HEATING IN THE STELLAR WINDS OF HOT STARS

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Abstract

Multicomponent radiatively driven winds in late B stars cause significant heating of the layers just above the photosphere. If heating is large enough to heat the circumstellar environment up to coronal temperatures, then a coronal wind may be present. In addition, the coronal region may be a site of significant X-ray emission being able to explain observed X-ray activity of early B stars.

Introduction

Stellar winds in hot stars are known to be radiatively driven. The radiative momentum is transferred from radiation to a gas by means of absorption. Not all chemical elements are equal absorbers, so some elements are accelerated more than the others. In the case that there is enough collisions that may redistribute the momentum over the entire gas (basically elastic collisions), the radiatively driven stellar wind behaves like a one-component fluid. This issue has been discussed by Castor et al. [1] and for the case of O star winds they concluded that the amount of collisions is sufficient to maintain the wind as a one-component flow. Corresponding continuity and momentum equations read

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2 \rho v\right) = 0,$$

$$v\frac{\mathrm{d}v}{\mathrm{d}r} = f^{\mathrm{rad}} - f^{\mathrm{grav}} - \frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}r},$$

Where f^{rad} is the radiative acceleration, is the gravitationa acceleration, p is the gas pressure, ρ is the density, and v is the flow velocity. The one-component approximation was then used in a majority of radiatively driven wind model calculations and computed models gave successful comparison with observations (for a review see Kudritzki & Puls [2]).

The possibility of a lower momentum transfer by collisions was first discussed by Springmann & Pauldrach [3]. First multicomponent hydrodynamic calculations of a radiatively driven stellar wind were performed by Babel [4,5]. Porter & Drew [6] studied the multicomponent wind using a simplified beta-velocity law. Later, Porter & Skouza [7] discussed the possibility of a wind reaccretion after its decoupling. Consistent hydrodynamic calculations of a multicomponent wind were performed by Krticka & Kubát [8,9,10]. The stability of such a wind has been discussed by Owocki & Puls [11] and Krticka & Kubát [12].

Multicomponent monotemperature winds

In a real radiatively driven wind the chemical species may be divided into three basic groups according to the ability to absorb radiation. The first group consists of radiatively accelerated particles that have enough ability to absorb radiation and, consequently, are significantly accelerated by absorption of radiation in spectral lines. The second group involves particles whose contribution to the radiative force is almost negligible compared to the first group. This group is taken along by friction with the first group. Since its role in the stellar wind is passive, we call this group as a passive component. In real stars it consists of hydrogen and helium. The third group are free electrons, which are accelerated by Thomson scattering and by friction as well. Each component is described by a set of equations of continuity, motion, and energy (here *a* stands for *i* - accelerated ions, *p* - passive component, and *e* - electrons),

$$v_{ra}\frac{\mathrm{d}v_{ra}}{\mathrm{d}r} = g_a^{\mathrm{rad}} - g - \frac{1}{\rho_a}\frac{\mathrm{d}p_a}{\mathrm{d}r} + \frac{q_a}{m_a}E + \frac{1}{\rho_a}\sum_{b\neq a} R_{ab},$$

$$\frac{3}{2}k\frac{\mathrm{d}T}{\mathrm{d}r}\sum_a v_{ra}\frac{\rho_a}{m_a} + \sum_a a_a^2\rho_a\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2 v_{ra}\right) = \\ = Q^{\mathrm{rad}} - \frac{1}{2}\sum_a\sum_{b\neq a} R_{ab}\left(v_{ra} - v_{rb}\right),$$

Where subscript denotes variables corresponding to the component *a*, *T* is the temperature, *E* electric polarisation field, and R_{ab} is the frictional force. The radiative force in the CAK approximation for the multicomponent wind reads (see Krticka & Kubát [9])

$$g_{\mathrm{i}}^{\mathrm{rad}} = \frac{1}{\mathfrak{Y}_{\mathrm{i}}}\frac{\sigma_e L}{4\pi r^2 c} f \left(\frac{n_e/W}{10^{11}\mathrm{cm}^{-3}}\right)^{\delta} k \left(\frac{\mathfrak{Y}_{\mathrm{i}}}{\sigma_e v_{\mathrm{th}}\rho_{\mathrm{i}}}\frac{dv_{r\mathrm{i}}}{dr}\right)^{\alpha},$$

with Abbott [13] force multipliers, *f* is the finite disk correction factor, *W* is the stellar dilution factor.

