Astron. Astrophys. 73, 190–192 (1979)

ASTRONOMY AND ASTROPHYSICS

On the Energy Balance of Stellar Coronae

F. Endler, R. Hammer, and P. Ulmschneider

Institut für Astronomie and Astrophysik, Am Hubland, D-8700 Würzburg, Federal Republic of Germany

Received July 29, 1977; revised June 26, 1978

Summary. From a survey of proposed coronal heating mechanisms we conclude that these processes not only provide a certain heating flux but also, through a damping length L, determine the mode of dissipation of this flux. Both for simplified and more elaborate models it is found that L determines both the magnitude and the position of the coronal temperature maximum. Such detailed determination of the corona model by the heating mechanism appears to contradict the concept of a minimum flux corona.

Key words: stellar coronae

1. Introduction

The concept of minimum flux coronae (Hearn, 1975) has recently been felt to be an important step towards the understanding of stellar coronae. Hearn (1975) has shown that for a given coronal base pressure p_0, the wind- and conductive energy losses of the corona increase with increasing corona temperature T_c. The coronal radiative losses on the other hand are known to decrease with increasing T_c (Cox and Tucker, 1969; McWhirter et al., 1975, Hearn, 1975). Near temperatures where these losses are comparable one should consequently find coronae where for a given base pressure p_0 the total coronal loss F_L is a minimum with respect to T_c. These coronae are called minimum flux coronae (Hearn, 1975). For stars of solar mass and radius for example, Fig. 1 shows the total losses F_L as well as the set of minimum flux coronae. In Sect. 2 we briefly discuss the computation of the coronal losses. Hearn (1975, 1977) argues that every corona is of the minimum flux type and on basis of the minimum flux idea properties of coronae of various types of stars were recently discussed (Haisch and Linsky, 1976; Mullan, 1976). With this concept for every given heating flux $F_H = F_L$ a unique minimum flux corona model can be found (c.f. Fig. 1) and the values of the base pressure p_0 and corona temperature T_c may be determined.

In our opinion the hope set into the minimum flux concept is premature. Although we find it highly probable that such a relation between p_0 and T_c exists, we think that this relation very likely is determined by the heating mechanism and therefore is a property of a given star. Among others our main reason for this is that every heating mechanism for stellar coronae discussed so far in the literature (c.f. Sect. 3) not only fixes the total heating flux but also specifies where this flux is deposited. In our opinion it is this second property of the heating mechanism which among the possible configurations ultimately determines the correct corona model and therefore the values of p_0 and T_c. As corona models are thus seen to depend in a detailed way on the heating mechanism it is very unlikely that they satisfy the additional constraint imposed by the minimum flux concept.

Send offprint requests to: F. Endler

2. Corona and Transition Layer Models

For an illustration of our arguments we have computed a series of simplified corona models for solar mass and radius. Following Hearn (1975) we assume an isothermal corona with temperature T_c which is attached to a thin transition layer with constant pressure p_0. Fig. 1 shows the total energy loss of the corona models for given T_c and p_0. Minimum flux corona models are indicated by a dashed line. For a constant energy loss $F_L = 1.0$ E6 erg/cm² s Fig. 2 gives a series of models that lie on a horizontal line in Fig. 1 and depend only on one parameter T_c or p_0. The computations necessary to construct these models are briefly summarized.

The coronal radiation and wind losses are evaluated as function of p_0 and T_c by methods similar to Hearn (1975). For the coronal conductive losses which belance the transition layer losses we use a slightly different treatment as Hearn. We assume that there is no dissipation of the heating flux in the transition layer (c.f. Ulmschneider, 1971; McWhirter et al., 1975). The stellar wind flux for the transition layer in our approximation is given by the enthalpy flux

$$F_E = \tfrac{5}{2} jkT \tag{1}$$

where $j = p_0 v/kT$ is the constant particle flux.

