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HEATING OF THE SOLAR CORONA

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Abstract

The maintenance of the million degree solar corona continues to be a challenging and an inspiring problem There are basically two different mechanisms of heating depending upon the dominance or otherwise of the magnetic field The nonmagnetic or mechanical heating processes operate when mechanical energy in the form of acoustic waves is available for dissipation The magnetic heating mechanisms consist of dissipation of hydromagnetic waves, anomalous dissipation of currents and magnetic reconnection The role of bright points in providing large scale heating through numerous small scale magnetic reconnections is emerging in a forceful manner The motion of footpoints of these bright points perhaps gives clues to the periods of waves which may also be contributing to the heating

Heating of the solar corona is a million degree question, the answer to which remains elusive inspite of the concerted efforts of many for many decades (Kuperus et al 1981, Wentzel 1981, Hollweg 1981, Pneuman and orrall 1986) The corona is continuously losing energy and momentum through radiative, conductive and convective processes The replenishment in the form of mechanical and magnetic energy has to come from within the convection zone Since solar corona is highly structured due to the presence of open and closed magnetic field lines, the energy requirements vary accordingly The corona in its quiet phase needs ~3 x 10^5 ergs/cm^2 sec, the coronal holes need ~8 x 10^5 erg /cm^2 sec and the active regions as much as 10^7 ergs/cm^2 ec In this review, the various proposals for coronal heating are discussed with a view to find out if out of a host of mechanisms one or more stand out as more appropriate It is also pointed out that dissipation of hydromagnetic waves, the anomalous dissipation of current and magnetic reconnection listed as different mechanisms are in fact the different manifestations, of a complex magnetic field configuration on varied spatial and temporal scales

Mechanical Heating

Acoustic waves are generated as a result of the turbulent motions in the convection zone via Lighthill mechanism (Stein and Leibacher 1980) The radiated power is approximately equal to the energy density in the turbulent motions divided by the time scale of turbulent motions multiplied by the efficiency factor Thus, the radiated power p is given by

$$p \simeq (\rho u^2) \frac{\ell}{u} (k\ell)^{2n+1} \tag{1}$$

where ℓ is eddy size u is velocity and (ℓ/u) is turnover time, $(k\ell)^{2n+1}$ is the efficiency factor and k is the wave factor of the acoustic waves Here n = 0 for a mass source, n = 1 for momentum source and n = 2 for quadrupole source of emission which corresponds to Reynold's stresses and is the dominant process in the convection zone For acoustic waves $K = \omega/C_s$ and $u/\ell \simeq \tau^{-1} \simeq \omega$, so that $k\ell \simeq u/C_s = M$, where ω is the frequency, C_s is sound speed and M is the mach number of turbulent motions Using these relations, one finds that the radiated power

$$P \propto u^8 \tag{2}$$

Since u is model dependent the emission is very uncertain For crude estimates one can take $\rho \sim 10^{-6}$ gms/cc, $C_S \simeq 10^6$ cm/sec, $(u/C_S) \sim \frac{1}{4}$, and flux $F \simeq Pl \sim 10^7$ ergs/cm^{2}sec Thus the flux seems to meet the requirement for coronal heating These waves travel upward in the gravitationally stratified atmosphere in which finite scale heights introduce cutoffs in frequency and limit the propagation to large heights For conditions typical of the temperature minimum region of the solar atmosphere waves must have periods ≃ 200 300 secs The upper corona does not receive sufficient acoustic flux

The energy flux carried by upward propagating waves of amplitude δV is given by

$$F \simeq \rho(\delta v)^2 C_S \tag{3}$$

For constant gas temperature, the constancy of wave flux requires that $\delta v \propto \rho^{-\frac{1}{2}}$ and therefore the wave amplitude increases as it propagates upwards in a medium of decreasing density As the phase velocity is greater in compression than in rarefaction an initially sinusoidal wave steepens into a sawtooth form and develops into a shock (Kuperus 1969) The wave mechanical energy is dissipated at a rate F/L where L, the dissipation length depends upon the period Short period waves dissipate low in the atmosphere and long period waves dissipate higher in the corona if they can reach there Therefore acoustic waves may be useful for heating the lower parts of the atmosphere outside the magnetic regions

Magnetic Heating

Recent high resolution studies of the outer solar atmosphere revealed that the corona is highly structured consisting of loop like structures outlining the magnetic field geometry The rest of the corona has coronal holes with open magnetic field lines Observations imply that coronal loops are the main sources of radiative losses and therefore magnetic fields must be actively responsible for the energy balance Magnetic fields can provide heating in several ways In addition magnetic field also play an important role by confining the plasma and by inhibiting the transport process

