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Stellar coronae: What can be predicted with minimum flux models?

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Summary. For a given star, minimum flux corona (MFC) models (Hearn, 1975) are uniquely determined by the total amount ϕ_{M0} of coronal heating. However, realistic coronae must depend also on the spatial distribution of the heat input. MFC predictions of various coronal properties are therefore wrong, the errors depending on the characteristic damping length L of the as yet unknown heating mechanism. To determine the possible errors of various MFC predictions, we compare MFC models with a grid of detailed coronal models that covers a range of two orders of magnitude in both parameters ϕ_{M0} and L. For given ϕ_{M0}, the pressure at the base of the transition region has a maximum as a function of L. This *maximum possible* pressure is the only quantity that can be predicted with sufficient accuracy by the MFC concept. MFC predictions of the *actual* base pressure, of the coronal temperature, and of the radius of the critical point can be wrong by more than a factor of 3, depending on the damping length of the heating mechanism. The MFC concept is absolutely unreliable in predicting the mass loss and the relative importance of the various kinds of energy losses. MFC predictions of the mass loss rate and of the energy losses due to stellar wind can be wrong by many orders of magnitude. Moreover, the MFC formulae (Hearn, 1975) were derived for an isothermal corona; hence, they cannot be used to determine such important quantities as the height of the temperature maximum, the temperature difference between the temperature maximum and the critical point, and the outward conductive energy losses. We suggest that for future applications the unreliable MFC formulae should be replaced by a grid of detailed models which account for the coronal dependence on L, such as the models underlying the present study.

Key words: mass loss – stellar atmospheres – stellar coronae – stellar wind – transition zone

I. Introduction

Hearn (1975) computed the energy losses of a simplified, two-component atmosphere model consisting of an isothermal corona and an isobaric transition region. He showed that there exists a certain coronal temperature which for given base pressure p_0 minimizes the sum of the coronal energy losses – or, alternatively, for given total energy loss ϕ_{M0} maximizes the base pressure p_0. The minimum flux corona (MFC) concept assumes that every stellar corona is of this type.

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This concept was applied by several authors to various kinds of investigations. Hearn (1975) discussed the energy balance of coronae around various types of stars; Mullan (1976), Hearn and Mewe (1976), and Muchmore and Böhm (1978) predicted coronal temperatures and base pressures by means of the MFC theory; den Boggende and Mewe (1979), den Boggende et al. (1978), Lampton and Mewe (1979), and Mewe (1979) discussed ANS soft X-ray observations for various stars; Mullan (1978; see also Wallenhorst, 1980) tried to explain the onset of high mass loss rates and the absence of transition region lines for late giants and supergiants by showing that in these stars the critical point of MFC models lies at the top of the chromosphere; Hearn (1977; see also Jordan, 1980) discussed the differences between coronal holes and quiet coronal regions; and Hearn and Kuin (1981) derived scaling laws for coronal loops.

Despite its widespread use, the MFC theory was criticized for various reasons. Some of the objections refer to the applicability of the models to certain magnetic configurations (Antiochos and Underwood, 1978; Vaiana and Rosner, 1978; Holzer, 1980) and to details of the wind loss formula (Antiochos and Underwood, 1978); in particular Endler et al. (1979) noted that the enthalpy loss of the transition layer must be included in the computation of the structure of the transition region (see also Mullan, 1978; Vaiana and Rosner, 1978). Several of these objections were discussed by Hearn (1979).

Furthermore, there is now agreement (Antiochos and Underwood, 1978; Mangeney and Souffrin, 1979; Hearn, 1979; Hearn and Kuin, 1981) that it has not been proven rigorously that only minimum flux coronae are stable, as was originally proposed by Hearn (1975). On the contrary, van Tend (1979) showed that minimum flux coronae are not more stable than any other kind of coronal model and that any stability analysis requires the knowledge of the unknown coronal heating mechanism and its time-dependent response to perturbations. Thus, there is no reason why among all possibilities only minimum flux coronae should be realized in nature.

