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MODELS FOR STELLAR WIND OF EARLY-TYPE STARS

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RESUMEN. La teoría sobre el viento propulsado radiativamente no predice correctamente los valores observados de la velocidad terminal y de la tasa de pérdida de masa en estrellas O y en las B tempranas. Con el propósito de explicar esta discrepancia, se ha investigado la sensibilidad de las predicciones teóricas a los errores de las fuerzas del oscilador. Los resultados indican que la dinámica del viento estelar es bastante sensible a los cambios en las fuerzas del oscilador de los elementos del grupo del hierro. Para algunas estrellas la tasa de pérdida de masa aumenta por un factor de 2, acercándose a las tasas observadas. Desafortunadamente, la velocidad terminal también aumenta al mismo tiempo, empeorando aún más la diferencia con el valor observado.

ABSTRACT. The radiatively driven wind theory does not correctly predict the observed values of the terminal velocity and mass loss rate for O and early B-type stars. Hoping to explain this discrepancy we investigated how sensitive the theoretical predictions are to erros in the oscillator strengths. The results show that the stellar wind dynamics is quite sensitive to changes in the oscillator strengths for the iron-group elements. For some stars the mass loss rate increases by a factor of 2, bringing them much closer to the observed rates. Unfortunately at the same time the terminal velocity also increases, making the discrepancy of that parameter with the observations even larger.

Key words: HYDRODYNAMICS – STARS: EARLY-TYPE – STARS: MASS LOSS

I. INTRODUCTION

The ultraviolet spectra of early-type stars (spectral type O and early B) show evidence for a stellar wind. The resonance lines of C IV, Si IV and N V show P Cygni profiles, consisting of a blue-shifted absorption component and a red-shifted emission component. These profiles are due to Dopplershifts in the material moving away from the stellar surface (Morton, 1967; Garmany et al., 1981; Gathier et al., 1981; Garmany and Conti, 1984; Groenewegen and Lamers, 1989; Groenewegen et al., 1989). Further evidence for a stellar wind can be found in the infrared part of the spectrum. There an excess flux is seen, compared to models which are calibrated on the visual part of the spectrum (and which do not include a stellar wind). This IR excess is due to bound-free and free-free scattering in the material around the star (Barlow and Cohen, 1977; Abbott et al., 1980, 1984; Lamers and Waters, 1984; Bertout et al., 1985; Blomme and Van Rensbergen, 1988).

The most detailed theory we have to explain the hydrodynamics of these stellar winds is the radiatively driven wind theory. The idea that radiation is capable of exerting a force was applied by Johnson (1925) to the central stars of planetary nebulae. Lucy and Solomon (1970) showed that for O-type stars the force due to a single strong spectral line is sufficiently large to overcome gravity. The hydrodynamics of the problem was first studied by Castor et al. (1975) who found that the radiation force due to lines was indeed capable of driving the stellar wind. Further refinements were made to the theory by Abbott (1982), Pauldrach et al. (1986), Pauldrach (1987) and Pauldrach et al. (1990). The recent detailed non-LTE models show good qualitative agreement with the observations.

Quantitatively however a few problems remain. First of all, the terminal velocities (v_∞) predicted by the theory are ~ 30 % too high (Groenewegen et al., 1989; Blomme, 1990). This discrepancy is most evident for main-sequence stars (and less for supergiants). It cannot be explained by errors in the mass of the star. These masses are taken from evolutionary tracks (Maeder and Meynet, 1987) and should be more accurate for main-sequence stars than for supergiants. A second problem is that the predicted mass loss rates ($\dot{M}$) are a factor of two lower than those derived from observations (Blomme, 1991). This has important consequences for stellar evolution during core hydrogen burning: a 60 $M_\odot$ star only loses 5 $M_\odot$ instead of 14 $M_\odot$ (Blomme et al., 1991). It must be stressed however that the various methods to determine the mass loss rate all have their inherent inaccuracies and that generally the rates are not known more accurately than within a factor of 2.

Other problems with the theory are that it does not explain the observed IR excess (Blomme and Van Rensbergen, 1988) and that the resulting ionization fractions are in error by a factor of 100 - 1000 (Groenewegen and Lamers, 1991). The latter two problems will not be discussed in this paper, but we'll concentrate on problems with the terminal velocity and the mass loss rate. Previous attempts to tackle these are given in Blomme et al. (1991) and Blomme (1991). They investigated the effect of rotation, limbdarkening, errors in the oscillator strengths, changes in the abundances and turbulence. Their results indicate that the problem with the terminal velocity can possibly be explained but not the one with the mass loss rate. Their estimate for the errors on the oscillator strengths was quite conservative however and the purpose of this paper is to have a more detailed look at the influence of these errors.

