2001BASI...29..231P

Bull. Astr. Soc. India (2001) **29**, 231–238

On solar coronal heating

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Abstract. We review heating of solar corona by magnetic fields/currents. Our emphasis is on micro- and nano-flares. In case of a microflare the energy release is ~10^{26} ergs whereas in a nanoflare ~10^{23} – 10^{25} ergs of energy is released. Flares have a distribution law over total radiated energy with exponent $\alpha = 1.8$. Extending the same power law to micro-and nano-flares and assuming that they constitute a dominant heating mechanism for solar corona α must be greater than 2. Many investigations lead to $\alpha < 2$ whereas a few yield $\alpha > 2$. The verdict remains inconclusive. More observational analyses and numerical simulations are needed to discriminate between the two cases.

1. Introduction

Ground-based and satellite observations have shown that the Sun has regions, namely chromosphere and corona, in its outer atmosphere in which the temperature is much higher than the photospheric value. These layers are characterized by large energy loss, e.g., the chromosphere loses energy predominantly by radiation and the corona by conduction, radiation and solar wind flows. To prevent these hot layers from rapidly cooling down to the photospheric boundary temperature some source of heating must be present.

A number of mechanisms for heating chromospheric and coronal layers have been proposed (cf., Narain & Ulmschneider 1990, 1996; Browning 1991; Narain & Kumar 1993; Kumar 2000; Narain & Agarwal 1994; Agarwal 2000; Narain 1998; Sharma 1999 and references contained therein). The proposed mechanisms heat the solar corona via acoustic waves, MHD waves, current dissipation / magnetic reconnection etc. It has now become quite clear that very likely the heating phenomena in the solar atmosphere cannot be explained by a single process but are rather due to the action of a multitude of mechanisms. Some of these may operate globally, others only in particular situations.

Heating by transients (flares, micro - and nono-flares) is one of the important mechanisms of coronal heating (Parker 1987, 1988). Flares are the most energetic events of transient energy releases by the Sun ranging from ~10^{29} ergs released for subflares to ~10^{32} ergs for the largest flares. The Sun also exhibits a broad spectrum of transient phenomena with total energy release substantially less than flares. Transient soft X-ray brightenings are observed in a continuum of intensities from flares down to tiny X-ray bright points.

According to Parker (1991) the X-ray corona is to be understood as a cloud of nanoflares. The energy of a nanoflare lies in the range 10^{23} – 10^{25} ergs. Each nanoflare is small single magnetic reconnection event which converts magnetic energy in fluid motions which are on a very small scale so that they are quickly damped by turbulence and viscosity. That is, the magnetic energy is converted into heat spread across the magnetic lines of force passing near the site of the nanoflare. Electron thermal conduction then rapidly spreads the thermal energy along the field. In addition the bending and compression of fields resulting from the reconnection event will generate a whole spectrum of longitudinal and transversal MHD waves which dissipate their energy away from the reconnection site.

The energy of a microflare lies in the range 10^{25} – 10^{26} ergs. A microflare may arise from impulsive relaxation via magnetic reconnection at strongly stressed field location which was formed as a result of the continuous shuffling of the foot points of coronal flux-tubes (loops). Microscopic magnetic reconnection processes are suspected to exit virtually anywhere on the solar surface and might reveal themselves as tiny non-thermal transients. According to an operational definition, a microflare consists of a burst of X-rays similar to an ordinary burst but are weaker. By hypothesis one can use flare parameters extrapolated to smaller peak fluxes, as a guide to microflare properties (Hudson 1991).

The coronal magnetic field lines are rooted in the dense and turbulent photosphere. The spectrum of driving photospheric motions is not precisely known but the time-scales of the order of tens or hundreds of seconds are expected with a peak around 300s (granulation time scale). Motions on a slower than Alfvenic time scale ($t_A = L/V_A$, L being the length of the coronal structure and V_A the Alfvén velocity) will cause the field to evolve quasi-statically through a sequence of magnetostatic equilibria. At any instant of time, the equlibrium is determined by the positions of the foot-points. In general, the motions which shear or rotate the foot points relative to each other generate currents in the coronal field. Since the plasma $\beta \ll 1$ these currents are approximately field-aligned and the equilibrium is force-free, $\vec{J} \times \vec{B} = 0$, $\vec{J}$ being the current density and $\vec{B}$ the magnetic induction. The currents store excess magnetic energy which, in principle, may be dissipated as heat. It is thought that rapid dissipation of such stored energy is the cause of solar flares which are large explosions releasing energy in wavelengths from X-rays to radio, totalling upto 10^{31} ergs or more per event. In this case the event may be triggered by a global loss of equilibrium or an ideal instability of the stressed magnetic field (Parker 1987, 1988). A more continuous released of smaller amount of energy may be the source of coronal heating. There is thus a close relationship between coronal heating and flare theories.