The most severe argument against the MFC concept, however, was published by Endler et al. (1979) and Mangeney and Souffrin (1979). They argued that for any stellar corona the coronal heating mechanism specifies not only the total heating flux ϕ_{M0} entering the transition region and corona but also the mode of dissipation of this flux, which may be characterized by the damping length L. The inclusion of the heating law determines the corona uniquely (cf. Couturier et al., 1980; Hammer, 1981, 1982e; Hearn and Vardavas, 1981; Kuperus et al., 1981; Martens, 1981; Souffrin, 1982); thus it removes the freedom to maximize the pressure. This means that, whether stable or not, minimum flux coronae are in general not consistent with the heating mechanism prescribed by the star.

Nevertheless, it might still be possible that a stellar corona depends only weakly on the details of the heat input. This possibility was suggested by Hearn and Kuin (1981), who noted that the large thermal conductivity leads to the redistribution of the dissipated energy within the corona, and who concluded therefrom that the corona should not depend strongly on the location where the energy is deposited – and thus on the damping length L. If this is true, the MFC concept could eventually *happen to* give rather good predictions of various coronal properties, regardless of the actual heating mechanism. In view of the numerous applications of such MFC predictions in the literature (see above), it is important to investigate their respective accuracy. This investigation is the main purpose of the present paper.

To examine how sensitively a corona depends on the heating law, it is necessary to consider detailed coronal models for which both the amount ϕ_{M0} of heating and the damping length L over which the energy is dissipated are varied over broad ranges. A grid of such models has recently become available (Hammer, 1981, 1982a – hereafter Paper I, 1982b – hereafter Paper II) in which both ϕ_{M0} and L are varied over two orders of magnitude. In these models the decrease of the mechanical energy flux ϕ_M was approximated by the generalized heating law

$$\phi_M = \phi_{M0} \exp\left(-\frac{r-R}{L}\right), \tag{1}$$

where r is the central distance in the spherically symmetric models; R is the radius of the base of the transition region; ϕ_M is the mechanical energy flux, which was normalized to the stellar surface by multiplication with r^2/R^2; and L is the e-folding damping length, which was assumed to be constant. This latter assumption is, however, not crucial, since heating laws of a different form, such as the weak shock acoustic heating law (Ulmschneider, 1970)

$$\frac{d\phi_M}{dr} = -\alpha\left(\frac{R}{r}\right) p^{-1/2} c^{-3/2} \phi_M^{3/2} \quad \text{with} \quad \phi_M(r=R) = \phi_{M0}, \tag{2}$$

were found to give virtually the same coronal model as heating law (1) with a suitably chosen value of L. In Eq. (2), p is the local gas pressure and c is the isothermal sound speed. The coefficient α depends on the shape and period of the waves. Furthermore, it was shown (Hammer, 1982c – hereafter Paper III) that all of these coronal models, which were computed for a star of solar mass and radius, are applicable to arbitrary stars by means of a certain variable transformation.

In Sect. II we compare these detailed models of magnetically open coronal regions with minimum flux models in terms of various characteristic coronal parameters that have often been used in the literature (cf. the above mentioned applications of the MFC concept). From this comparison we conclude that the MFC concept is unreliable in predicting any quantity but the *maximum possible* (not the *actual*) value of the base pressure.

This result is opposite to the conclusions drawn by Vardavas and Hearn (1981) from a similar comparison of MFC predictions with detailed coronal models. As is discussed in Sect. III, this discrepancy is mainly caused by the fact that both the models and the discussion of Vardavas and Hearn were too strongly limited. These limitations have been removed by the new calculations of Hearn (1982) who also finds that the various MFC predictions may be severely in error.

In Sect. II we give a complete comparison of the MFC predictions with detailed coronal models; in Sect. III we discuss the investigations of Vardavas and Hearn (1981) and of Hearn (1982); and in Sect. IV we present our conclusions.

II. Comparison of MFC models with detailed coronal models

A. Base pressure

Figure 1 shows, for two versions of the MFC model and for detailed corona models, the pressure p_0 at the base of the transition region as a function of the mechanical heating flux. The MFC estimate of the base pressure is surprisingly good for relatively small damping lengths [radiation dominated coronae; cf. Paper II and Hammer (1982d)] For large L, however, the discrepancy is more severe – especially when the heating flux ϕ_{M0} is also large (wind dominated coronae). Then the actual pressure can be smaller than the MFC pressure by more than a factor of 3.

