RADIATIVE WIND ACCELERATION IN EARLY TYPE STARS

N. Panagia
Istituto di Radioastronomia CNR
Bologna, Italy

F. Macchetto
ESA Space Science Department
Noordwijk, Netherlands

ABSTRACT. The processes of radiative acceleration of stellar winds in OB stars by single and multiple photon scattering are considered. Single scattering can be the dominant accelerating process for stars later than B2 ($T_{eff} < 2 \times 10^4$ K) and can account for terminal velocities up to 500 - 1000 km s^{-1}. Multiple scattering of photons in the approximate range 200 - 500 Å provides additional wind acceleration for stars earlier than B2 to reach terminal velocities of up to 2000 - 4000 km s^{-1}. A systematic increase of the terminal velocity as a function of the effective temperature is predicted. Observational data confirm this expectation quite well.

Optical and ultraviolet line observations of OB stars have shown that the wind velocity increases rather gradually with the radius and becomes close to the terminal value only at large distances from the photosphere (e.g. Lamers and Morton, 1976). This implies that substantial acceleration takes place at several stellar radii and, therefore, radiation is the most likely cause of it. Moreover, by combining data on mass loss rates (e.g. Tanzi et al., 1981) and terminal velocities (e.g. Abbott,1978) for OB supergiants one finds that the momentum carried by the wind monotonically increases with the effective temperature of the stars (cf. Table 1) reaching values of about $\dot{M}\, v_{term} \simeq 0.6$ L/c for the earliest types. The total momentum, i.e. including both the momentum carried to infinity by the wind and that needed to overcome gravity, is even higher and becomes very close to the theoretical limit of L/c. The problem is to understand how to transfer so efficiently momentum from the radiation field to the wind.

The process most commonly considered is single scattering of line radiation. This process works as follows. An atom with a transition occurring at λ_o can absorb a stellar photon at a wavelength λ in the

C. Chiosi and R. Stalio (eds.), Effects of Mass Loss on Stellar Evolution, 173–178.

Table 1. The Momentum Problem for Supergiants

T_{eff} (K)	Spectral Type	$\frac{\dot{M}\, v_{term}}{L/c}$	$\frac{\text{Total Momentum}}{L/c}$
10000	A 0	0.04	0.14
20000	B 2	0.17	0.34
30000	O 9.5	0.37	0.61
40000	O 4	0.64	0.93

in the layer where $\lambda = \lambda_o (1-v/c)$. Since the photon is subsequently reemitted isotropically a net momentum of $h\nu/c$ is released to the gas. The efficiency of single scattering is proportional to the number of absorbing lines and to their strength. Most of the strong lines which contribute to this process occur in the ultraviolet, i.e. shortward of 3000 Å. The momentum rate $\dot{P}$ provided by this process is related to the observed line blocking b_λ as

$$\dot{P}(\text{single scattering}) = \int_0^\infty b_\lambda\, L_\lambda/c\, d\lambda = \bar{b}\, L/c$$

The spectrum averaged line blocking $\bar{b}$ is observationally found not to exceed 20-30%. For example, $\bar{b}$ can be estimated to be ∿0.27 for P Cyg (B 1 Ia; Cassatella et al., 1979) and ∿0.24 for ζ Pup (O4 If; Lamers and Morton, 1976; Macchetto and Panagia, 1978). Therefore, it is clear that single scattering may account for the wind acceleration only in relatively cool stars, i.e. those with $T_{eff} \leq 20000$ K or spectral type later than B2.

An additional momentum supply is needed for hotter stars. This can be provided by multiple scatterings of ultraviolet photons. The process consists of a sequence of scatterings which occur successively at opposite sides of the expanding envelope. Since in this process a photon is back scattered, the momentum released in each scattering is $\geq h\nu/c$ and, therefore, the total momentum transferred can be quite substantial. In order to be efficient this process requires that: a) The optical depth of the involved lines is high so that back-scattering is more probable than forward scattering; b) The lines are closely spaced with a separation of $\Delta\lambda \simeq \lambda v/c$ so that a photon scattered backward can find at the opposite side of the envelope another line suitably tuned for absorbing it again; c) These lines occur in a spectral region where the flux is high enough. These conditions are met by far UV lines in the approximate range of $\lambda \sim 200 - 500$ Å. Therefore, multiple scattering can be an efficient process for hot stars ($T_{eff} > 30000$ K). The number of scatterings effectively occurring at opposite sides of the envelope (N) is limited by: 1) Optical depth (usually decreasing with the distance from the star) which determines the probability of back scattering; 2) The probability of hitting the star and being lost for the process. This probability is highest near the stellar surface and decreases

