# STELLAR MASS FLUX AND CORONAL HEATING BY SHOCK WAVES

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## 1. INTRODUCTION

The heating of the solar corona and the solar wind phenomenon are basically related, however, the two parts are generally modelised independently : the models of the transition zone and corona are restricted to levels lower than the temperature maximum and the solar wind models begin above it. Here we study a self-consistent oversimplified model which maintains the global balance of energy sources and sinks from the chromospheric level to the interplanetary medium. The heating mechanism chosen is the shock wave dissipation ; it was shown by Gonczi et al (1977) that overlapping shock waves could carry a significant mechanical energy flux towards a static corona ; here we apply the same mechanism to an expanding corona. The model includes self-consistently the different coupling between convective energy flux, conductive flux, radiative losses in optically thin atmosphere, shock wave pressure and dissipation terms. The input parameters are the base pressure, the base temperature and the mechanical flux introduced at chromospheric level in form of shock waves. If these three parameters allow a solar wind expansion, the output results are the radial variations of the density, of the temperature, of the solar wind velocity and of the mechanical flux. Due to the presence of a boundary layer associated to the steep temperature gradient in the transition zone, the three input parameters cannot be arbitrarily fixed, in fact when we impose two of them, the third one cannot vary within a large interval (i.e. within a factor of two or less), this point has been qualitatively discussed in a previous paper : Couturier et al. (1979)

## 2. BASIC EQUATIONS AND METHOD.

An extended paper covering these topics is in preparation ; due to the restricted room given to contributed papers, we shall only give the general structure of the differential system which is solved in our model and we shall not define the notations currently used.



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$$F_m = \rho v r^2 \tag{1}$$

$$\frac{dT}{dr} = - \frac{F_c}{\varkappa T^{5/2}} \tag{2}$$

$$\rho v \frac{dv}{dr} = - \frac{d}{dr}(p + P_*) - \frac{\rho GM}{r^2} \tag{3}$$

$$\frac{1}{r^2}\frac{d}{dr}(r^2 \Phi_*) = - \rho v P_* \frac{d}{dr}\left(\frac{1}{\rho}\right) - \frac{\rho T \Delta s_*}{\tau_*} \tag{4}$$

$$\frac{1}{r^2}\frac{d}{dr}\left\{\left(\underset{A}{\frac{v^2}{2}} - \underset{B}{\frac{GM}{r}} + \underset{C}{\frac{5p}{2\rho}}\right) + \underset{D}{\frac{r^2 F_c}{F_m}} + \underset{E}{\frac{r^2 \Phi_*}{F_m}} \frac{2v+c}{v+c}\right\} = - \frac{\rho^2 \varphi(T)}{F_m} \tag{5}$$

We assume a stationary radial expansion of the flow, with a mass flux $F_m$ (Eq 1). We include the gradient of the shock wave pressure in the momentum (Eq 3). The radial variations of the mechanical flux $\Phi_*$ (Eq 4) are given by the work done by the shock pressure and by the dissipative term : $\Delta s_*$ is the entropy production for overlapping shock waves of period $\tau_*$ ; $\Phi_*$, $\Delta s_*$ and $P_*$ are related to the thermodynamical variables and to the shock strength : explicit expressions for a static corona are given in Gonczi et al.(1977), in the present case the detailed expressions will be given in the extended version in preparation. The energy conservation equation(5) will be used as a differential equation for the conductive flux $F_c$. The quantities A, B, C, D, E are used for reference in Table 2, they are respectively related to the kinetic energy flux, the potential energy flux, the enthalpy flux, the conductive flux and the mechanical flux. The radiative losses $\rho^2 \varphi(T)$ has been evaluated by various authors (for instance McWhirter et al. 1975). The optically thin medium hypothesis limits the validity of the function $\varphi(T)$ to temperatures above 50000°K.