For constant mechanical energy flux ϕ_{M0}, Fig. 2 shows, as functions of L, the base pressure and the coronal temperature, which is represented by both the maximum coronal temperature T_m and the temperature T_c at the critical point. While the MFC model is uniquely determined for specified heating flux, the actual corona is seen to depend also on L and thus on the spatial distribution of coronal heating. In particular, the coronal temperature increases monotonically with increasing L, while p_0 first increases and then decreases.

In other words, the base pressure as a function of the coronal temperature has a maximum. This behavior was correctly predicted by Hearn (1975). However, it is the distribution of heating (i.e., the actual value of L) that determines where the corona is situated in relation to this maximum. For small L the corona is seen to have a lower temperature, while for large L it has a higher temperature than the corona with maximum p_0. On the other hand, the MFC concept assumes that every corona is of the maximum pressure type (cf. van Tend, 1979); thus, it aims at estimating $p_{0,\max}$. Figures 1 and 2 show that in this respect the original MFC formulae are less successful than the modified version after Endler et al. (1979). The principal improvement of

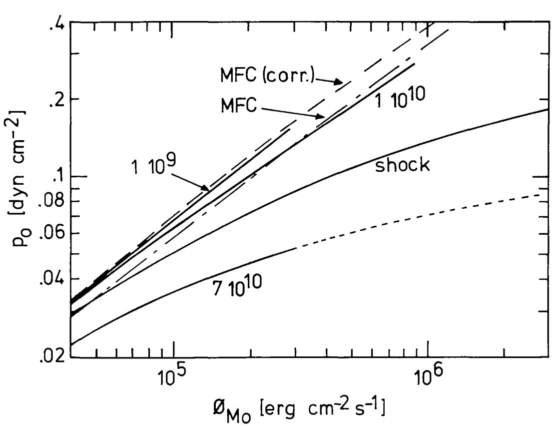

Fig. 1. Pressure p_0 at the base of the transition region as a function of the coronal heating flux ϕ_{M0}. For heating law (1) the damping length L (in cm) is indicated. The curve for the shock heating law (2) refers to $\alpha = 1\,10^{-3}\,\mathrm{s}^{-1}$. Also shown are the predictions of the MFC model (Hearn, 1975) and of a variant of this model which correctly treats the enthalpy losses of the transition region (Endler et al., 1979)

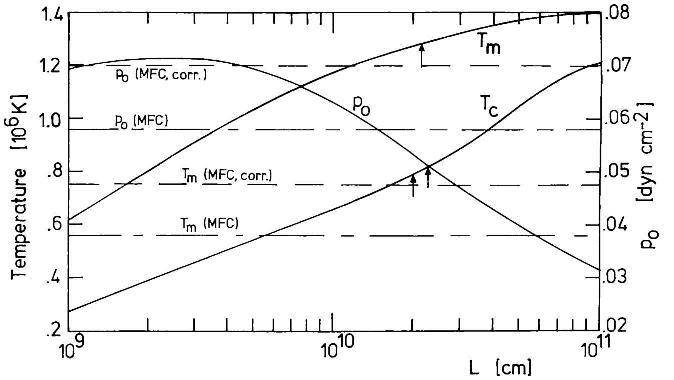

Fig. 2. Pressure p_0 at the base of the transition region, maximum coronal temperature T_m, and temperature T_c at the critical point, as functions of the damping length L. All data refer to a fixed coronal heating flux $\phi_{M0} = 1\,10^5$ erg cm^{-2} s^{-1}. The values corresponding to the shock heating law ($\alpha = 1\,10^{-3}$ s^{-1}) are indicated by arrows. The predictions of the MFC model (Hearn, 1975) and of a variant of this model are independent of the damping length