The main driving force for the passive plasma, namely the frictional force between charged particles reads

$$R_{ab} = -n_a n_b k_{ab} G(x_{ab}),$$

where x_{ab} is the dimensionless velocity difference,

$$k_{ab} = \frac{4\pi \ln \Lambda q_a^2 q_b^2}{kT} \frac{v_{ra} - v_{rb}}{|v_{ra} - v_{rb}|}$$

is the friction coefficient and *G(x)* is the Chandrasekhar function (see Fig. 1).

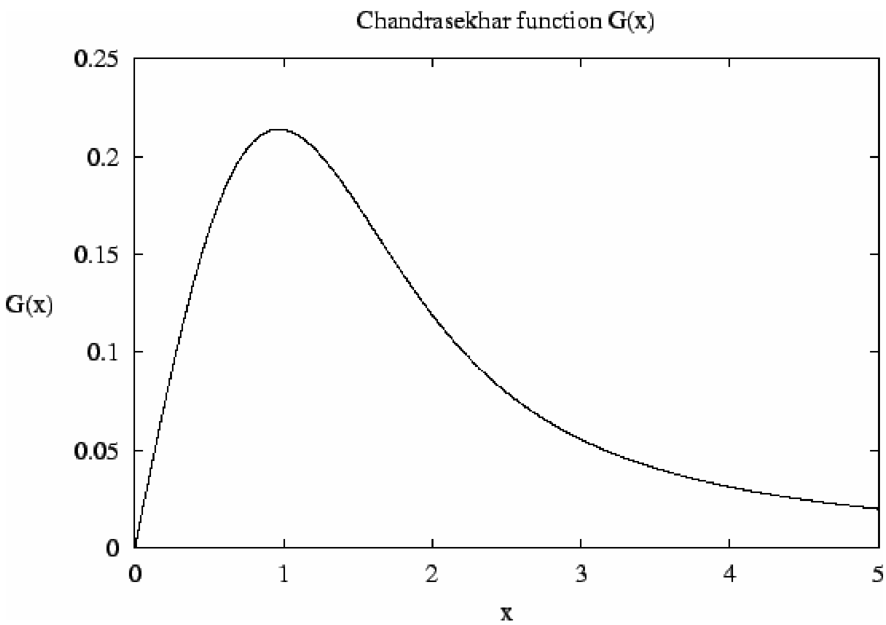

Figure 1: The Chandrasekhar function *G(x)*

The radiative energy term involves free-free heating, free-free cooling, bound-free heating, and bound-free cooling due to hydrogen.

Calculations of the three-component wind models show the same results as for the one component wind for the case of galactic O stars, which means that the one-component approximation is an adequate one for winds of these stars. On the other hand, there is a relatively large heating for lower effective stellar temperatures, namely for the main-sequence B type stars. An interesting fact is that for lower effective temperatures we obtain higher wind temperatures, a consequence of a frictional heating, which rises with decreasing effectiveness of elastic collisions. Detailed results of the three component calculations as well as the complete list of equations are presented in Krticka & Kubát [9].

Multitemperature winds

A more general treatment of the three-component wind adds the possibility of different temperatures for different components. The basic difference is in the energy equation, which now reads

$$\frac{3}{2}kv_{ra}\frac{\rho_a}{m_a}\frac{\mathrm{d}T_a}{\mathrm{d}r}+a_a^2\rho_a\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2v_{ra}\right)=Q_a^{\mathrm{rad}}+$$
$$+\frac{1}{\sqrt{\pi}}\sum_{b\neq a}K_{ab}\frac{2k\left(T_b-T_a\right)}{m_a+m_b}\frac{\exp\left(-x_{ab}^2\right)}{\alpha_{ab}}+$$
$$+\sum_{b\neq a}\frac{m_b}{m_a+m_b}K_{ab}G(x_{ab})\left|v_{rb}-v_{ra}\right|,$$