The generation of waves from convective turbulence is modified by the presence of magnetic field (Wentzel 1981, and references therein) New wave modes are excited, the propagation and dissipation characteristics are changed Specific hydromagnetic waves that are related to heating are slow and fast magnetosonic waves and Alfven waves Hydromagnetic waves are specially suitable for coronal loops since the latter can act as waveguides These waves can also transfer momentum to the solar wind The hydromagnetic waves must have energy flux $\sim 10^5$ 10^7 ergs/cm^2 sec in order to heat the corona The energy flux in a uniform medium is given by

$$F = (\rho V^2)V_A$$

$$V_A = B/\sqrt{4\pi\rho}$$

The amplitude b corresponding to the velocity V is found as $[V/V_A = b/B]$ For $F \sim 10^6$ ergs/cm^2 sec, $B = 10^2$ Gauss and $\rho \sim 10^{-15}$gms/cc the velocity amplitude $V \sim 10^6$ cm/sec This is uncomfortably close to the upper limits placed on velocities derived from observed line width Therefore simple energy considerations make wave heating marginally possible The other requirement is the right damping length It should not be so short that the waves never reach the corona and it should not be too long that they overshoot the corona and act in the solar wind This constrains the period of waves for chromosphere, corona and the solar wind The three different wavelength regimes are (Wentzel 1981)

1 Waves with periods of hours may be caused by the slowest motions in or below the photosphere The wavelengths are too large for the coronal loops They can certainly heat the largest coronal streamers and accelerate solar wind

2 Waves with periods of a few minutes certainly dominate the photospheric motions Their wavelengths are comparable to loop radii These are surface waves and travel along surfaces where the Alfven speed changes discontinuously In loops, a large difference in gas density on adjacent magnetic flux tubes, provides a surface of discontinuity Ionson (1978) proposed coronal heating by Alfvenic surface waves which have several attractive features Waves with periods of a few minutes are efficient carriers of energy over a cross section larger than that of the loop Due to the resonance between the local Alfven frequency and the source frequency, most of the energy is deposited in a thin region This provides a testable feature of the theory The waves propagate with a speed which lies between the Alfven speeds on the two sides of discontinuity The essential form of dissipation occurs when the change in the field strength or density occurs over a thin but finite transition zone The velocity amplitude becomes singular where the wave speed is equal to the local Alfven speed In this region, the MHD approximation breaks down, ion gyroradius effects, electron inertia become important and Alfven wave couples to kinetic Alfven wave which suffers collisional damping Intense heating over a few kilometers destroys the resonance between surface and kinetic Alfven wave More self consistent treatment is expected to widen the sheaths Coronal loops are believed to have force free magnetic fields, heating by Alfvenic surface waves in such a field geometry has been considered by Krishan (1981)

3 Alfven waves with periods of a second or less may be excited by the motion of foot points of coronal loops These waves travel along the loop length and collide at the top which gets heated preferentially Gokhale (1974) and recently Parker (1987) has emphasized the role of X ray bright points in heating the corona These are nothing but sites of nanoflares which being numerous in number can heat most of the corona The study of motion of the foot points within the X ray bright points can give clue to the excitation of extremely short period waves These waves cannot be observed directly The corresponding motions manifest themselves through Doppler widths However, is there a unique way of deriving waves from Doppler width ?

Heating of Small Loops by Electric Currents

Alfven waves are good heating candidates for large loops They do not meet the requirements of small, dense and intensely emitting loops Dissipation of magnetic energy is invoked in several astrophysical situations If resistance provides the heating, then MHD must break down and in such circumstances it is more appropriate to talk of currents than magnetic fields Solar flares are believed to be caused by current dissipation Its scaled down version may be adequate for general coronal heating The sources of current lie in the convection zone If extrapolation of potential photospheric magnetic field traces out loops in the corona then the current in the loops must be weak so as to avoid large changes in the shape of the loops The stability of loops and the motions near the foot points of loops suggest the continual generation and dissipation of electric currents (Tucker 1973, Nolte et al 1979, Rosner et al 1978 a,b) Large variation observed in loop sizes and brightnesses has led to two ways of current dissipation For very compact loops the pressure balance is given by

