Effects of High Velocities on Photoionization Lines

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Abstract. We have treated formation of spectral lines in a comoving frame where photoionization is predominant over collisional processes. We have assumed that the radiation field for causing photoionization is a function of Planck function. We have also considered the situation in which the continuum contributes to the radiation in the line. In all the models the quantity B/A (ratio of outer to inner radii) is kept equal to 10 and the total optical depth is taken to be 10^3. The velocity is assumed to be varying according to the law $dV/d\tau \sim -1/\tau$ where τ is the optical depth ($\tau > 0$) in the given shell. The velocities at the innermost radius ($r = A$) are set equal to 0 and at the outermost radius ($r = B$), the maximum velocities are taken to be 0, 1, 3 and 10 Doppler units. The calculated line profiles are those seen by an observer at infinity. P Cygni-type profiles are observed in the case of a medium with no continuum absorption. For a medium with continuum absorption double peaked asymmetric profiles are noticed when the velocities are small; the two emission peaks merge into a single asymmetric peak for larger velocities.

Key words: photoionization lines—comoving frame—radiative transfer equation

1. Introduction

Thomas (1957) first studied the photoionization effects on the formation of lines. Jefferies and Thomas (1959) extended these calculations to obtain source functions in a photoionization-dominated line in a semi-infinite atmosphere with a chromospheric temperature rise. However, most of the attempts are aimed at investigating the line formation in a static medium. Recently, Vardavas and Cannon (1976) investigated the effects of partial frequency redistribution on the formation of these lines in a plane parallel atmosphere in which the gases move with differential velocities. Although they have employed moving media, their main purpose was to

establish the differences in the emergent radiation field of the line in which the photon redistribution takes place according to R_{II} and R_{III} functions. However, in these calculations, the velocity employed is only one mean thermal unit although it is possible that in reality the gases move with velocities many times more than one unit of mean thermal velocity.

To obtain the solution of line transfer in high velocity media, one must solve it in the comoving frame and the radiation field should then be translated to a point at infinity. We present in the next section the results of such calculations.

2. Results and discussion

The solution of the radiative transfer equation in a comoving frame has been described earlier (Peraiah 1980). The line source function which we have employed in the transfer equation is as given by (Mihalas 1978)

$$S_L(r) = \frac{\int J_x \phi_x \, dx + \epsilon B + \eta B^*}{1 + \epsilon + \eta}, \tag{1}$$

where ϕ_x is the profile function of the line and $x = (\nu - \nu_0)/\Delta s$, Δs being some standard frequency interval. The quantities ϵB, ϵ and η and ηB^* are the collisional and photoionization source and sink terms respectively (see Athay 1972). As our main interest is to see how the photoionization lines form, we have always set $\epsilon = 0$ and in the case of the model with continuum absorption, we have set β (the ratio of the continuum absorption to that in the line per unit frequency interval) equal to 10^{-6}. The frequency-dependant source function is computed by the formula (Grant and Peraiah 1972)

$$S(r, x) = \frac{\phi(x)}{\phi(x) + \beta} S_L(r) + \frac{\beta}{\phi(x) + \beta} S_C(r), \tag{2}$$

where $S_C(r)$ is the continuum source function which is set equal to the Planck function B and B^* is put equal to $f_r B$ where $f_r \leqslant 1$. The velocity is considered to be changing as $dV/d\tau \sim -1/\tau$ where τ is the optical depth in the shell $|\tau| > 0$ and V is the average velocity of the gas over this shell. However, we have set $V_A = 0$ when $\tau = \tau_{max}$ and $V_B = 0, 1, 3, 10$ mtu at $\tau = 0$. A Doppler profile has been chosen with total optical depth at line centre as 10^3 and the factor η is put equal to 10^{-3} in all cases. The Planck function is taken to be unity and the quantity B/A (ratio of outer to inner radii) is set equal to 10.