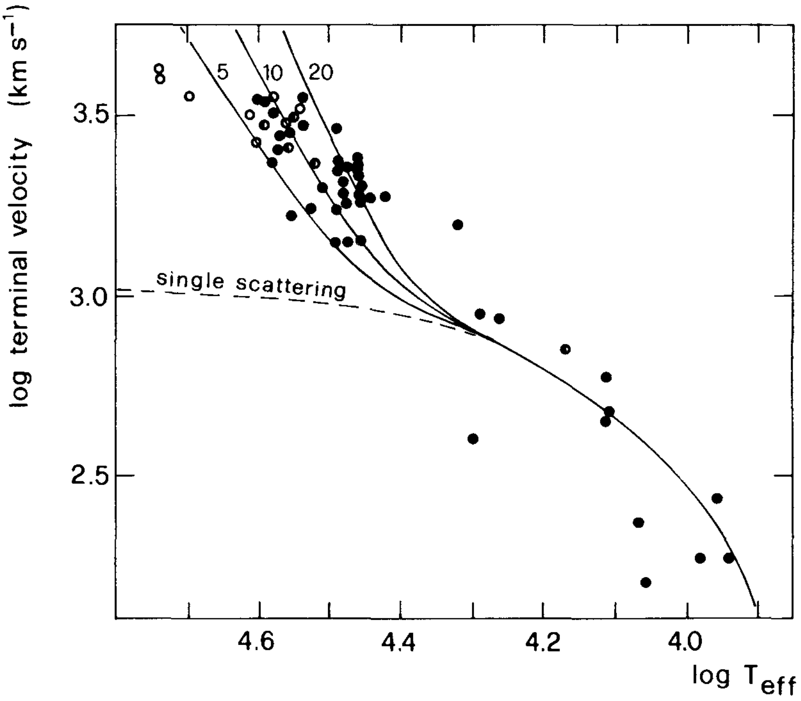

Figure 1. Curves of v_{term} as a function of T_{eff} for several values of the number of multiple scatterings. Observational data of supergiants (filled dots), giants (half-filled dots) and main-sequence stars (open circles) are also presented.

outwards; 3) The number of closely spaced lines which can participate in this kind of process. Rows of up to 10-20 lines are present in the far ultraviolet. Combining these effects the results are that: i) The maximum efficiency of multiple scattering occurs at some distance from the star, typically at 2-4 stellar radii; ii) The average number of scatterings for FUV photons is expected to be in the range 5-20. Therefore, the wind acceleration is expected to be still appreciable at several stellar radii, as observed. The momentum released to the wind by multiple scattering is

$$\dot{P}(\text{multiple scattering}) \simeq N \int_{200\text{Å}}^{500\text{Å}} L_\lambda/c \, d\lambda$$

Then, this process can contribute to wind acceleration as much as simple scattering for stars with effective temperature around 30000 K and becomes dominant for the hottest stars.

As a consequence, the terminal wind velocity is expected to steadily increase with the effective temperature. Figure 1 displays the computed curves of v_{term} as a function of T_{eff}. The average line blocking is assumed to be 0.3 for all stars. Three values of the effective