Here v is the subsonic wind velocity, k the Boltzmann constant and T the temperature. Following McWhirter et al. (1975) we assume for the radiative flux F_R of the transition layer

$$\frac{dF_R}{dh} = p_0^2 B T^{-5/2} \tag{2}$$

where h is the geometrical height measured from the foot of the transition layer and $B = 6.6$ E11 cm s K$^{5/2}$ g^{-1}.
For the conductive flux we have

$$F_c = -\bar{K} T^{5/2} \frac{dT}{dh} \tag{3}$$

where $\bar{K} = 1.1$ E-6 g cm s^{-3} K$^{-7/2}$. The energy balance in the transition layer requires

$$\frac{d}{dh}(F_E + F_R + F_c) = 0. \tag{4}$$

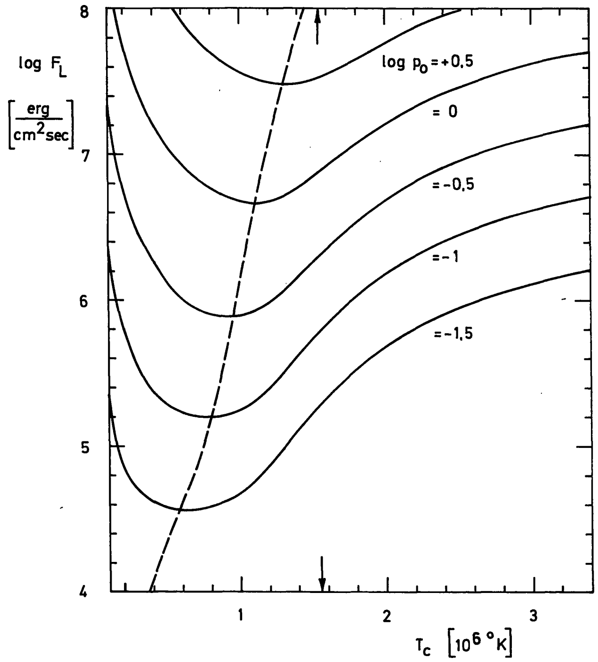

Fig. 1. The total energy loss F_L (erg/cm^2 s normalized to the stellar surface) between coronal base point and sonic point as function of the coronal temperature T_c for various base pressures p_0 and for a star with solar mass and radius

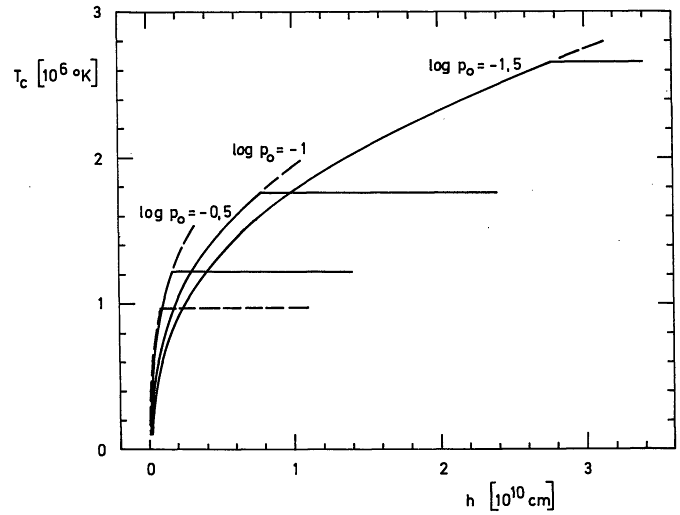

Fig. 2. Temperature T as function of height h in various corona models for star of solar mass and radius. All models have the same total energy loss flux of $F_L = 10^6$ erg cm^{-2} s^{-1}. The dashed model corresponds to the minimum flux corona

From these equations assuming that T and $|F_c|$ are large compared to their initial values one can derive analytically

$$\frac{5}{2} jkT = -F_c - \frac{p_0^2 \bar{K} B}{\frac{5}{2} jk} \ln\left(1 - \frac{\frac{5}{2} jk}{p_0^2 \bar{K} B} F_c\right). \tag{5}$$