In fact the coronal field may be filled with many sites of small-scale reconnection (current sheets) where magnetic energy is released as heat (Tucker 1973; Levine 1974; Kumar & Narain 1985). Observations from Solar Maximum Mission (SMM) (Porter et al. 1987) show a sequence of small, localized X-ray bursts which may be the signatures of reconnection events. As already pointed out, this evidence suggests that flares occur over a board spectrum of energies. For example, a nanoflare may be associated with reconnection in one current sheet whereas a full-scale flare occurs when a global instability triggers reconnection in a whole collection of current sheets simultaneously. Such an interpretation requires that coronal field contains many localized strong current sheets or filaments. It is important that such current sheets could be resolved in the forseeable future.

In a picture of coronal heating Moore et al. (1991) believe that microflares occur sporadically throughout quiet regions and are seated in small magnetic bipoles embedded in the magnetic network along the edges of the supergranules. Their birth-rate over the entire Sun is the order of 10^3 s^{-1} and that the energy release in every microflare is such that it corresponds to an energy flux of 10^6 erg cm^{-2} s^{-1} over the whole surface of the Sun.

The coronal heating requirement for quiet regions is of order of 10^5 erg cm^{-2} s^{-1} whereas the energy flux required for coronal holes and solar wind is of order of 10^6 erg cm^{-2} s^{-1} (Withbroe & Noyes 1977). Hence the quiet and non-hole coronal regions may be heated by network microflares if much of the energy they release goes to coronal heating.

The network microflares are seated at the base of the corona and appear to be magnetically isolated from the bulk of the corona. They fill a very small fraction of the volume of the corona. The energy transfer from microflares heats the corona low in the legs of the large coronal loops. The injected heat is then distributed along the full extent of each coronal loop by conduction and mass flow along the loop. This scenario is applicable to coronal holes as well as to magnetically closed (loop) regions (Figure 1).