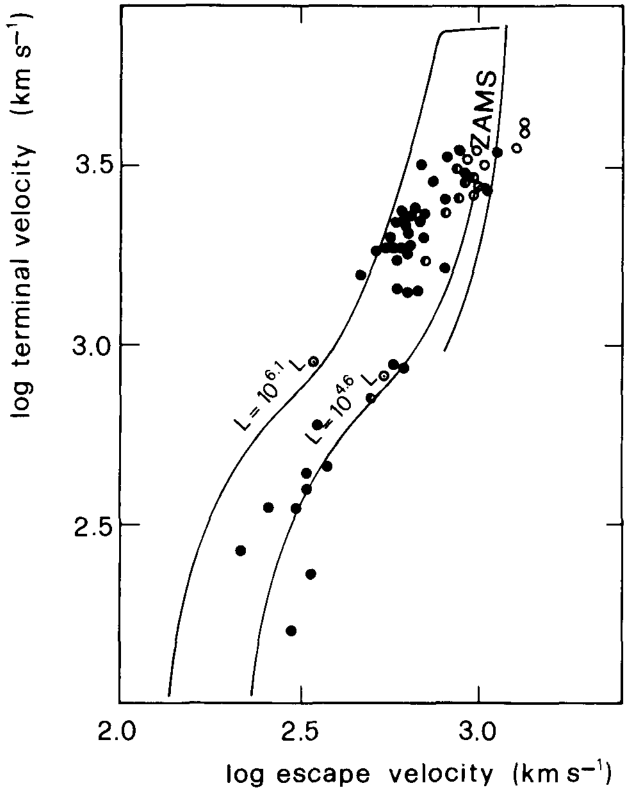

Figure 2. Curves of v_{term} as a function of v_{escape} for N = 10. Observational data of supergiants (filled dots), giants (half-filled dots) and main-sequence stars (open circles) are also presented.

number of multiple scatterings of FUV photons are considered, namely N = 5 - 10 - 20. For comparison, we also show the measured values of v_{term} for several OB stars taken from the lists of Abbott (1978), Hutching and von Rudloff (1980) and Lamers (1980). It is apparent that single scattering may be enough for accelerating the winds of B-type stars (T_{eff} < 30000 K) but would produce too low velocities for O-type stars. On the other hand, multiple scattering is an important contributor to the wind acceleration for O-type stars and accounts for the largest part of it in the earliest types where v_{term} exceeds 2000 km s^{-1}. The scatter of the observed values of v_{term}, which is mostly due to experimental uncertainties, prevents one from accurately estimating the number of scatterings for FUV photons. However, by looking at Figure 1 it is clear that values of $N \simeq 5 - 10$ are enough for matching the observations.

It is also instructive to consider the behaviour of the terminal velocity as a function of the escape velocity, which is presented in Figure 2 for the case of N = 10. Curves are given for zero-age main-sequence stars and for stars at two luminosities, L = $10^{6.1}$ and $10^{4.6}$ $L_{\odot}$.

The masses and radii of stars along these sequences were taken from Chiosi et al. (1978). For comparison, the observational points for the same selection of stars as in Figure 1 are also displayed. We see that while for the earliest type stars the terminal velocity is about $v_{term} \simeq 3\ v_{escape}$ (Abbott, 1978) for the later types it becomes $v_{term} \simeq v_{escape}$. This observational result is easily explained by the different prevailing mechanisms for wind acceleration in the two cases, i.e. single scattering for B-type stars and multiple scattering for O-type stars.

We conclude that radiative acceleration by both scattering processes accounts naturally for the observed properties of winds in O and B type stars. Also, we note that the terminal velocities for giant and main-sequence stars are very similar to those of supergiants (cf. Figure 1) whereas the mass loss rates of the former classes are systematically lower than for the latter ones (Tanzi et al., 1980). This suggests that the wind acceleration is effectively decoupled from the process which causes the mass loss and, by inference, that radiation pressure may not determine the mass loss rate in an OB star.

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DISCUSSION

HAMANN: Did you take into account the possibility that in any scattering following the first one a photon may transfer momentum in the inward direction?

PANAGIA: Yes, this has been done in a statistical way. At any rate, the probability for the momentum to be transferred inward is not high and, therefore, it is not an important effect.

ŠÍMA: Why the method Monte -Carlo often used for multiple scattering of photons especially in reflection nebulae was not used and the analytic method was prefered?

PANAGIA: The analytic procedure I have used is still probabilistic in essence. It is equivalent to a Monte-Carlo calculation in which the probabilities for the individual effects which enter to determine the multiple scattering process are analytically combined to give a final probability for multiple scattering to occur.