The coronal conductive loss can be calculated from Eq. (5) if p_0, T_c and j are specified. For an isothermal corona however with a wind solution going through the sonic point the particle flux depends only on T_c and p_0,

$$j = \frac{v_0(T_c) p_0}{kT_c} \tag{6}$$

where $v_0(T_c)$ is a function given by Parker (1958). Thus with Eqs. (5) and (6) we determine the coronal conductive flux as function of T_c and p_0. The height h in the transition layer finally is computed using Eqs. (4) and (5):

$$h = -\int_{T_0}^{T_c} \bar{K} T^{5/2} \frac{dT}{F_c(T)}. \tag{7}$$

3. Coronal Heating Mechanisms and Their Influence on the Corona Models

For the presently unknown coronal heating mechanism several authors have assumed an acoustic process (de Jager and Kuperus, 1961; Kuperus, 1965, 1969; Ulmschneider, 1967, 1971; Kopp, 1968, 1972; de Loore, 1970; Hearn, 1972, 1973; Lamers and Kuperus, 1974; McWhirter et al., 1975; Flower and Pineau des Forêts, 1976; Vanbeveren and de Loore, 1976; Flower, 1977) while others have proposed a magneto-acoustic (Osterbrock, 1961; Uchida, 1963) or an Alfvén wave mechanism (Piddington, 1973; Uchida and Kaburaki, 1974; Hollweg, 1978). In addition to these mechanisms high resolution observations of the Sun have revealed very broad non-gaussian line profiles (Brueckner et al., 1978) which are attributed to gas jets with velocities that may exceed 200 km s^{-1}. This could constitute yet another important coronal heating mechanism.

Most of these heating mechanisms may be represented by a heating law of the form

$$\frac{dF_H}{dh} = -\frac{F_H}{L} \tag{8}$$

where L is a damping length over which most of a given heating flux will be dissipated.

Various authors (e.g. Lamers and Kuperus, 1974; Kopp and Orrall, 1976) have assumed that L is a constant. For acoustic waves for example L depends on p, T and the wave period (McWhirter et al., 1975; Vanbeveren and de Loore, 1976). In addition to p and T the length L depends on F_H if heating by acoustic shock waves is considered (Kuperus, 1965, 1969; Ulmschneider, 1967, 1971; de Loore, 1970; Kopp, 1968, 1972; Flower and Pineau des Forêts, 1976; Flower, 1977; Ulmschneider et al., 1978). L depends on geometry and magnetic field strength if heating by magneto-hydrodynamic waves is assumed (see discussion by Wentzel, 1977). Rosner et al. (1978) have recently given a table of L values for various heating mechanisms, while Jordan (1976) has discussed empirical values of L.

In all these discussions it is clear that L is by no means a free parameter but is determined completely by the processes which transport the heating flux F_H into the upper atmosphere.

Let us now discuss the corona models of Fig. 2 which have a common total energy loss flux F_L. The heating flux F_H in these simplified models is dissipated primarily at the point where the corona and the transition layer are fitted. Here a large fraction of F_H is used to balance the coronal conductive losses and to produce the discontinuity in the temperature slope. The remaining amount of heating is dissipated in higher layers to balance the coronal radiation and wind losses. In a more realistic corona the fitting point of the simplified model corresponds to a height where a considerable part of F_H has been dissipated such that the temperature slope has been noticeably changed compared to models without heating. After Eq. (8) this characteristic length is roughly given by the damping length L. [See Fig. 2 of McWhirter et al. (1977).] Thus we may roughly identify the damping length L with the thickness of the transition layer of our simplified model. From Fig. 2 but also quite generally we conclude that L therefore determines the magnitude of the coronal temperature. This view is consistent with results of Lamers and Kuperus (1974) and McWhirter et al. (1977, Fig. 2) who have shown that L determines the maximum of the coronal temperature, although these authors did not explicitly include stellar wind.

The damping length L moreover is a measure of the geometrical height of the coronal temperature maximum. At the height of the temperature maximum in a realistic model the heating flux will have been largely used up for the complete balance of conductive losses. If thus at the temperature maximum F_H has decreased lets say by about one or two orders of magnitude, the distance D between the foot of the transition layer and the coronal temperature maximum after Eq. (8) must lie roughly between 2 L and 5 L. This correlation between D and L is confirmed by steady state calculations (e.g. Ulmschneider, 1971 Fig. 5 case 2.0; McWhirter et al., 1977 Fig. 2), which yield a value D of about 5 L.