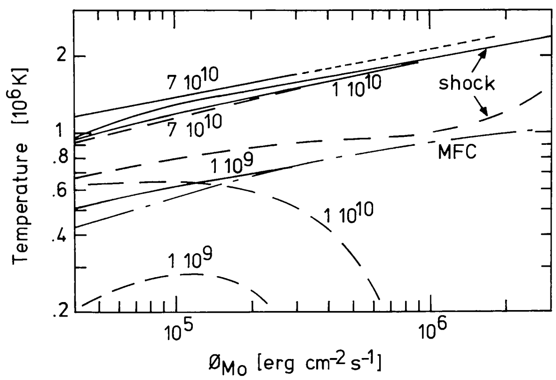

Fig. 3. Maximum coronal temperature T_m (solid curves) and temperature T_c at the critical point (dashed curves) as functions of the mechanical heating flux ϕ_{M0}. Shown are the curves for heating law (1) with damping lengths L (in cm) as indicated, for the shock heating law (2) with $\alpha = 1\,10^{-3}$ s^{-1}, and for the MFC concept after Hearn (1975)

the latter work lies in the correct treatment of the influence of enthalpy losses on the structure of the transition layer. This is done in a semianalytical way (cf. also Paper I), using a somewhat different fit to the radiative losses than the one used by Hearn (1975).

Why does the MFC concept, despite its simplifying assumptions, yield such a good estimate of the largest possible pressure? As shown in Figs. 1 and 2 the pressure reaches its maximum value for relatively small L (e.g., near $L \approx 2.5\,10^9$ cm in the special case $\phi_{M0} = 1\,10^5$ erg cm^{-2} s^{-1} shown in Fig. 2). This implies that most of the available energy goes into radiation (cf. Paper II). The radiative losses, however, depend sensitively on the density and thus on the pressure. Hence, for given total energy loss the possible variation of the base pressure of such radiation-dominated models (i.e. models with small L) is restricted to a narrow range (cf. Figs. 1 and 2). Moreover, in these models a significant part of the radiation originates from the lower transition region. In this thin zone the simplifying assumptions of the MFC model (such as plane geometry, constant pressure, and negligible heating) are clearly fulfilled.

B. Temperature

The energy losses of the MFC concept have been computed for an *isothermal* corona. It is difficult to compare the temperature of this isothermal corona with the temperature *structure* of detailed corona models. Nevertheless, Figs. 2 and 3 show that both the maximum temperature T_m and the temperature T_c at the critical point vary with L. This variation is larger than a factor of 2 for T_m and almost a factor of 10 for T_c. Contrary to that, the MFC model predicts only one single temperature value for given ϕ_{M0}. Moreover, the MFC concept cannot in principle account for the fact that the actual corona is always significantly nonisothermal. According to Fig. 3, T_c can be smaller than T_m by more than a factor of 10.

We conclude that the MFC temperature has no real physical relevance; the actual coronal temperature may be either much larger or much smaller, depending on the heating mechanism. In any case the actual corona is not isothermal as is assumed in the MFC concept.

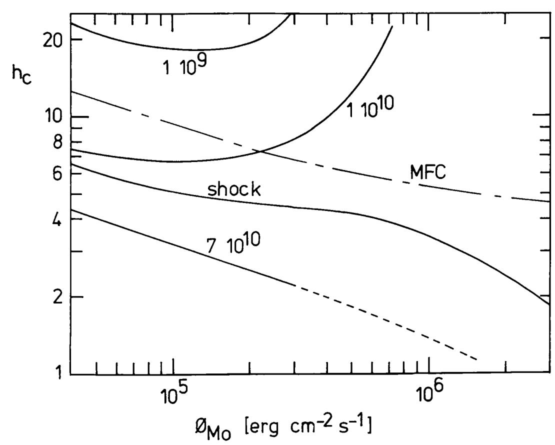

Fig. 4. Height h_c of the critical point above the base of the transition region, measured in units of the stellar radius, as a function of the mechanical heating flux ϕ_{M0}. The curves refer to heating law (1) with damping lengths L (in cm) as indicated, to heating law (2) with $\alpha = 1\,10^{-3}$ s^{-1}, and to the MFC concept after Hearn (1975)

C. Height of the critical point

One of the most interesting applications of the MFC concept in the literature is due to Mullan (1978). On the basis of observed values of the base pressure (Kelch et al., 1978), he computed the height h_c of the critical point of MFC models for various types of stars and derived a line in the HR diagram for which the critical point already occurs in the dense layers of the transition region and chromosphere. For stars crossing this line during their evolution he predicted the sudden onset of strongly enhanced mass loss. A critical discussion of these arguments has been given by Linsky and Haisch (1979), Haisch et al. (1980), and Castor (1981).

