CAN HOT STAR WINDS BE DRIVEN BY RADIATION PRESSURE?

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Abstract.

The mechanisms by which early type (O and B) stars loose mass is investigated. The phenomena occuring close to the photosphere are crucial for the structure of the wind. It is shown that the effects of radiation are not sufficient to explain the observed winds. A general scheme for energy balance including a corona is proposed.

Introduction

This communication is concerned with a theoretical study of stellar winds for early type stars like O and B stars.

We don't intend to investigate one particular star, but rather we try to understand which physical phenomena cause winds such as those observed, i.e., with high terminal velocities (600-3000 km/s) and large mass loss rates (10^{-6} M_O/yr). These phenomena are certainly in strong relation with radiation transfer processes, which can be expected to be important in the high luminosity stars under consideration.

Recently, models have been built in order to describe such stellar winds. Our aim is to point out the underestimated consequences of some assumptions concerning: 1) the existence of radiative equilibrium throughout the wind, 2) the inner boundary conditions of the wind, 3) the non-local character of radiative transfer.

Equations

We use the following assumptions

- no time dependence (steady state); this excludes stars with high variability like Be stars for instance.

- spherical symmetry (rotation and magnetic fiels are assumed to be negligible). The equations governing the structure of the wind are those expressing:

C. Chiosi and R. Stalio (eds.), Effects of Mass Loss on Stellar Evolution, 167–171.

- mass conservation $4\pi r^2 \rho(r) v(r) = \dot{M}$ (1)
- momentum transport

$$v \, dv/dr = -\nabla p/\rho + f_r - GM/r^2 \quad (2)$$

where p, f_r denote respectively the thermal pressure and the radiative force. Note that the forces due to the thermal pressure gradient and radiation are both directed outwards, contrary to gravity.

- evolution of the internal energy of the gas. We can state it under the following form

$$A - B \; (+\mathcal{M}) = \Gamma^{-1} \, \psi(v,T) \quad (3)$$

In equation (3) A describes heating by absorption of radiation, B describes cooling by emission of radiation, $\mathcal{M}$ is some eventual unspecified extra source of energy due, for instance, to wave dissipation, Joule effect or anything else.

ψ accounts for the variations of the thermal energy and the work of the thermal pressure. Γ is the usual undimensioned luminosity to mass ratio.

Now, under realistic conditions for A, B, ψ, Γ, the ratio ψ/Γ is negligible compared to A or B, due to the high value of Γ ($\Gamma \sim 10^{-1}$ for early type stars). Thermal conduction is also negligible except in case of very high temperature gradients unlikely except in thin hot coronas (say 10^6 °K for a thickness of 10^{-5} stellar radius).

Finally, when there is no extra energy term ($\mathcal{M} = 0$), radiative equilibrium holds throughout the wind (A = B)

Nevertheless, one should never omit that radiative equilibrium can locally break, if the extra source term $\mathcal{M}$ locally becomes of the order of magnitude of one of the radiative terms A or B.

Boundary conditions

They are very important in this problem.

We can consider the stellar wind as an intermediate medium between two definite media : the interstellar medium outward, and the optically thick stellar core bounded by the photosphere.

At the outer boundary we require that no radiation comes from the exterior, and that the thermal pressure be very small at infinity compared to that at the photosphere.

We can define the inner boundary, namely the photosphere as the place where radiation thermalizes at al wavelengths, both in the continuum and in the lines. Therefore, at the inner boundary the optical depth is at least of the order of ten for all wavelengths. Moreover, we set that the temperature at the inner boundary is of the order of the effective temperature of the star.

Now, the thermalization of radiation is described using Milne's equation for the radiative flux.

This last condition was not taken into account in previous works dealing with self consistent wind models, and in particular in the pioneer work by Castor, Abbot and Klein in 1975.

In fact, this condition is very stringent because the way in which the radiative force increases from the photosphere up to large radial distances is strongly dependent on the nature of the radiative flux in the inner part of the wind.

Model

We modelize the opacity per unit mass in the continuum and in the lines by a picket-fence model. The contribution of the lines to the radiative force is derived from the solution of the radiative transfer equation using the comoving frame method of Mihalas, Kunasz and Hummer (1976).

We consider an extended atmosphere in radiative equilibrium everywhere (we set $\mathcal{M} = 0$ in equation (3)). Cases in which $\mathcal{M} \neq 0$ will be discussed later.

We solve the coupled transfer and hydrodynamical equations simultaneously. It has it be pointed out that such calculations

1) allow us to get rid of the Sobolev approximation and
2) contrary to previous works, take into account the strongly non local nature of radiation transfer and the inner boundary conditions.

Results

With realistic opacities and star parameters (mass, luminosity, star radius, etc) for stars like ζ Pup, one finds that the driving forces do not allow winds with both realistic terminal velocities and mass loss rates.

Despite the highly non local and self consistent character of the problem, it is possible to outline roughly the physics involved.

The reason why no wind is found is that the radiative force increases with radial distances too slowly to become efficient as soon as the force due to thermal pressure vanishes

Fig. 1 - Qualitative behaviour of the driving forces.
R_* : photospheric radius.