II. MODEL CALCULATIONS

To model the stellar wind, we have to solve the equations of hydrodynamics:

$$\begin{cases} \dot{M} = 4\pi r^2 \rho v \\ v \dfrac{dv}{dr} = -\dfrac{1}{\rho}\dfrac{dP_{gas}}{dr} - \dfrac{GM_*}{r^2}(1-\Gamma) + g_{lines} \end{cases} \tag{1}$$

where $\dot{M}$ is the mass loss rate, ρ and v are the density and velocity as a function of distance (r) to the centre of the star. The gas pressure $P_{gas} = a^2 \rho$ with a the sound velocity, M_* is the mass of the star and Γ is the ratio of the luminosity to the Eddington luminosity. The important effect that is included in the radiatively driven wind theory is the acceleration due to spectral lines (g_{lines}). Note that we do not include the energy equation: instead we assume $T_e = T_{eff}$ in the whole wind. In reality however the temperature decreases outward as can be seen from the calculations by Drew (1989) and Gabler et al. (1989). Furthermore the hydrodynamical equations have been taken as spherically symmetric and time-independent. When time-dependent calculations are made (Owocki et al., 1988), shocks form in the stellar wind. The time-average of these results however is reasonably close to the time-independent results. This, together with the enormous amount of computer time saved, justifies our use of the time-independent equations.

The acceleration g_{lines} is due to the scattering of photons in the spectral lines, where part of the momentum of the radiation field is transferred to the material in the wind. If we apply Eq. (2-75) of Mihalas (1978) to the spherically symmetric, steady-state case, we find for a single line:

$$g_{line} = -\frac{dP_{line}}{dr} = \frac{2\pi}{c}\int_0^{+\infty} d\nu \int_{-1}^{+1} \mu d\mu\, \chi_\nu I_\nu \tag{2}$$

where χ_ν is the absorption coefficient for the line and I_ν the specific intensity. The integration is over frequency (ν) and angle ($\mu = \cos\theta$). To calculate the line-force, we approximate the absorption profile by a δ-distribution (the Sobolev approximation). We also assume that the photons stream out radially from the star. This allows us to get a simple analytical formula for the optical depth, solve the transfer equation and finally get:

$$g_{lines} = g_{electron}\, \mathsf{M} \tag{3}$$

where $g_{electron}$ is the acceleration due to electrons, $\mathbf{M}$ is called the force-multiplier and is given by:

$$\mathbf{M} = \sum_{\text{all lines}} \frac{F_\nu}{F} \frac{1 - e^{-t\eta}}{t} \Delta\nu_D \tag{4}$$

$$t = \frac{\sigma_e \rho v_{th}}{\frac{dv}{dr}}$$

$$\eta = \frac{1}{\sigma_e \rho \Delta\nu_D} \frac{\pi e^2}{m_e c} g_i f_{ij} \left(\frac{n_i}{g_i} - \frac{n_j}{g_j} \right)$$

F_ν is the flux emitted at the line-centre, F is the frequency-integrated flux, v_{th} is the thermal velocity of the ion, $\Delta\nu_D = \nu_o v_{th} / c$ is the Doppler width, $\sigma_e \rho$ the electron scattering opacity, f_{ij} the oscillator strength, g_i and g_j the statistical weights of the lower and upper level of the transition and n_i and n_j the respective number densities. The optical depth in the spectral line is $t\eta$. Knowledge of the weighted oscillator strengths (gf) of all contributing lines is needed to calculate η for each line.