However, especially the height of the critical point is a quantity that is badly predicted by the MFC concept. Figures 4 and 5 show that h_c varies with L by roughly a factor of 10 –

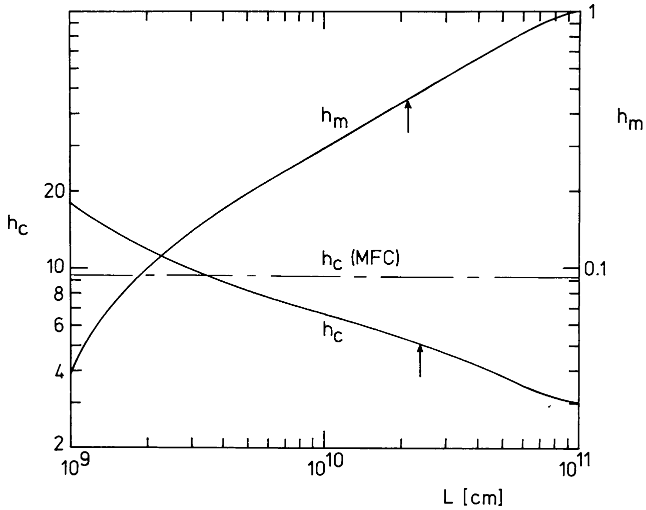

Fig. 5. Heights of the temperature maximum (h_m) and of the critical point (h_c) in units of the stellar radius [$h=(r-R)/R$] as functions of the damping length L. The values corresponding to the shock heating law (2) with $\alpha = 1\,10^{-3}\,s^{-1}$ are indicated by arrows. The MFC concept after Hearn (1975) predicts a value of h_c which does not depend on the damping length. All data are for constant $\phi_{M0} = 1\,10^5$ erg cm^{-2} s^{-1}

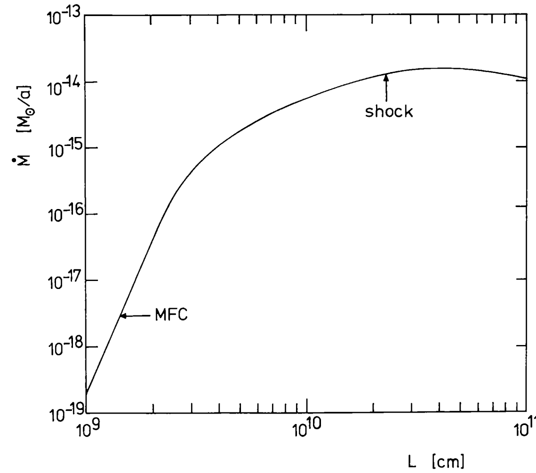

Fig. 6. Mass loss $\dot{M}$ in units of solar masses per year as a function of the damping length L, for constant coronal heating flux $\phi_{M0} = 1\,10^5$ erg cm^{-2} s^{-1}. The values for the shock heating law (2) with $\alpha = 1\,10^{-3}\,s^{-1}$ and for the MFC concept after Hearn (1975) are indicated by arrows

whereas the MFC concept yields only one single critical radius for given ϕ_{M0}. Furthermore, it is seen that h_c can increase as well as decrease with ϕ_{M0}, depending on L. Thus, the knowledge of the heating law (or damping length) is absolutely necessary for the prediction of the location of the critical point.

D. Height of the temperature maximum

Moreover, the MFC concept cannot predict the height h_m of the coronal temperature maximum. This quantity, which according to Fig. 5 depends strongly on L, would probably also be necessary for considerations like those of Mullan (1978).

E. Energy balance

Although the MFC concept was derived from energy balance considerations, the nature of the energy balance turns out to be one of the weakest points of this concept. For $\phi_{M0} = 1\,10^5$ erg cm^{-2} s^{-1}, for example, and a star of solar mass and radius, the MFC concept predicts a purely radiation dominated corona with completely negligible wind losses. However, detailed computations (cf. Figs. 8 and 10 of Paper II) show that with varying L the corona may change from one with only radiative losses into one with equally important contributions of radiation, wind, and outward thermal conduction at the critical point. This strong dependence of the various kinds of energy losses on L is even more pronounced for larger values of ϕ_{M0}.

