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# Heating of the solar and stellar coronae

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**Abstract.** The problem of heating of the solar and stellar coronae by acoustic, magnetoacoustic and Alfvén waves and by magnetic energy dissipation has been reviewed. Some miscellaneous mechanisms such as mass accretion, magnetic flux emergence, spicules and velocity filtration etc are also briefly described. Our analysis favours Alfvén waves, magnetic energy dissipation and velocity filtration heating. In case of Alfvén waves the generation and dissipation needs more precise study. For magnetic energy dissipation the instruments which can resolve length-scales of the order of 1 km at the solar surface are crucially needed. In order to test the validity of the velocity filtration theory the computation of the intensities of UV lines by taking into account Coulomb effects, realistic geometry and ambipolar diffusion must be available. Further the mechanism of production of high energy particles at the base of the corona is also highly desirable.

## 1. Introduction

It is now well-established that the outer atmospheres, particularly the coronal regions of the Sun and other stars have temperatures of million degree Kelvin. They lie in between two cooler regions in spite of their extremely high thermal conductivity. The coronal material loses energy predominantly by thermal conduction, radiation and solar and stellar winds (Withbroe & Noyes 1977). In order to replenish these losses some source of energy must be present.

Since the thermal and electrical conductivities of the coronae are very large hence the surrounding regions will receive energy from the coronae via thermal conduction and the temperatures will soon equalize. The matter density in the corona is quite low hence it cannot absorb enough electromagnetic radiation from inner regions to maintain its high temperature.

The solar observations show numerous open and closed magnetic field regions in the solar corona. The closed-field regions have stronger magnetic fields and are brighter than open-field regions (coronal holes). This implies that the solar magnetic fields play an important role in the coronal heating.

Various mechanisms have been put forward to explain the solar and stellar coronal temperatures (see, e.g., Narain & Ulmschneider 1990, 1996 and references therein). Basically the sources of heating are of two types, namely external and internal. For example, the accretion of matter by a star leads to atmospheric heating and it comes under external source category. The source of energy for all internal mechanisms is the convection zone which produces acoustic waves, magnetoacoustic and Alfvén waves and magnetic fields and currents. These waves propagate through photosphere, chromosphere and transition region to corona. Predominantly, different sources heat different regions of the stellar atmosphere.

## 2. Acoustic wave heating

Due to turbulent motions in the convection zone acoustic waves are produced. Their energy flux is given by

$$F_s = \rho u^2 c_s , \tag{1}$$

where $\rho$ is the matter density, u is the velocity of turbulent motions and $c_s$, the adiabatic sound speed, is given by

$$c_s = (\gamma p/\rho)^{0.5}. \tag{2}$$

In photosphere $\rho \sim 10^{-7}$ gm/cm$^3$, u~0.5 km/s and $c_s$~0.8 km/s which together with equation (1) yields $F_s \sim 10^7$ erg/cm$^2$/s. The total losses in the corona are of the same order (Withbroe & Noyes 1977). Thus acoustic waves have just sufficient flux of energy to heat the corona. When these waves propagate outwards from the photosphere their velocity increases continuously because of decreasing matter density. In the lower chromosphere they become shocks and lose most of their energy via thermal conduction and viscosity of the medium. Now they do not have sufficient energy to heat the corona.

## 3. Heating by magnetoacoustic waves

In a homogeneous medium permeated with a uniform magnetic field three types of MHD waves are generated (Osterbrock 1961). They are Alfvén waves, fast and slow MHD waves, the latter two are called magnetoacoustic or magnetosonic waves. The slow waves propagate almost parallel to the ambient uniform field with a phase velocity which is smaller than that of the fast waves. The fast waves may propagate in any direction with respect to the uniform magnetic field. As these waves propagate from sub-photospheric regions outwards, due to decrease in matter density their velocity increases similar to acoustic waves. In the upper chromosphere they become MHD shocks and lose their energy through the resistivity and the viscosity of the medium. Davila and Chitre (1991) obtain a heating rate of ~ $10^5$ erg/cm$^2$/s for acoustic waves impinging on magnetic arches of a chromospheric canopy. Another problem is that they are not produced in adequate amount in the subphotospheric layers (Parker 1991a, b; Collins 1992). In view of the above uncertainties they cannot be held responsible for heating the corona.

It is now well-established that solar (may be stellar) magnetic fields are not homogeneous (Stenflo 1994 and references therein). In such a case a complex pattern of waves may be produced. Some of them are torsional, kink and sausage magnetic flux tube waves. They may be body and or/surface waves (Roberts 1991). The generated fluxes of these waves may be of the same order or higher than required but still there are uncertainties (Choudhuri et al. 1993 a,b; Porter et al. 1994).

## 4. Heating by Alfvén waves

Similar to magnetoacoustic waves the Alfvén waves are also produced by the convective motions in the convection zone. They are purely magnetic waves in which magnetic field variations are transverse to the ambient uniform field. They propagate, strictly, parallel to the ambient uniform field, with a phase velocity, $v_A$, given by

$$v_A = B_0/(4\pi\rho)^{0.5}, \tag{3}$$

where $B_0$ is the ambient uniform magnetic induction (field). The energy flux of the Alfvén waves is given by

$$F_A = \rho\, u^2\, v_A\ . \tag{4}$$

Assuming $B_0$ = 50 G in the photosphere the Alfvén velocity, as given by equation (3), is ~0.45 km/s and the Alfvén wave flux using equation (4), is $\sim 10^7$ erg/cm$^2$/s which is of the same order as the losses from the corona.