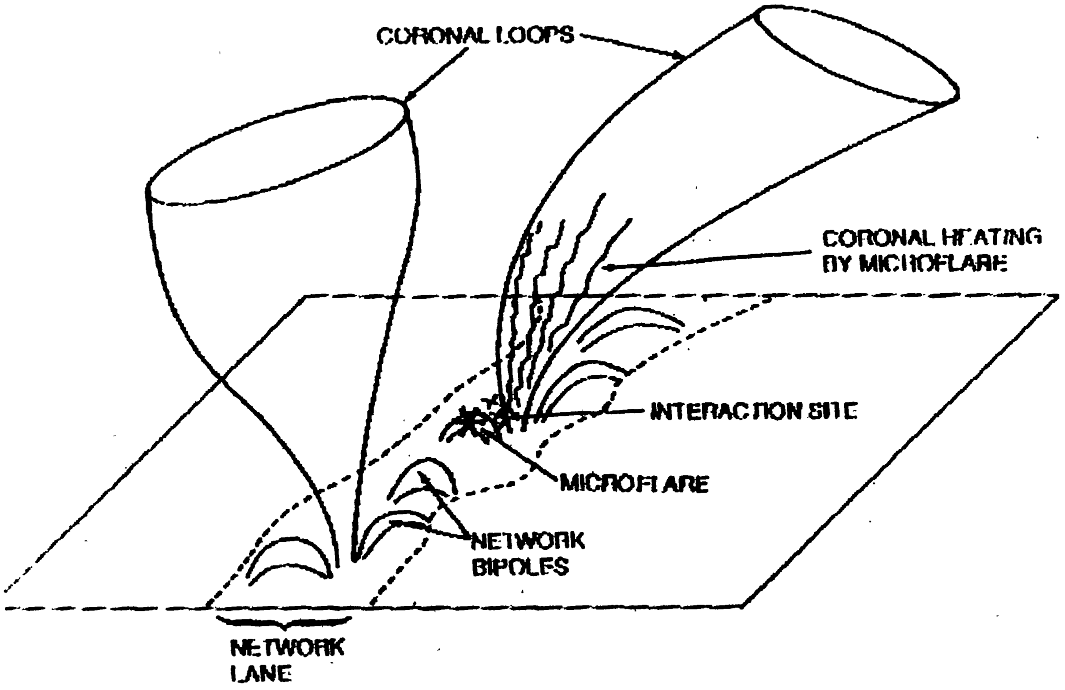

Figure 1. Scenario for the heating of high coronal structure by microflares in short low - lying loops. Following initial release in low loops spanning small bipoles in the magnetic network, energy is transferred to corona via secondary neutral sheets formed where the expanding low loops push against the legs of adjacent coronal looks (Moor et al. 1991)

To observe whether microflares inject substantial heat into the ends of coronal loops or holes it is necessary that sequences of soft X-ray images with a few arc seconds of resolution be taken.

Network microflares seem to generate Alfvén waves which may heat coronal holes by intermittent magnetic levitation (Moore et al. 1992). This is in addition to direct heating by microflares.

In the next section theoretical details and data are presented. Section 3 contains discussion and conclusions in the light of recent developments. Throughout cgs system of units have been used.

2. Theoretical details

If small flare-like events (micro-and nano-flares) are to explain the steady state energy dissipation required for coronal heating and to drive solar wind expansion they must have a different distribution law in relation to ordinary flares.

Let the number of events per unit energy and time be denoted by P(E) = dN / dE. Then the total number of events per unit time in the energy range (E_{min}, E_{max}) is given by

$$N = \int_{E_{min}}^{E_{max}} P(E)dE, 2 \tag{1}$$

The total heating rate (power) in the aforesaid energy range will be

$$\epsilon = \int_{E_{min}}^{E_{max}} P(E)E\ dE. \tag{2}$$

Following Hudson (1991) the distribution law over total (radiated) flare energy E generally follows the relationship :

$$P(E) = dN / dE = A\ E^{-\alpha} \tag{3}$$

where exponent α is positive, and A is a factor which will vary with the degree of activity. Equations (2) and (3) combine to give

$$\epsilon = \int_{E_{min}}^{E_{max}} A\ E^{1-\alpha}\ dE = \frac{A}{2-\alpha}[E_{max}{}^{2-\alpha} - E_{min}{}^{2-\alpha}]. \tag{4}$$

As already pointed out, for micro-and nano-flares to be important for the heating of the cornoa α must be greater than 2. Another possibility is that these small flare-like events do not follow the same power law distribution as is the case with normal flares.

Porter et al. (1995) present simultaneous observations of a solar active region in the ultraviolet and X-ray of microflare events from February to november 1980. They find that the energy per event in a distribution scales with the total 1548 Å (CIV) line flux rather than with the total X-ray flux L_x. Therefore

$$L1548 \;\; \alpha \;\; E. \tag{5}$$

Suppose total X-ray flux scales with λ_{1548} Å line flux as follows :

$$L_x \; \alpha \; L^{\beta}_{1548} \text{ or } L_x \; \alpha \; E^{\beta} \tag{6}$$

where β is a positive exponent. Let the distribution of events with total X-ray flux is given by

$$dN \,/\, dL_x \quad \alpha \quad L_x^{-y} \tag{7}$$

where the exponent γ is another positive constant. Now equations (6) and (7) may be combined to get

$$dN \,/\, dE \quad \alpha \quad E^{-\gamma\beta + \beta - 1} \tag{8}$$

A comparison of equations (3) and (8) yields

$$\alpha = \gamma\beta - \beta + 1 \tag{9}$$

The observational analysis of McClymont and Canfield (1986) leads to the value $\beta = 1.67$ whereas that of Crossby et al. (1993) yields $\gamma = 1.53$. These values together with equation (9) give $\alpha = 1.89$ which is less than 2 This implies that heating is dominated by larger flares. However, the observational analysis of Porter et al. (1995) gives $\beta = 2.22$ which together with $\gamma = 1.53$ and equation (9) leads to $\alpha = 2.18$. That is, α is greater than 2 and the heating is dominated by micro - and nano-flares.