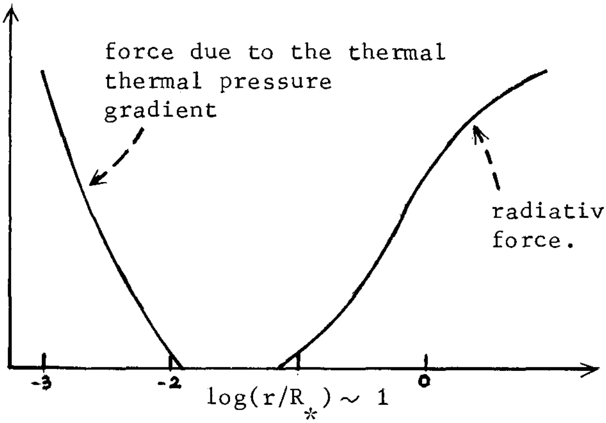

Fig.1 is a schematic picture showing qualitatively the behaviour of the forces due to pressure and radiation as functions of the radial distance. The scale height of the force due to pressure is roughly that of density, which decreases rapidly. On the contrary, the radiative force, small near the photosphere because of the thermalization of radiation, increases at large radial distances due to the Doppler shift.

of the lines. Close to the photosphere, the driving force is that due to pressure whereas it is that due to radiation in the outer part of the wind. However, if there is a "gap" between the regions in which these forces are efficient, which is found, then a wind with suitable features is impossible. The fact that the radiative force increases too slowly is related to the very stringent boundary condition at the photosphere (thermalization).

To summarize, under the assumption of no additional heating ($\mathcal{M}= 0$), radiative equilibrium holds throughout the extended atmosphere, and then the radiative force is not sufficient to drive the wind; therefore, purely radiation driven winds are unlikely. We also note that the inner part of the wind (typically one tenth of the stellar radius R_*) is of crucial importance for the structure of the whole wind.

Conclusions

All this suggests that at least one of the assumptions concerning spherical symmetry, steady state or radiative equilibrium should be revisited. Hereafter we look at the way in which radiative equilibrium may be disrupted. Using (3), we can estimate the thickness H of the region where radiative equilibrium can break. Assuming for instance that $\mathcal{M}$ represents acoustic waves dissipation, one finds $H \sim 10^{-5}R_*$, which is much smaller than the scale height of density ($\sim 10^{-3} R_*$). Although this region is very thin, it is large enough to account for the presence of highly ionised atoms, such as OVI if produced by X-rays, according to Cassinelli's and Olson's (1979) mechanism.

Fig.2 shows a possible scheme for energy balance in the wind. The curve represents the temperature T as a function of r (with no scale). At the photosphere, T is of the order of T_{eff}. Farther there is a thin region ($\gtrsim$ H) where some mechanical energy is dissipated, leading to a high temperature such as a coronal temperature. At larger r, radiative equilibrium holds ; thus there is a region in which the radiative equilibrium can be called "paradoxical" in the sense that the temperature can be large compared to usual radiative equilibrium temperatures ($\lesssim T_{eff}$), because it has to fit in with that in the thin "corona".

Therefore, we see that a localized dissipation of energy, in a very thin region, may give rise to a thick hot region that can change strongly the dynamics and finally explain the observed winds.

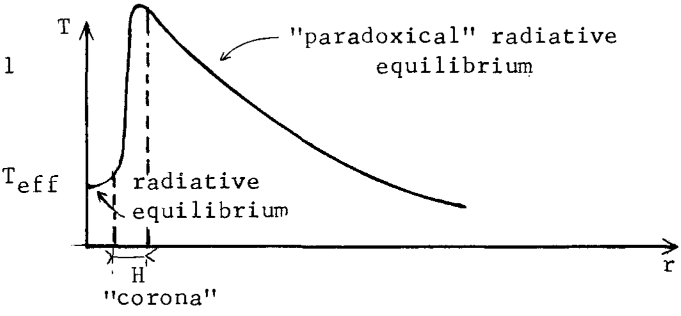

Fig. 2 - General scheme for energy balance.

References

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Mihalas, D., Kunasz, P.B., Hummer, D.G.: 1976, Astrophys. J. 210, 419.

DISCUSSION

LAMERS: Castor et al. in their model of radiative driven winds need a mixture of saturated and unsaturated lines (i.e. $0 < \alpha < 1$). Your picket fence opacity model implies that you adopt either thin or thick lines but not a mixture. Is it possible that your conclusion, that radiation pressure alone cannot produce the observed wind, is due to the fact that you use only one type of optical thickness?

LEROY: There are two parts in your question. First I do not agree with you when you say that CAK's model takes into account a mixture of saturated and unsaturated lines: this is only true using an approssimate local expression derived from Sobolev's approximation which is relevant only in the supersonic part of the wind. In fact in the subsonic part CAK assume that the radiative force profile is of small importance (provided it is rather small), in contradiction with our results. Then, though it is difficult to introduce simultaneously weak and strong lines in one computations we can emphasize that increasing the line opacity still increases the scale height within which the radiative force becomes comparable to gravity (calculations have been performed with line opacities up to 100 times the electronic continuum opacity). This result still suggests arguments against deriving a stellar wind by radiation pressure.