J. Astrophys. Astr. (0000) **00**, 000–000

Nanoflares as a Possible Coronal Heating Agent*

Lalan Prasad† and N.K. Lohani‡
Department of Physics, M.B. Govt. P.G. College, Haldwani, Nainital - 263141, India

2005 May 29

Abstract. We present the concept of coronal heating by nanoflares and the characteristics of active regions which result presumably from a series of discrete events of various energies analogeus to a large number of more or less random heating agents. The flare associated with small impulsive events of magnetic energy dissipation is from 5 x 10^{23} to 10^{25} ergs, called nanoflares and it is treated as heating agents. The analysis of these agents are represented by a power law distribution as a function of their energies with a negative slope of ≥ 2. We discuss the physical characteristics of nanoflare heating process in respect of power law distribution and formulate the coronal luminosity. We estimate the coronal radiation energy and generation rate by nanoflares.

Key words: Sun: corona, flares, nanoflares, power law

1. Introduction

Coronal heating by microflares and nanoflares has been extensively investigated (e.g. Klimchuk 2004, Dennis 1985 and Hudson 1991). The power law index for nanoflares should be larger than the critical index 2, so that the total amount of nanoflares can make a dominant contribution to the coronal heating. Hudson (1991) extended the work and studied the coronal response to heat inputs by nanoflares with power law index larger than 2. The heating mechanism comprises three physical aspects: (i) the generation of a carrier of mechanical energy, (ii) the transportation of mechanical energy into the chromosphere and the corona and (iii) the dissipation of this energy. Energy carriers are mainly hydrodynamic and magnetic heating mechanisms. As the magnetic energy dominates the coronal energy density, the release of free magnetic energy, possibly present in the corona in the

*Paper presented in the International Solar Workshop on 'Transient Phenomena on the Sun and Interplanetary Medium' organised during April 5-7, 2005 by the Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital.

†e-mail:lprasad@iucaa.ernet.in
‡e-mail:lohani@iucaa.ernet.in

form of electric current (Mitra and Benz 2001). The early idea through the building up of free magnetic energy and it must dissipate in the corona (Gold 1964). The impulsively heated loops could cool by conduction and radiation releasing an amount of magnetic energy into the corona to keep it hot. Thus, the solar corona is heated by the combined numerous small flare like events called nanoflare. A fundamental difference is perhaps that large flares occure only in active regions, requiring larger magnetic fields, while microflares and nanoflares can occure everywhere in the quite sun or even in coronal holes (Aschwanden 2004). The hot corona having a great assembly of high-temperature elemental magnetic filaments which are created with the coronal magnetic field through randomly distributed impulsive heating agents. Hence the coronal heating by considering the nanoflare as the lower energy population of a board spectrum of flare like agents. Several small flares heat the loop plasma up to ≥ 5 x 10^6 K (Shimizu 1995) and they are one of the main agents to generate high temperature ≥ 5 x 10^6 K in the corona (Watanabe 1995 and Yoshida et al. 1996). Parker (1988) proposed that the energy dissipation of the stressed magnetic structures takes place in the corona by large number of small impulsive events (nanoflares).

2. Theoretical details

In this section we deals the power law distribution function under limited energy range and also discuss the coronal radiation. It is well established that the size distribution of various solar energy release events has the form of a power law. The solar radio type I bursts which are frequently observed at meter wavelengths, involve extremely small amount of energy i.e., also in terms of nanoflares.

2.1 *Power law distribution*

Observations of solar flares have indicated that their energy distribution follows a power law with negative slope (Hudson 1991, Cargill and Klimchuk 1997, 2004). The coronal heating may be the result of frequent microscopic energy releases, which Parker has termed nanoflares (Mercier and Trottet 1997). The magnetic energy release occurs in discrete much smaller events than observed. It means that small impulsive events of 10^{23} to 10^{25} ergs (nanoflares) do sustain the hot corona. (e.g. Cargill 1994, Haisch 1991). For the phenomena of nanoflares the slope of power law need to be more negative than - 2. The power law distribution in terms of total flare energy released can be represented as

$$\frac{dN}{dE} \sim E^{-\alpha} \tag{1}$$

where α is the power law index and dN is the number of small impulsive agents between energy range E and E + dE. Smaller number of events (Lin et al. 1984) characterise the power law distribution with $\alpha \sim 2$. For nanoflares the power law index should be larger than the critical value 2. As a result, the total amount of nanoflares can play a dominant role in the heating of solar corona (Hudson 1991, Kopp et al. 1993). This index agrees well with the observations (Shakhovskaya 1989). The basic power law can be represented in the terms of a normalization factor A (Kreplin et al. 1997).