In Fig. 1 (a, c, d), the total source functions are presented for the parameters shown in the respective figures. At $\tau = \tau_{max}$, we notice that the source functions are maximum. When the photoionizing radiation is equal to the Planck radiation that is, $f_r = 1$, the source function falls off by about 5 orders of magnitude. When the quantity $f_r = 10^{-2}$, the source function falls one order of magnitude more than in the previous case and those corresponding to higher velocities are reduced much more. A small amount of continuum emission ($\beta = 10^{-6}$) is introduced and the corresponding source functions are given in Fig. 1 (b) for $f_r = 1$. Here, again, we see the same
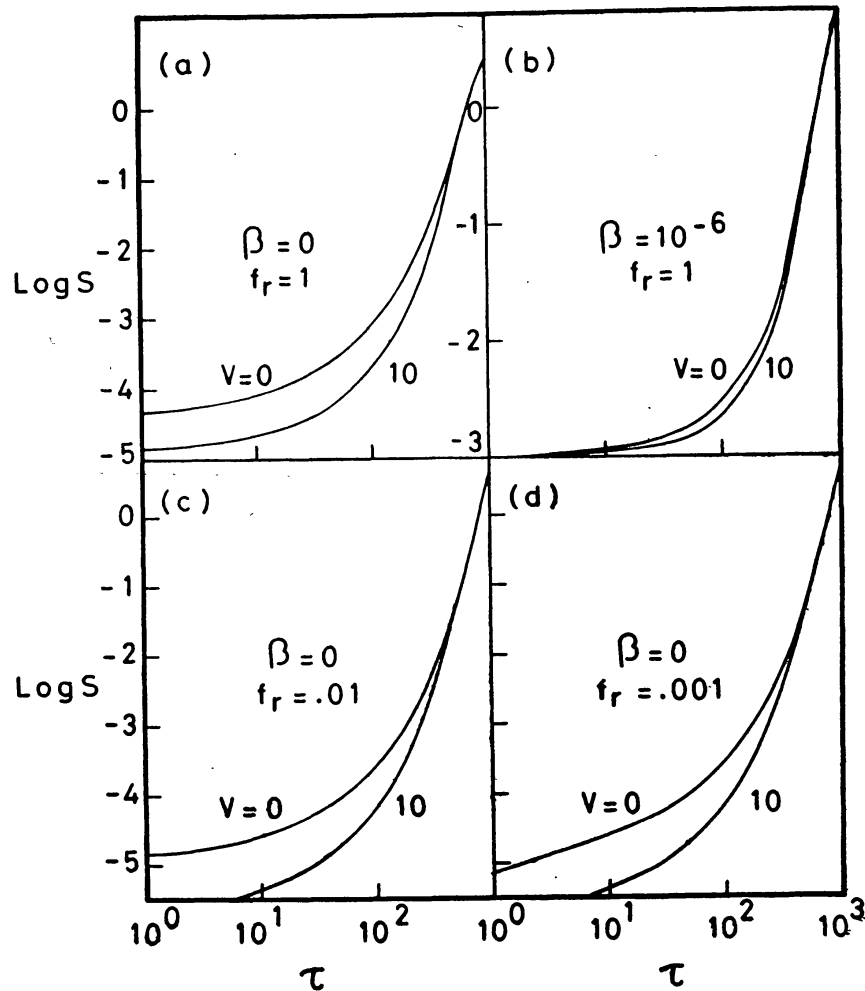
Figure 1. Source function dependence on optical depth for different values of f_r and β. The ratio of outer to inner radii of the atmosphere $B/A=10$.

