\dot M}{4\pi} - k\right] = -M_\star G\,(1-\Gamma) + 2\,a^2 r - \frac{\dot M}{4\pi}\frac{1}{v}\frac{{\rm d}a^2}{{\rm d}\tau},$$

the equation of continuity $\dot M = 4\pi\rho\,v\,r^2$, and our definition of the optical depth ${\rm d}\tau = \rho\,{\rm d}r$. The equation of motion has a critical point where $[...] = 0$. This happens when $v(r)$ reaches the value of the fast radiative-acoustic wave mode (Abbott 1980). At this point the right hand side of the equation must also be zero for $\frac{{\rm d}v}{{\rm d}\tau}$ to be defined.

The three equations must be solved for $\rho(\tau)$, $v(\tau)$ and $r(\tau)$. For given start values of ρ, v and r at some arbitrary point in the atmosphere the solution is easily obtained by direct integration. To determine the three start values we need three conditions: For the radius we have two conditions viz $r(\tau_\star) = R_\star$ at the inner boundary and $r(0) = R_{\rm max}$ at the outer boundary. $R_\star$ and $R_{\rm max}$ are defined by the radial depth grid, and $\tau_\star = -\int_{R_\star}^{\infty}\rho\,{\rm d}r$ by the density structure of the precedent model atmosphere calculation. The system is closed by the critical condition for the equation of motion. In relation to Castor et al. (1975) we omit the regularity condition by our linearized approach, but we gain two conditions by the inclusion of the preservation of optical depth, which is indispensable for the application to a model atmosphere code.

For the numerical solution we perform a Runge-Kutta integration of the three equations, starting at the outer boundary with $r = R_{\max}$. The outer boundary values of ρ and v are adjusted until the critical condition and the condition $r(\tau_\star) = R_\star$ are fulfilled simultaneously. The obtained solution for $\rho(r)$ and $v(r)$ is then fed back into our model atmosphere code. Generally, a fully consistent solution is reached after ≈ 10 iterations between non-LTE radiation transport and hydrodynamics.

3. Model calculations

For first tests we choose a model with $L_\star = 10^{5.8} L_\odot$ and $T_\star = 37\,\mathrm{kK}$, which reproduces the observed flux distribution (UV to IR) and the photospheric H/He line profiles of the O4 supergiant ζ Pup. Apart from H and He, the model comprises complex model atoms of CNO and the iron group. The latter is treated by "super levels" and includes $\approx 10^7$ spectral lines from the Kurucz data. The models allow for clumping, i.e. the radiation transport is solved for the averaged opacity whereas the statistical equations are solved for an enhanced clump density $D \times \rho$ (see e.g. Hamann & Koesterke 1998).

Problems occur for smooth wind models, because the radiative acceleration just above the photosphere drops below the gravitational acceleration, i.e. no monotonic solution can be obtained. As demonstrated in Fig. 1, this problem is circumvented by assuming a clumped wind structure. In our test model we increase the clumping factor D up to values of 64 in the optically thin part of the atmosphere (for $\tau_{\mathrm{ross}} < 0.015$). Due to the ρ^2-dependence of the recombination rates, the populations below the main ionization stage are thereby increased, which leads to a larger fraction of optically thin line opacities.

Fig. 1 shows the different contributions to the wind acceleration in our test model. With a stellar mass of $M_\star = 48\,M_\odot$ the observed terminal wind velocity of ζ Pup ($v_\infty = 2100\,\mathrm{km/s}$) is reproduced, but the resultant mass loss rate ($10^{-6.3} M_\odot/\mathrm{yr}$) lies far below the value of $\approx 10^{-5.6} M_\odot/\mathrm{yr}$ that is needed to reproduce the observed UV wind profiles. The obvious discrepancy between model and observation may be attributed to still lacking trace elements, or to the constant line broadening velocity of $100\,\mathrm{km/s}$ assumed in our models. The latter is a reasonable value for the outer wind, but may lead to an overestimation of line blanketing effects in the photosphere (i.e. a too low $T_\star$ + an increased blocking of UV photons).