$$\nabla p = J \times B \tag{4}$$

Then one can consider the current dissipation as the consumption of magnetic field, the process ending with its weakening due to diffusion For more extended loops, higher in the corona, it is useful to consider basically current free configurations (the extrapolated photospheric fields) along which weak currents are driven from below the photosphere The currents lead to a twisted geometry of magnetic field The energy associated with these fields must be replenished in a few days if current dissipation is to match the observed radiation losses The heat balance of a coronal loop is described by

$$\frac{\partial Q}{\partial t} = \frac{d}{ds}\left(T^{\frac{5}{2}}\frac{dT}{ds}\right) \quad p(T) \tag{5}$$

where Q is the internal energy the first and second term on the right side describe conduction and radiation losses respectively A typical temperature of 10^6 K along a length 10^{10}cm is reduced significantly in an hour or so unless replenishment occurs that fast Current dissipation is more efficient in narrow surfaces or filaments The joule heating is given by

$$\varepsilon_H = \eta J^2 \tag{6}$$

where resistivity $\eta = 4\pi\gamma_{ei}/\omega_p^2$, γ_{ei} is the electron ion collision frequency and ω_p is the electron plasma frequency The current density $J = neV_D$ when n is the electron density and V_D is the relative velocity between electron and ions Since conduction only redistributes energy the real requirement is that heating rate must be equal or greater than the radiation loss or

$$\varepsilon_H \geq n^2 f(T) \tag{7}$$

where f(T) is the temperature dependent radiation loss factor Eq (7) gives

$$V_D^2 \geq \frac{f(T)}{e^2\eta} \tag{8}$$

Now the magnetic field δB produced by the current J is given by

$$\nabla \times \delta B = \frac{4\pi}{C} J, \text{ or } V_D = \frac{C\,\delta B}{4\pi n e\,\delta \ell}$$

where $\delta\ell$ is the width of the current channel

Therefore the condition on the width of current channel is found to be

$$\delta\ell \leq \frac{C\,\delta B}{4\pi n}\sqrt{\frac{\eta}{f(T)}} \tag{9}$$

$\delta\ell \sim 10^3$ cm for typical coronal parameters Larger V_D can give higher currents which can admit larger width of the current channel, but this brings in other effects If the drift velocity V_D is larger than the ion sound speed, ion acoustic instability is excited which increases the resistivity η by several orders of magnitude (Krishan 1978) The joule dissipation rate increases tremendously thereby easily satisfying Eq (7)

Magnetic Reconnection in Loops

Current sheaths are efficient sites for anomalous joule dissipation of current, but due to the presence of intense current, they are also susceptible to tearing instabilities (Spicer 1976 1977 Colgate 1978) A single current sheath can thus break up into a multitude of current sheaths thereby providing right conditions for magnetic reconnection It is proposed that coronal magnetic regions are heated with the dissipation occuring via minireconnections of current sheaths of thickness 0 1 1 km distributed throughout the loops But how are current sheaths generated and maintained ? Now, current sheaths are essentially sheared magnetic fields One can also look at them as Alfven or fast modes in the inhomogeneous medium In that case, perhaps Alfven wave dissipation and magnetic reconnection are two languages for describing the same phenomena

Circuit Approach

Plasma structures have been looked at as open or closed transmission lines Attempts have been made to define circuit parameters such as impedence Q values, inductance, capacitance and resistance for coronal structures (Ionson 1982) This is another language used to describe the electrodynamic coupling of photosphere, chromosphere and corona The circuit equations reduce to more conventional plasma heating equations in some limiting cases For example for quality factor $Q >> 1$, the circuit equation describe an oscillator which is nothing but the hydromagnetic waves in case of plasma Power absorption is maximum at the oscillator period This may correspond to 5 minute photospheric oscillations which feed the corona The case $Q < 1$ corresponds to current dissipation Although, the circuit approach deals with coronal heating at a global scale, one has to fall back on the microphysics in order to get any quantitative estimates of the circuit parameters

Wrapping of Magnetic Field Lines

Gold (1964) suggested that coronal heating may be due to the continuous dissipation of small scale wrapping and twisting of coronal magnetic field lines caused by the convective motions Parker (1983) has advanced this idea to show that the complex twisted field geometry, resulting from the motion of foot points, is prone to dissipation, thereby transferring the mechanical energy associated with convection into heat in the corona The observable features of this scenario are the X ray bright points The analysis of their motion may provide clues to the possible existence of extremely short period waves and therefore of small current sheaths

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