Common processes which influence all components are advection cooling, adiabatic cooling, heat exchange by collisions, and friction. However, not all heating and cooling processes are effective for all wind components. Radiative bound-free and free-free transitions affect only electrons - they transfer energy between radiation field and electron gas. Accelerated ions are subject to the so-called Gayley-Owocki heating (sometimes also called Doppler heating), which is caused by the fact that radiation is absorbed and then reemitted at different wind velocities (and thus Doppler shifted). The energy difference is then consumed for heating the ionic gas. This effect was first discussed by Gayley & Owocki [14]. Recently, it was rederived directly from the Boltzmann kinetic equation by Krticka & Kubát [10].

Results of multitemperature calculations generally confirm monotemperature three-component results, the only qualitative difference that in the heated region the component temperatures slightly differ. There is no heating in the O star domain, as for monotemperature flows. Detailed results may be found in Krticka & Kubát [10].

Consequences of coronal temperatures

If large heating leads to coronal temperatures (of order 10^7 K), then such medium has to emit X-ray radiation. This has been really observed, an average X-ray luminosity of main-sequence B3 stars according to ROSAT observations (Cohen [15]) is $10^{-9}\,L$. For our models the X-ray luminosity is 10^{-11} -10^{-7} L, so the observed X-ray energy falls into the approximate theoretical interval. It points out an interesting possibility of generation of X-ray radiation in B stars by frictionally heated plasma.

Another consequence is that high temperature totally changes the ionization structure of the wind, and, consequently, also the absorption coefficients. Then the radiation driving force may be significantly affected by these changes and the radiatively driven wind may be probably ``switched off" due to insufficient absorption. If the temperature in the corona is high enough, a coronal wind may appear. Kubát et al. [16] named such wind as a radiation induced wind. However, they did not find enough heating from the friction in a two-component wind, so the coronal wind from B stars remains still suspicious.

Conclusions

Frictional heating and GO heating lead to substantial heating of the wind and may change the outflow velocity. Large heating may lead to formation of a coronal region. Frictional heating is another possible source of X-ray radiation in addition to shocks. There is a possibility of launching the coronal wind in hot stars, but the frictional model does not yield enough heating.

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Bibliography

[1] Castor, J. I., Abbott, D. C., Klein, R. I. 1976, in Physique des mouvements dans les atmosphcres stellaires, R. Cayrel & M. Sternberg eds., CNRS Paris, p.363

[2] Kudritzki, R. P., Puls, J. 2000, *Ann. Rev. Astron. Astrophys.* **38**, 613

[3] Springmann, U. W. E., Pauldrach, A. W. A. 1992, *Astron. Astrophys.* **262**, 515

[4] Babel, J. 1995, *Astron. Astrophys.* **301**, 823

[5] Babel, J. 1996, *Astron. Astrophys.* **309**, 867

[6] Porter, J. M., Drew, J. E. 1995, *Astron. Astrophys.* **296**, 761

[7] Porter, J. M., Skouza, B. A. 1999, *Astron. Astrophys.* **344**, 205

[8] Krticka, J., Kubát, J. 2000, *Astron. Astrophys.* **359**, 983

[9] Krticka, J., Kubát, J. 2001, *Astron. Astrophys.* **369**, 222

[10] Krticka, J., Kubát, J. 2001, *Astron. Astrophys.* **377**, 175

[11] Owocki, S. P., Puls, J. 2002, *Astrophys. J.* **568**, 965

[12] Krticka, J., Kubát, J. 2002, *Astron. Astrophys.* **388**, 531

[13] Abbott, D. C. 1982, *Astrophys. J.* **259**, 282

[14] Gayley, K. G., Owocki, S. P. 1994, *Astrophys. J.* **434**, 684

[15] Cohen, D. H., Cassinelli, J. P., MacFarlane, J. J. 1997, *Astrophys. J.* **487**, 867

[16] Kubát, J., Krticka, J., Pustylnik, I. B. 2004, *New Astron.* **9**, 215