Moreover, we want to emphasize that outward conductive losses cannot in principle be treated with the MFC concept because of the assumption of an isothermal corona. These losses are important for large L and small ϕ_{M0} (Paper II and Hammer, 1982d).

F. Mass loss

The most severe discrepancies occur for the mass loss rate $\dot{M}$, which according to Fig. 6 varies with L by many orders of magnitude – whereas the MFC concept again predicts one single value. Figure 6 shows that the actual mass loss rate may be either smaller than predicted by the MFC concept (when the actual coronal heating mechanism is characterized by a small damping length L) or larger by a factor of up to 10^4 (when L is large). Thus, the MFC concept is absolutely unreliable in predicting energy loss ratios or mass loss rates.

III. Related work

So far the basic physics of coronal heating is not known – either for the Sun (Kuperus et al., 1981) or for other stars. Obviously, however, the associated damping length cannot be expected to be the same for various kinds of coronal regions on various kinds of stars. Even for the Sun the values of L that are discussed in the literature (for references see Paper I) vary by one or two orders of magnitude. Therefore, the MFC concept, which neglects the coronal dependence on L, can only be meaningful if for a given star and a given coronal heating flux the corona does not depend significantly on the damping length L, even when L is varied over a *broad*, hence reasonable, range. The results of the preceding section cover a sufficiently large range of L values to show that magnetically open regions of stellar coronae in fact depend on L; thus the MFC concept is unreliable.

Recently, Vardavas and Hearn (1981) have also compared detailed coronal models with MFC predictions; however, from their data they drew the opposite conclusion. There exist three main reasons for this discrepancy. First, the parameter range of their models was too strongly limited, as Vardavas and Hearn already recognized. They considered only a very special heating mechanism (acoustic waves) and varied the associated free parameter (namely, the wave period) by only a factor of two. Hence, they restricted the corresponding damping length in a similarly drastic way. Second, in their models the wave period and the coronal heating flux varied simultaneously. Thus, they could not examine the dependence of stellar coronae on the spatial distribution of heating for given coronal heating flux, as would be necessary for a critical test of the MFC concept. Third, the discussion of Vardavas and Hearn did not include several important coronal properties which played a central role in recent applications of the MFC concept (cf. Sect. I) and which must also be considered (as we have done in Sect. II) in order to judge the overall reliability of this concept.

After submission of the original version of this paper, which is based on results presented in Hammer (1981), we received a preprint of the paper Hearn (1982). This paper, which had been submitted at virtually the same time as ours, deals with the effects of extremely long acoustic wave periods, corresponding to very long damping lengths. In this new work, the above mentioned limitations of the earlier paper by Vardavas and Hearn (1981) are removed. As a result, Hearn (1982) also finds that the various MFC predictions may be severely in error, particularly for large damping lengths. Moreover, the new coronal models of Hearn (1982) exhibit various trends that have already been found and explained (Hammer, 1981, 1982d, Papers I and II) by one of the present authors. It is important to note that the models of Hammer and of Hearn have been computed with completely different methods. In view of these differences, the agreement between the results of both calculations is remarkable and encouraging. The fact that the results of Hearn corroborate the earlier computations of Hammer suggests strongly that both numerical methods are correct.

IV. Discussion and conclusions

The MFC concept (Hearn, 1975) assumes that the corona of a given star depends only on the total amount ϕ_{M0} of coronal heating. Contrary to that, general arguments (Endler et al., 1979; Mangeney and Souffrin, 1979) as well as detailed corona models (Hammer, 1981; Papers I and II; Vardavas and Hearn, 1981; Hearn, 1982) prove that open coronal regions depend also on the spatial distribution, or characteristic damping length L, of coronal heating.

Therefore, MFC predictions of various coronal properties, which have often been used in the literature, must necessarily be wrong. The respective error depends on the characteristic damping length of the actual, as yet unknown, coronal heating mechanism. To determine the possible errors of these various MFC predictions, we have compared MFC models with a grid of detailed coronal models that covers a range of two orders of magnitude in both parameters ϕ_{M0} and L. The results may be summarized as follows.