type of variation as shown in Fig. 1 (a, c and d) with the exception that the fall is steeper at larger optical depths and that the source function at $\tau=0$ is only about three orders of magnitude less than that at $\tau=\tau_{\max}$. In this case, the variations in the amount of gas velocity do not introduce substantial changes in the source functions. We notice that the source functions are reduced considerably, particularly at $\tau=0$. This is due to the fact that as the atmosphere expands, the density of the matter and hence the radiation field in the outer layers are correspondingly reduced so that equation of continuity is satisfied. The results for the cases $f_r=10^{-2}$ and 10^{-3} are quite similar to those presented in Fig. 1(b), and, therefore, are not shown here. The line profiles emerging from the medium are presented in Fig. 2. In Fig. 2 (a) the flux profiles for $f_r=1$ are described. When $V_B=0$, we notice that the profile is symmetric with small wing emission and self-reversal at the central absorption. However, this disappears when motion is introduced and we see an absorption core and an emission on the red side. A further increase in the velocity changes the profiles to imitate that of a P Cygni star. Fig. 2(b) and (c) give the profiles for $f_r=10^{-2}$ and 10^{-3} respectively and we do not notice any self-reversal even when the gas is not in motion. These profiles have very deep absorption cores and a small amount of emission on the red
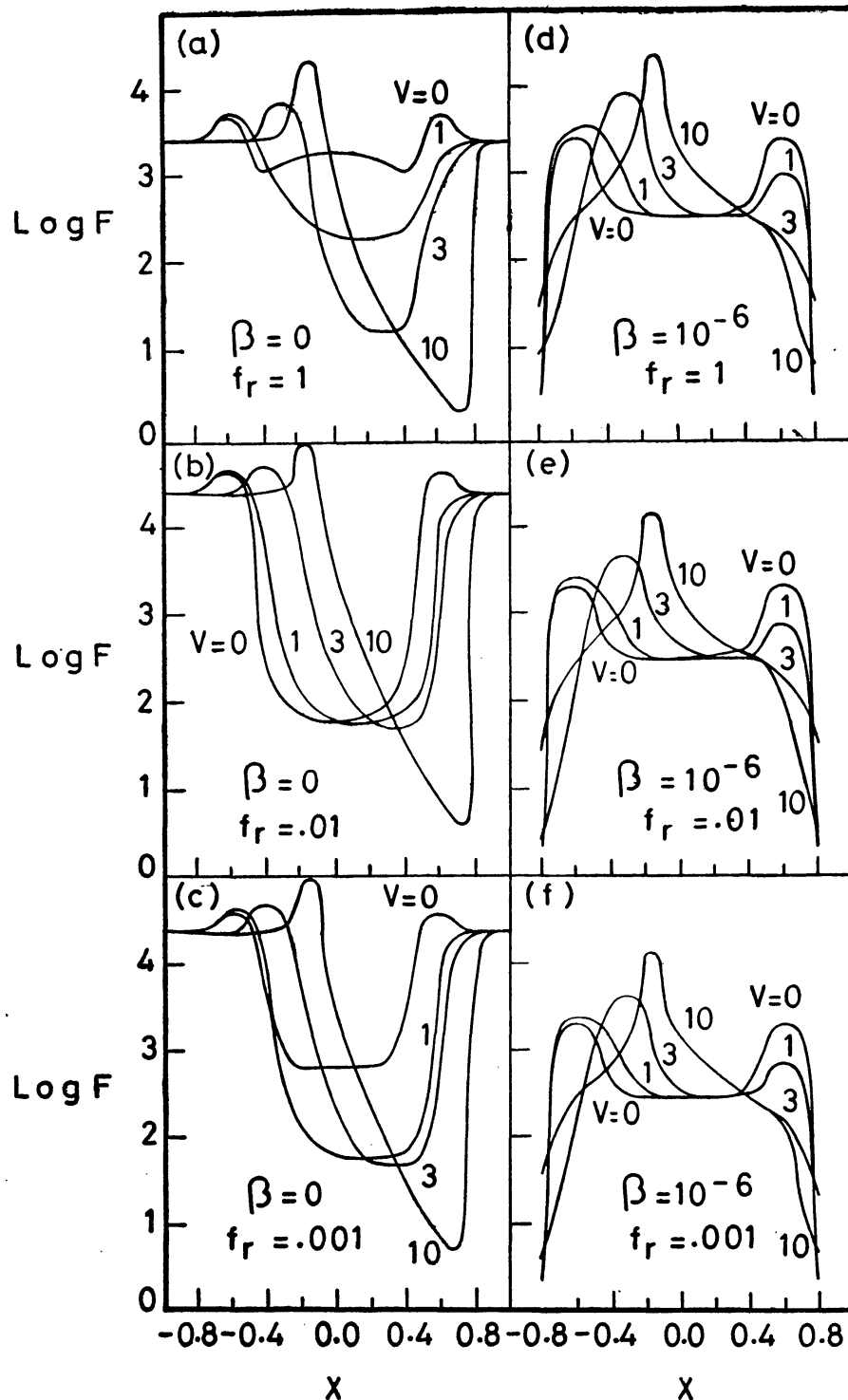
Figure 2. Flux profiles at infinity for different values of the parameters β and f_r. In all cases $B/A=10$, $F=F_x/F_{min}$, where F_x is the flux at frequency point x.

side.   It should be noticed that when $f_r=10^{-2}$ (Fig. 2b) the depth of the absorption cores for $V_B=0, 1, 3$ do not differ substantially and when f_r is reduced by a factor of 10, the depths of absorption cores are progressively increased. As the velocity increases, the P Cygni nature of the profiles becomes quite evident. Fig. 2 (d, e, f) contain the

profiles corresponding to the case with $\beta=10^{-6}$. The flux profiles of Fig. 2(d, e, f) are in emission whereas those in Fig. 2 (a, b, c) are in absorption. This is because we have introduced emission in the continuum and this is shown in the profiles. We notice another important effect, that is, for smaller velocities, the profiles have emission in the wings, and when the velocity increases, we get one single emission peak at the centre of the line. The main reason for this kind of result is, when the atmosphere expands, more matter is transferred into the side lobes of the star and therefore more radiation is scattered into emission.

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