In both the simplified isothermal corona models as well as in more realistic cases the property of the heating mechanism to prescribe a damping length L will thus select a specific model. This is shown for instance in Fig. 2 where the specification of L determines the height of the fitting point between transition layer and corona. It thus appears unlikely that this prescription of L will lead to the selection of a corona model of the minimum flux type.

4. Discussion and Conclusions

On basis of a survey of recent coronal heating mechanisms we conclude that these processes not only provide a certain amount of total heating flux but also determine the mode of dissipation of this flux. If the variation of the heating flux is written in the form of Eq. (8) we have shown that the damping length L should roughly determine the coronal temperature as well as the position of the coronal temperature maximum. We find that the property of the heating mechanism to prescribe the damping length removes the freedom of choice between corona models of equal heating flux. A given heating mechanism will thus lead to a relation between the coronal temperature T_c and the base pressure p_0. As the heating mechanism depends in a specific way on the given star it would be difficult for a corona model produced by this mechanism to additionally satisfy the minimum flux constraint. We thus conclude that a general minimum flux concept cannot apply.

References

Brueckner, G. E., Bartoe, J. D. F., Van Hoosier, M. E.: 1978, NRL preprint

Cox, D. P., Tucker, W. H.: 1969, *Astrophys. J.* **157**, 1157

De Jager, C., Kuperus, M.: 1961, *Bull. Astron. Inst. Neth.* **16**, 71

De Loore, C.: 1970, *Astrophys. Space Sci.* **6**, 60

Flower, D. R., Pineau des Forêts, G.: 1976, *Astron. Astrophys.* **52**, 191

Flower, D. R.: 1977, *Astron. Astrophys.* **58**, 185

Haisch, B. M., Linsky, J. L.: 1976, *Astrophys. J.* **205**, L39

Hearn, A. G.: 1972, *Astron. Astrophys.* **19**, 417

Hearn, A. G.: 1973, *Astron. Astrophys.* **23**, 97

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

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

Hollweg, J. V.: 1978, *Solar Phys.* **56**, 305

Jordan, C.: 1976, *Phil. Trans. Roy. Soc. London* A **281**, 391

Kopp, R. A.: 1968, Air Force Cambridge Res. Lab. Rept. **4**, Bedford, Mass.

Kopp, R. A.: 1972, *Solar Phys.* **27**, 373

Kopp, R. A., Orrall, F. Q.: 1976, *Astron. Astrophys.* **53**, 363

Kuperus, M.: 1965, *Rech. Astron. Obs. Utrecht* **17**, 1

Kuperus, M.: 1969, *Space Sci. Rev.* **9**, 713

Lamers, H. J. G. L. M., Kuperus, M.: 1974, in Ph. D. thesis H. J. G. L. M. Lamers, Utrecht

McWhirter, R. W. P., Thonemann, P. C., Wilson, R.: 1975, *Astron. Astrophys.* **40**, 63

McWhirter, R. W. P., Thonemann, P. C., Wilson, R.: 1977, *Astron. Astrophys.* **61**, 859

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

Osterbrock, D. E.: 1961, *Astrophys. J.* **134**, 347

Parker, E. N.: 1958, *Astrophys. J.* **128**, 664

Piddington, J. H.: 1973, *Solar Phys.* **33**, 363

Rosner, R., Tucker, W. H., Vaiana, G. S.: 1978, *Astrophys. J.* **220**, 643

Uchida, Y.: 1963, *Publ. Astron. Soc. Japan* **15**, 376

Uchida, Y., Kaburaki, O.: 1974, *Solar Phys.* **35**, 451

Ulmschneider, P.: 1967, *Z. Astrophys.* **67**, 193

Ulmschneider, P.: 1971, *Astron. Astrophys.* **12**, 297

Ulmschneider, P., Schmitz, F., Kalkofen, W., Bohn, H. U.: 1978, *Astron. Astrophys.* **70**, 487

Vanbeveren, D., de Loore, C.: 1976, *Solar Phys.* **50**, 99

Wentzel, D. G.: 1977, *Solar Phys.* **52**, 163