1. For given ϕ_{M0}, the base pressure p_0 as a function of the coronal temperature has a maximum, as was pointed out by Hearn (1975). The minimum flux, or maximum pressure, corona concept aims at estimating this maximum pressure value. We have found that the MFC concept, in spite of its various simplifying assumptions, gives a surprisingly good estimate of this *maximum possible* base pressure. The *actual* base pressure, on the other hand, depends on the damping length; it is smaller than the maximum possible value predicted by the MFC concept by a factor of up to 3. For extremely wind dominated coronae, the error can even be larger.

2. Contrary to the assumption underlying the MFC formulae, the corona is not isothermal. Its detailed temperature structure varies considerably with L. The MFC temperature differs from both the maximum coronal temperature and the temperature at the critical point by factors of up to 3, in some cases even more. This large discrepancy cannot be resolved by means of the energy-loss-weighted temperature $\bar{T}$ which was recently introduced by Vardavas and Hearn (1981).

3. Depending on L, the height of the critical point can differ by more than a factor of 3 from the corresponding MFC prediction.

4. The MFC concept is absolutely unreliable in predicting the mass loss rate and the relative importance of the various kinds of energy losses. The MFC predictions of the mass loss rate and of the energy losses due to stellar wind can be wrong by many orders of magnitude.

5. Important quantities such as the height of the temperature maximum and the usually considerable difference between the maximum coronal temperature and the temperature at the critical point cannot be predicted by the MFC concept. Further, outward thermal conductive energy losses, which for some heating mechanisms are important, are neglected in the MFC concept.

These results show that all previous applications of the MFC concept (cf. Sect. I) are subject to large uncertainty factors. Magnetically open regions of stellar coronae, as opposed to MFC models, depend not only on the total amount of coronal heating, but also on its spatial distribution. This corroborates the general arguments of Endler et al. (1979) and Mangeney and Souffrin (1979). The suggestion of Hearn and Kuin (1981) that the coronal dependence on the distribution of heating should be weak because the large thermal conductivity leads to a redistribution of the dissipated energy, is only partially correct. It is precisely this redistribution that is an important factor for the coronal energy balance. Although the maximum coronal temperature changes by "only" a factor of 2 or 3 when L varies over two orders of magnitude (cf. Figs. 2 and 3), conductive energy redistribution necessitates coronal temperature gradients. As a result, the temperature at the critical point already varies by a factor of 10. Owing to the extremely sensitive temperature dependence of both the stellar wind and the outward thermal conduction (cf. Paper II), the mass loss rate and the various kinds of energy losses vary by several orders of magnitude.

We acknowledge that the MFC concept has been an important and fruitful idea on the ongoing process of our understanding of coronal physics. In his original MFC paper, Hearn (1975) derived useful formulae (see also Endler et al., 1979; Mewe, 1979) for estimating the various kinds of coronal energy losses of arbitrary stars as functions of the coronal temperature and base pressure; and he also showed that for a given star and for a given coronal heating flux there exists a maximum possible value for the coronal base pressure. At the time when the MFC concept was published there was no complete grid of coronal models available that depended only on the parameters characterizing the star and the coronal heating law. With the MFC concept it was possible to get rapidly an idea of how the corona of a given star *might* look, because the MFC represents one of many possible coronal configurations. The common error in the application of this concept, however, has always been the assumption that a corona *is*, or even *must be*, of the MFC type.

The present work shows clearly that for a given star (i.e., given mass and radius) the corona depends not only on the amount of coronal heating (as in MFC models), but also very sensitively on its spatial distribution, or characteristic damping length. This means that for a given star *two* coronal parameters (such as base pressure, maximum temperature, total radiative losses, mass loss, heating rate, or damping length) must be known in order that coronal models can be used to determine the physical state of the corona. For this purpose the models underlying the present study (Papers I–III) are well suited, as they represent a complete grid of models for stars with arbitrary (within certain limits; cf. Hammer, 1981) mass, radius, coronal heating flux, and damping length. And even if only a single coronal parameter is given, these models allow us to find relations between other parameters and to estimate the possible uncertainty of various quantities due to the unknown properties of coronal heating. Therefore, a grid of models of this type can fully replace the MFC concept; and eventually it will bring us one step closer to the solution of how coronae are heated.