For a given wind temperature, the value of $\mathbf{M}$ can be calculated for a range of values of t and n_e / W (electron density divided by the geometric dilution factor). To derive the number densities needed we used the simple ionization and excitation formulae given by Abbott (1982). Then a best-fit is made of $\mathbf{M}$ against t and n_e / W:

$$\mathbf{M} = k\, t^{-\alpha} \left(\frac{n_e}{W} \right)^{\delta} \tag{5}$$

where k, α and δ are the force-multiplier parameters. Finally a correction is made to include the non-radial streaming photons, giving:

$$g_{lines} = g_{electron}\, k\, t^{-\alpha} \left(\frac{n_e}{W} \right)^{\delta} K \tag{6}$$

where the correction factor K is given by:

$$K = \frac{1 - \left[\mu_*^2 \left(1 - \frac{v}{r} \frac{dr}{dv} \right) + \frac{v}{r} \frac{dr}{dv} \right]^{\alpha+1}}{(\alpha + 1) \left(\frac{R_*}{r} \right)^2 \left(1 - \frac{v}{r} \frac{dr}{dv} \right)} \tag{7}$$

where μ_* is the cosine of the angle covered by the stellar radius at the distance r. Once the stellar parameters (effective temperature, luminosity and mass) are known, the equations of hydrodynamics can be solved. The numerical details are given in Pauldrach et al. (1986) and Blomme (1991).

III. RESULTS AND DISCUSSION

Numerical models were calculated for the sample of stars studied by Pauldrach et al. (1986, 1990). Table 1 shows the stellar parameters. A "standard" set of models was calculated using the oscillator strengths from the Abbott data-tape (Abbott, 1982). The resulting mass loss rates and terminal velocities are also shown in Table 1. It must be stressed that these values are not the best available as they are based on a modified LTE formula (Abbott,

TABLE 1. The sample of stars from Pauldrach et al. (1986 - upper part, 1990 - lower part of the table). The stellar parameters (effective temperature, luminosity,mass and escape velocity) are from Blomme (1991). The resulting mass loss rates ($\dot{M}$) and terminal velocities (v_∞) from the "standard" models are also given. All velocities are in 10^3 km s^{-1} and all mass loss rates in 10^{-6} $M_\odot$ yr^{-1}.

star	log T_{eff}	log $L/L_\odot$	$M/M_\odot$	v_{esc}	$\dot{M}$	v_∞
typical O5	4.69	6.01	60	0.99	11.6	3.00
P Cyg	4.26	5.64	17	0.19	44.4	0.33
ε Ori	4.45	5.91	90	0.85	5.86	2.10
ζ Ori-A	4.48	5.79	87	0.97	3.2	2.53
9 Sgr	4.70	5.91	64	1.18	6.8	3.58
48099	4.59	5.40	45	1.15	1.17	2.81
42088	4.60	4.89	14	0.89	0.34	2.45
λ Cep	4.62	5.91	53	0.87	9.41	2.46
A1	4.71	6.30	118	1.18	21.6	3.77
A2	4.63	6.34	107	0.84	41.7	2.14
A3	4.59	6.36	108	0.72	46.8	1.93
A4	4.55	6.42	95	0.45	95.8	1.40
B1	4.55	6.15	73	0.69	29.0	2.08
B2	4.53	6.20	66	0.50	54.0	1.17
C1	4.66	5.82	57	1.09	5.86	3.51
C2	4.60	5.88	53	0.84	8.76	2.55
C3	4.55	5.91	52	0.70	11.1	2.33
C4	4.51	5.93	51	0.61	11.6	1.49
C5	4.58	6.00	44	0.54	24.2	1.53
C6	4.54	6.02	44	0.47	28.8	1.39
D1	4.61	5.49	38	1.01	2.00	2.19

1982) for the ionization and excitation in the wind and *not* on full non-LTE calculations as in Pauldrach (1987). They remain useful however for *differential* comparisons.

The Abbott data-tape is a compilation of gf values for the lower 10 ionization stages of the elements H to Zn. The line-acceleration is dominated by those ions with most spectral lines, i.e. those of the iron-group elements. More than 48 % of all lines in the line-list are due to the elements Cr, Mn, Fe and Ni. We assumed that each individual oscillator strength (for these ions) could be wrong by an order of magnitude. We then modified the oscillator strengths of the lines for all ions of the iron-group elements to give us an "alternative" line-list. This was done by changing log gf to log gf ':

$$\log gf' = \log gf + x \tag{8}$$

where x was chosen at random following a Gaussian distribution with mean = 0 and standard deviation = 1. In Fig. 1 we compare the results from the "alternative" line list with the "standard" line list. It can be seen that mass loss rates in some cases increase by a factor of two - which brings them much closer to the (uncertain) observational values. For the terminal velocities however, there is also an increase - which goes in the wrong direction to explain the discrepancies with the observations.