The broken line in Fig. 1 indicates the radiative acceleration for a model with the same atmosphere structure as our hydrodynamic model, but with the clumping factor set to $D = 1$ throughout the entire wind. Whereas the effect of clumping is relatively small in the low-density part of the wind, it increases with increasing density and has a rather strong influence in the acceleration region just above the photosphere.

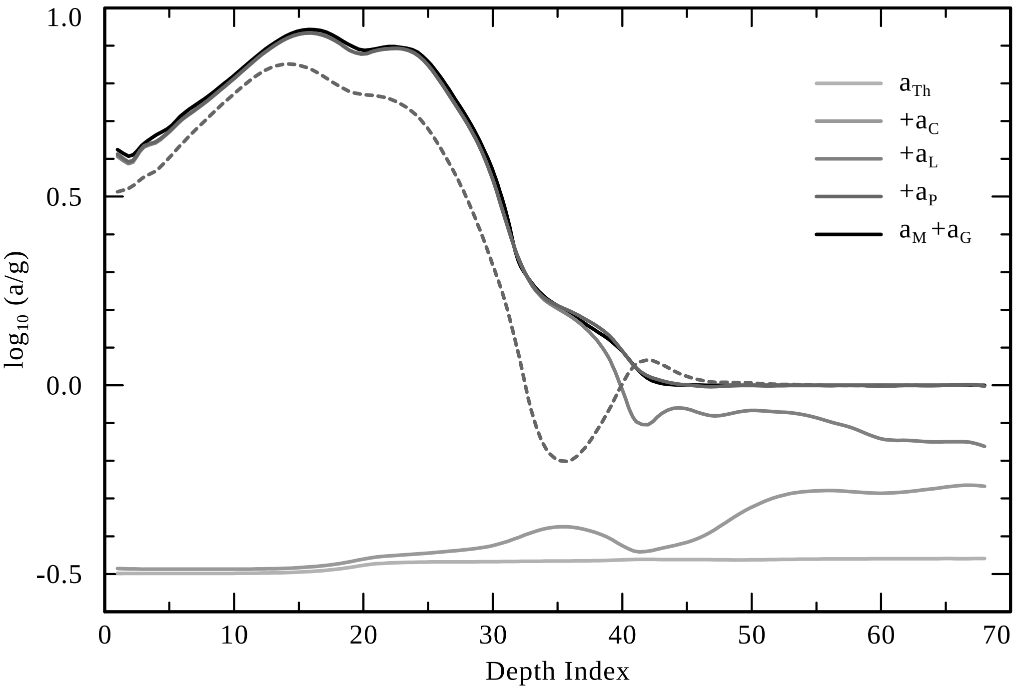

Figure 1. The different contributions to the wind acceleration in units of the local gravity $g(r)$ vs. depth index (outer boundary: 0; inner boundary: 70). The black line (in the background) indicates the mechanical + gravitational acceleration ($a_{\mathrm{M}} + a_{\mathrm{G}}$) as calculated from the hydrodynamic velocity structure and the adopted stellar mass. The grey lines indicate the different contributions to the outward directed wind acceleration (from light to dark grey): The radiative acceleration on free electrons (a_{Th}), on continua ($a_{\mathrm{Th}} + a_{\mathrm{C}}$), the total radiative acceleration including lines ($a_{\mathrm{Th}} + a_{\mathrm{C}} + a_{\mathrm{L}}$), and the total wind acceleration including the pressure term ($a_{\mathrm{Th}} + a_{\mathrm{C}} + a_{\mathrm{L}} + a_{\mathrm{P}}$). The high degree of consistency between the radiation transport an the equation of motion is indicated by the coincidence between the black and the dark grey curve. The hydrodynamic model is calculated with a very high clumping factor, which is increased up to values of $D = 64$ in the outer part of the wind. The effect of switching D back to 1 on the wind acceleration is indicated by the broken line.

References

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