Equations 2 to 5 form a system of four first-order differential equations, the independent variables are v, $\Phi_*$, T and $F_c$ ; $\rho$ is related to these variables through equation 1, so $F_m$ is a free parameter. The boundary conditions are the following : three input parameters fix the base temperature $T_\odot$ , the mass density $\rho_\odot$ and the mechanical flux $\Phi_\odot$ at the chromospheric level $r = R_\odot$. Two free parameters $F_{c\odot}$ and $F_m$ are adjusted in order to get a solution i) which crosses the critical point for supersonic expansion, ii) which gives asymptotic temperature $T\ (r \to \infty) \to 0$. The choice of the mass flux and of the initial conductive

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flux is very "sensitive" ; for computation we use an adaptation of the shooting-splitting method described by Couturier (1977).

## 3. RESULTS AND CONCLUSION.

For one set of input parameters, tables 1 and 2 give some characteristic quantities obtained at four levels : the chromospheric level (I) the temperature maximum (II), the critical point (III) and the earth orbit (IV). To get this solution we find $F_{c\odot}=-2.10^3$ erg $cm^{-2}$ $s^{-1}$, $F_m$ = 7.7 $10^{10}$ g $s^{-1}$ $sterad^{-1}$. Quantities in table 2 are normalized with the total energy flux per unit mass which remains constant in the solar wind: $4.10^{14}$ erg $g^{-1}$. The radiative losses above level I amount to $9.10^4$ erg $cm^{-2}$ $s^{-1}$.

| TABLE 1 | $r/R_\odot$ | n (e $cm^{-3}$) | T (°K) | $\Phi_*$(erg $cm^{-2}s^{-1}$) | v(km $s^{-1}$) |
|---|---|---|---|---|---|
| I | 1. | 2.2 $10^9$ | 5.25 $10^4$ | 1.18 $10^5$ | 0.04 |
| II | 1.29 | 1.75 $10^7$ | 1.25 $10^6$ | 1.13 $10^4$ | 2.92 |
| III | 8.25 | 1.3 $10^4$ | 5.72 $10^5$ | 3. $10^{-2}$ | 97.3 |
| IV | 214. | 7.88 | 1.41 $10^5$ | 0. | 239. |

| TABLE 2 | $r/R_\odot$ | A | B | C | D | E |
|---|---|---|---|---|---|---|
| I | 1. | 0. | 4.76 | 0.054 | 205. | -0.001 |
| II | 1.29 | 0.0001 | 3.68 | 1.29 | 3.35 | 0. |
| III | 8.25 | 0.118 | 0.577 | 0.591 | 0.0005 | 0.867 |
| IV | 214. | 0.711 | 0.022 | 0.145 | 0. | 0.166 |

Taking into account the fact we have only three degrees of freedom for the input of this oversimplified model, we consider that the results fit reasonably the observations.Even if the observational support for sufficient mechanical fluxes in form of shocks remains questionable,the heating mechanism through another process will give the same structure of differential system,and the computing method is at hand to solve the problem. The extended version will discuss the degree of flexibility in the choice of input parameters and will apply the model to stellar winds.

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*DISCUSSION*

*Kuperus:* There seems to be increasing evidence that the propagation and dissipation of shock waves in a plane parallel or radially symmetric atmosphere, not taking into account the magnetic field, cannot satisfactorily explain the hot corona with its multitude of structures.

*Couturier:* I agree with your remark; the purpose of our work is to show that the energy balance through the whole corona and transition zone imposes severe constraints on the chromospheric parameters. That point represents some progress for the study of stratified stellar atmospheres. The next step will be to introduce just MHD shock waves as soon as we have performed the treatment of the evolution of such waves in a stratified atmosphere. The description of expanding flux tube of open magnetic fields will also be possible with some crude assumptions. I do not think, however, that we could get in that way a self consistent description of the inhomogeneous structures of the transition zone, but, for other atmosphere and solar mass loss studies, it is more important to reduce the number of input parameters in a self-consistent model than to develop a complex model with more degrees of freedom which could be fitted to solar observations. Smoothing the inhomogeneous structures of the corona would not affect the global energy balance in open field regions as long as non-resistive dissipation of magnetic fields is not a predominant mechanism.

*Lemaire:* At which altitude in your model is the mean free path of a thermal proton becoming larger than the density scale height?

*Couturier:* Above the critical point!