When Alfvén waves propagate to corona from the site of their origin, they suffer little dissipation due to the resistivity and the viscosity of the ambient medium if $B_0 \gtrsim$ 10-20 G (Priest 1982). But in a medium with non-uniformity in density or magnetic field some more efficient dissipative mechanisms such as resonant absorption (Ionson 1978), phase-mixing (Heyvaerts & Priest 1983), nonlinear mode-coupling (Kleva & Drake 1992) and intermittent magnetic levitation (Moore et al. 1992) need more detailed study. The Alfvén waves may be generated in nano/micro-flares. The generated fluxes from convection zone and other sources should be more precisely investigated.

## 5. Heating by magnetic field dissipation

This mechanism seems to be more appropriate for active regions where many magnetic flux tubes (coronal loops) exist. Foot-point motions due to granular and supergranular flows as well as due to differential rotation can lead to a build up of magnetic energy in coronal loops. The heating flux (DC) entering the loop is given by

$$F_{DC} = (B_0^2/4\pi)\ (u^2/l_c)\ t\ , \tag{5}$$

where $B_0$ is the uniform magnetic field along the loop, u is the velocity of the photospheric foot point motions, $l_c$ is the length of the coronal loop from one foot point to the other and t is a characteristic time for the build up of the magnetic energy. For DC flux t is much smaller than the Alfvén transit time $t_A = l_c/v_A$. For an active region with u ~ 0.5 km/s, $B_0 \sim$ 100 G, $l_c \sim 10^5$ km, the time required to build up an energy flux of $\sim 10^7$ erg/cm$^2$/s, as given by equation (5), is 14 hours (Parker 1986).

According to Parker (1991c) almost all strong continuous deformations of an initially uniform magnetic field in an infinitely conducting fluid cause the field to develop current sheets as the field relaxes to equilibrium. The dissipation at the current sheets in the bipolar magnetic fields of active regions is the principal heat source for the solar X-ray corona. The dissipation is episodic so that the magnetic energy is converted to thermal energy in small transient bursts, called nano flares, in which about $10^{23}$-$10^{25}$ erg of energy is released. Taking $10^{23}$erg per nanoflare as an average, the mean output of $10^7$ erg/cm$^2$/s requires about one new nanoflare per second in each area $10^3 \times 10^3$km$^2$. This theory has been extended to include all stars with magnetic fields and coronae (Parker 1993).

## 6. Miscellaneous heating mechanisms

*A. Heating by mass accretion:*

Hoyle, (1949) proposed that when Sun moves in the galaxy it captures particles whose potential and kinetic energies get converted to heat and thus the solar corona may be heated. This theory cannot explain the solar wind phenomena and the process is not important for the Sun but it is quite important for the outer atmospheres of pre-main sequence stars (Narain & Ulmschneider 1990 and references therein).

*B. Heating by spicules:*

The material in the spicules is somehow raised to a relatively greater height and thus it possesses gravitational potential energy much in excess of its kinetic energy. This potential energy may then be converted into thermal energy as the spicular material falls back (Athay & Holzer 1982). This mechanism by itself cannot heat the corona. The mechanism of acceleration of spicular matter should be specified.

*C. Heating by magnetic flux emergence:*

According to Book (1981) the structures containing magnetic flux with field strengths ~20 G emerging from the solar surface can supply sufficient heat through expansion to the solar atmosphere to explain coronal temperatures. Gokhale (1975) used the mechanism to explain solar x-ray bright points.

*D. Velocity filtration heating:*

Scudder (1992) postulates that at the foot of the transition layer, where the gas becomes optically thin and fully ionized, the Maxwellian distribution function of the particles somehow obtains a strong suprathermal tail. Because the Coulomb cross section gets rapidly smaller as the particle energy increases therefore the particles of this hot tail rise essentially without collisions against the gravitational potential to coronal heights such that only the hottest survive. These particles raise the temperature of the corona to values in excess of $10^6$ K. This heating theory has been applied to closed and open flux tubes on the Sun and stars (Scudder 1994). The heating process is slightly more efficient in closed than in open flux-tubes. The solar wind ions are heated through this mechanism in proportion to their masses. Scudder has not specified the origin and form of the non-Maxellian distribution

Quite recently Anderson et al. (1996) tested the above velocity filtration coronal heating theory by calculating predicted UV emission line intensities for comparison with observed values. They consider five different non-Maxwellian particle distributions in the lower corona and use the Vlasov equation to estimate the distribution at all heights. For each height they calculate the emission line intensity for a number of ions for comparison with the Skylab data. To facilitate comparison with observations they obtain apparent emission measure from the computed UV emission lines. They find that: i) the emission measure decreases with temperature as is observed for lines formed below $10^5$ K. ii) the theory cannot simultaneously reproduce the increasing emission measure observed for higher temperature lines.

Thus the existing version of velocity filtration heating theory does not match UV observations. But this conclusion is not crucial because Anderson et al. (1996) neglect Coulomb collisions, realistic geometry and ambipolar diffusion.

## 7. Conclusions

i) The most likely agents for heating coronae are Alfvén waves and magnetic field dissipation.

ii) The generation mechanism and generated fluxes of Alfvén waves need further precise study.

iii) A spatial resolution of the order of 1 km at the solar surface is needed to test the dissipation of magnetic energy in current sheets, sheaths, and filaments because the scale length of dissipation, $L_{ohm} \sim (c^2 \eta \, t_{ohm}/4\pi)^{0.5}$, with coronal ohmic resistivity $\eta \sim 10^{-14}$s, $t_{ohm} \sim 10^4$s, turns out to be of the same order (Rosner et al. 1978).

iv) The velocity filtration heating does not require any local heating source except that the origin and the form of the non-Maxwellian distribution must be specified. The correctness of the theory should be tested by computing the intensities of UV lines by taking into account Coulomb collisions, realistic geometry and ambipolar diffusion.

v) Most of the mechanisms do contribute towards the energy budget of the corona.

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