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References

Antiochos, S.K., Underwood, J.H.: 1978, *Astron. Astrophys.* **68**, L19

den Boggende, A.J.F., Mewe, R.: 1979, in *X-ray Astronomy*, Proc. 21st COSPAR Symp., eds. W. A. Baity and L. E. Peterson, p. 193

den Boggende, A.J.F., Mewe, R., Heise, J., Gronenschild, E.H.B.M., Schrijver, J.: 1978, *Astron. Astrophys.* **67**, L29

Castor, J.I.: 1981, in *Physical Processes in Red Giants*, eds. I. Iben, Jr., and A. Renzini, Reidel, Dordrecht, p. 285

Couturier, P., Mangeney, A., Souffrin, P.: 1980, in *Solar and Interplanetary Dynamics*, IAU *Symp.* **91**, eds. M. Dryer and E. Tandberg-Hanssen, Reidel, Dordrecht, p. 127

Endler, F., Hammer, R., Ulmschneider, P.: 1979, *Astron. Astrophys.* **73**, 190

Haisch, B.M., Linsky, J.L., Basri, G.S.: 1980, *Astrophys. J.* **235**, 519

Hammer, R.: 1981, Ph.D. Thesis, University of Würzburg

Hammer, R.: 1982a, *Astrophys. J.* **259**, 767 (Paper I)

Hammer, R.: 1982b, *Astrophys. J.* **259**, 779 (Paper II)

Hammer, R.: 1982c, *Astrophys. J.* (in preparation) (Paper III)

Hammer, R.: 1982d, in *Second Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, eds. M. S. Giampapa and L. Golub, SAO Spec. Rept. **392**, 121 (1982)

Hammer, R.: 1982e, in *Advances in Space Research* (in press)

Hearn, A.G.: 1975, *Astron. Astrophys.* **40**, 355

Hearn, A.G.: 1977, *Solar Phys.* **51**, 159

Hearn, A.G.: 1979, *Astron. Astrophys.* **79**, L1

Hearn, A.G.: 1982, *Astron. Astrophys.* **116**, 296

Hearn, A.G., Kuin, N.P.M.: 1981, *Astron. Astrophys.* **98**, 248

Hearn, A.G., Mewe, R.: 1976, *Astron. Astrophys.* **50**, 319

Hearn, A.G., Vardavas, I.M.: 1981, *Astron. Astrophys.* **98**, 230

Holzer, T.E.: 1980, in *Cool Stars, Stellar Systems, and the Sun*, ed. A. K. Dupree, SAO Spec. Rept. **389**, p. 153

Jordan, C.: 1980, *Astron. Astrophys.* **86**, 355

Kelch, W.L., Linsky, J.L., Basri, G.S., Chiu, H.-Y., Chang, S.-H., Maran, S.P., Furenlid, I.: 1978, *Astrophys. J.* **220**, 962

Kuperus, M., Ionson, J.A., Spicer, D.S.: 1981, *Ann. Rev. Astron. Astrophys.* **19**, 7

Lampton, M., Mewe, R.: 1979, *Astron. Astrophys.* **78**, 104

Linsky, J.L., Haisch, B.M.: 1979, *Astrophys. J. Letters* **229**, L27

Mangeney, A., Souffrin, P.: 1979, *Astron. Astrophys.* **78**, 36

Martens, P.C.H.: 1981, *Astron. Astrophys.* **102**, 156

Mewe, R.: 1979, *Space Sci. Rev.* **24**, 101

Muchmore, D.O., Böhm, K.H.: 1978, *Astron. Astrophys.* **69**, 113

Mullan, D.J.: 1976, *Astrophys. J.* **209**, 171

Mullan, D.J.: 1978, *Astrophys. J.* **226**, 151

Souffrin, P.: 1982, *Astron. Astrophys.* **109**, 205

van Tend, W.: 1979, *Solar Phys.* **64**, 229

Ulmschneider, P.: 1970, *Solar Phys.* **12**, 403

Vaiana, G.S., Rosner, R.: 1978, *Ann. Rev. Astron. Astrophys.* **16**, 393

Vardavas, I.M., Hearn, A.G.: 1981, *Astron. Astrophys.* **98**, 241

Wallenhorst, S.G.: 1980, *Astrophys. J.* **241**, 229