Although we changed log gf symmetrically, there is a net influence on the line-acceleration. This is due to the fact that most of the driving lines are weak and therefore we can approximate Eq. (4) by:

$$\frac{1-e^{-t\eta}}{t} \approx \eta \propto gf \tag{9}$$

So the line force is (approximately) linear in gf, but the changes we made are symmetric in *log* gf (i.e. an increase of gf by a factor of 10 is equally likely as a decrease by a factor of 10). This will result in an increase of the line acceleration.

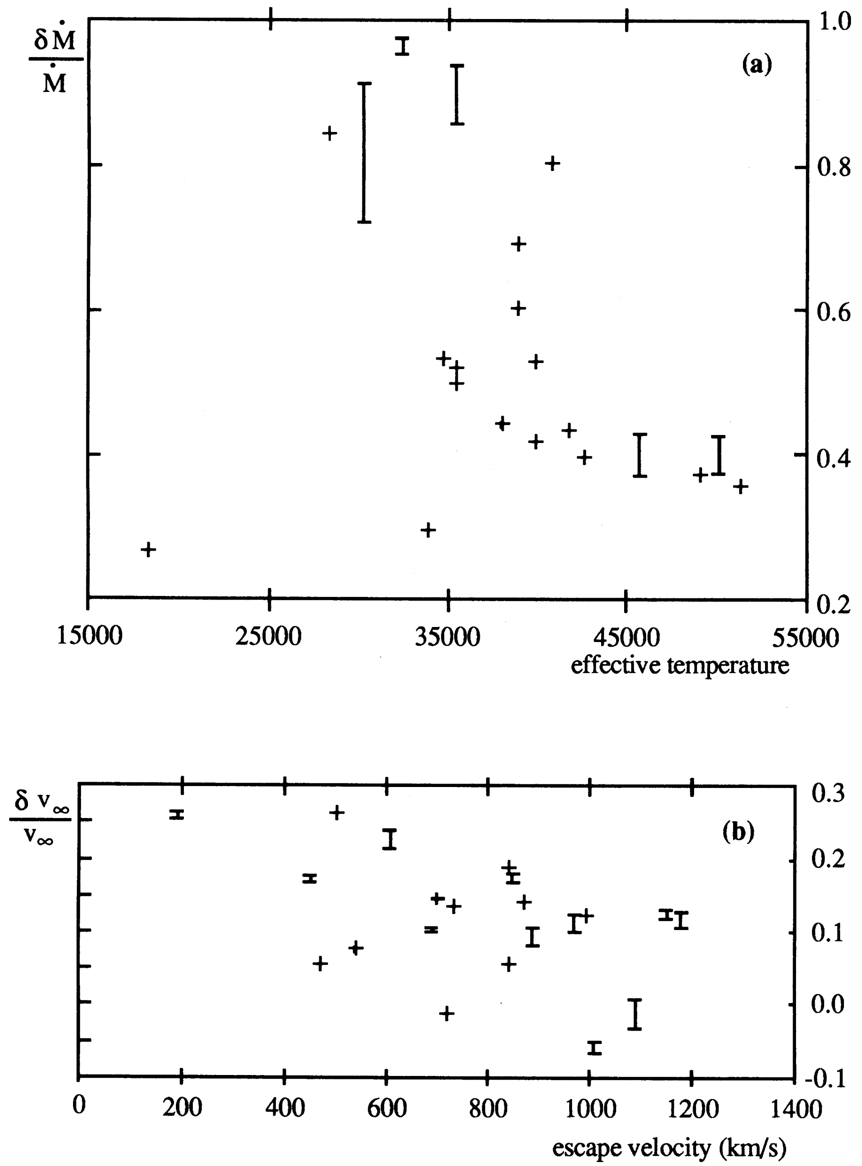

Figure 1 --- The influence of errors in the oscillator strengths. We show the relative change of the mass loss rates (a) and terminal velocities (b) for a sample of stars. Due to the numerical procedure the resulting mass loss rates and terminal velocities cannot be derived with unlimited accuracy. An indication of the uncertainty in the results is given by the error ranges shown in the figure.

It must be stressed that the present results are only a numerical experiment intended to assess the importance of errors in the oscillator strengths for the radiatively driven wind theory. The real errors could be smaller than presented here and they are probably more systematic than we assumed. The conclusion is that these errors could be sufficiently large to make a quantitative comparison between theory and observations impossible. Therefore more accurate oscillator strengths are needed for the iron group elements before more progress can be made in quantitative applications of the radiatively driven wind theory.

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