3. Discussion and conclusions

It would be worthwhile to describe briefly some observational analyses and numerical simulations.

Drake (1971) analyzed soft X-ray flares between 2 July 1966 and 18 September 1968. He found that the distribution of bursts by the peak flux can be represented by a power law with exponent −1.75 ± 0.01 over a range of two orders of magnitude in peak flux.

Dennis (1985) reviewed data on solar hard X-ray bursts for Solar Maximum Mission from launch to February 1985. He has presented perhaps the best determined distribution function with a power law having the exponent $\alpha = 1.8$.

Crossby et al. (1993) investigated hard X-ray solar flare observations from 1980 to 1989 with Hard X-ray Burst spectrometer (HXRBS) on SMM satellite. They analysed over 12000 solar flares. The exponents obtained by them range from −1.48 to −1.73.

Recently Dmitruck and Gómez (1997) and Dmitruck et al. (1998) have studied the dynamics of an externally driven solar coronal loop by numerical simulation. The temporal behaviour of energy dissipation rate shows clear indications of intermittency. They associate the impulsive events of magnetic energy dissipation from 5×10^{24} to 10^{26} ergs to the so called nanoflares. Their statistical analysis of impulsive events yields a power law distribution as a function of their energies with a negative slope of 1.5. Although this value is consistent with the previous studies yet it does not support the idea that nanoflares should have an exponent greater than 2. This numerical simulation study implies that the relatively infrequent large-energy events contribute more to the heating rate than the much more numerous small energy events.

Judge et al. (1998) have studied high signal–to-noise profiles of 0 IV emission lines obtained using the SUMER instrument on SOHO. Their data analysis reveals evidence for compressive waves propagating downward from the corona to the chromosphere. Their analysis lends support to the dominance of the nanoflare mechanism for coronal heating over other theories that invoke upward wave propagation. However, they do not rule out the possibility of other mechanisms, such as resonant absorption of Alfvén waves, capable of generating downward propagating waves.

Quite recently Aschwanden (1999) has critically examined power law distribution for flares, flare-like events or non-flaring heating events at extreme-ultraviolet (EUV), soft X-ray (SXR) and hard X-ray (HXR) wavelengths obtained by Krucker & Benz (1998), Aschwanden et al. (2000), and Parnell & Jupp (2000). In these studies the exponent ranges from –1.58 to –2.59. Aschwanden (1999) estimates total power available from heated flare plasmas and finds it to be shorter by a factor of ~ 10^3 for active regions and by a factor of ~ 30 for the quiet Sun.

It may be concluded that the heating of solar corona by transients (flares/micro-/ nanoflares) is a very attractive possibility but more observational analyses and numerical simulations are needed to pronounce the final judgement.

In order to get a satisfactory solution to the coronal heating problem following three-prong approach seems highly desirable :

I. Observational approach

a) measurements of temperature and density structures on as small a temporal and spatial resolution as possible be made.

b) to detect wave motions and / or turbulence levels the measurements of velocity fluctuations with correlation studies have to be made.

c) to distinguish whether heating is resistive or viscous separate measurements of ion and electron temperatures must be made.

d) to have adequate knowledge of the power spectrum of the photosphere detailed measurements of fine-scale photospheric velocity and lines of sight magnetic fields together with the overlying coronal structure should be made simultaneously.

II. Laboratory experimentation

Since it is not possible to take unlimited observations of the Sun therefore the laboratory experimental results with suitable modifications should be used to test the proposed theories Laboratory studies of plasma turbulence may be important in determining the likely power spectra and other features of MHD turbulence in the solar atmosphere.

III. Numerical simulation

Analytical approaches cannot cope with the complexity of the solar atmosphere hence large scale numerical simulations are to be performed.

Acknowledgements

The authors are grateful to the organisers of the 20th ASI meeting at D.D.U. University, Gorakhpur for providing an opportunity to deliver an invited talk to one of them (U.N.). Fruitful discussions with Prof. A. Bhatnagar, Prof. P. Venkatakrishnan and Dr. A. Ambastha, Udaipur Solar Observatory, Udaipur for improving the contents of this article are also gratefully acknowledged. thanks are due to Prof. P. Ulmschneider and Prof. Vinod Krishnan for carefully reading the manuscript.

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