$$\frac{dN}{dE} = AE^{-\alpha}. \tag{2}$$

The heating of corona by nanoflares is strongly supported by the observations (Mitra and Benz 2001) which suggest that the smallest flares contribute most of the heating. The total power of heating can be obtained from equation (2), simply by multiplying with E and then integrate over their entire range of nanoflares energy

$$P = \int_{E_{min}}^{E_{max}} \frac{dN}{dE} E dE \tag{3}$$

or

$$P = \frac{A}{\alpha - 2}[(E_{min})^{2-\alpha} - (E_{max})^{2-\alpha}]. \tag{4}$$

In the above equation, the term $(E_{max})^{2-\alpha}$ is ignored (Shimizu and Tsuneta 1997) because the power law index α should be larger than the critical value 2

$$P \simeq \frac{A}{\alpha - 2}(E_{min})^{2-\alpha}. \tag{5}$$

A major part of required energy for coronal heating is provided by nanoflare due to their abundance existence in connection with the major flares for smaller values of α. The variation of power law with different values of power law index with an average cut off energy E_{min} = 10^{24} ergs is shown in fig 1 (a, b, c and d). By the comparative study of all four figures (a, b, c and d) having similar characteristics only the change can exist by their energy values. It means that the characteristics of nanoflares $\alpha > 2$ is almost similar to microflares $\alpha < 2$. Therefore, according to the very simple treatment, the slope of the distribution of events is larger than 2, implying that small events dominate the heating process. In a very similar trend of the power law distribution, the flare driven coronal luminosity can be expressed as

$$L_f = \int_{P_{min}}^{P_{max}} \frac{dN}{dP} P dP \tag{6}$$

or

$$L_f = \frac{k}{\alpha - 2}[(P_{min})^{2-\alpha} - (P_{max})^{2-\alpha}]. \tag{7}$$

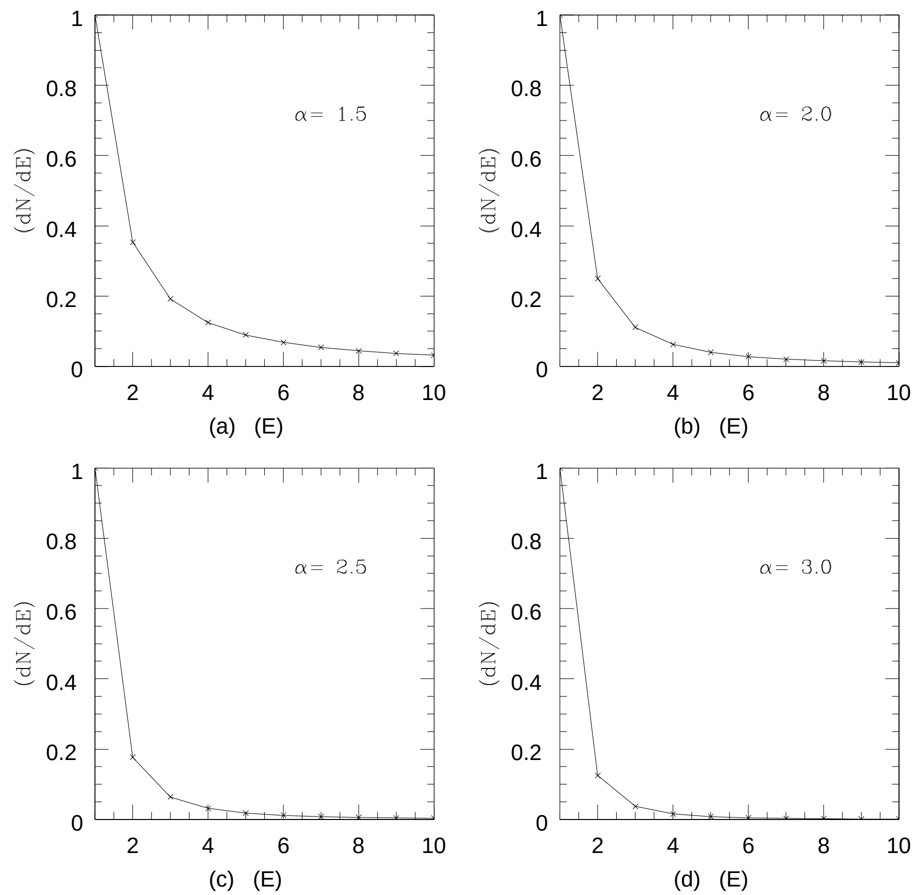

Figure 1. The variation of the rate of flaring agents with flaring energy for different values of power law index α. (a) α = 1.5, (b) α = 2.0, (c) α =2.5 and (d) α = 3.0

The second part in the RHS of equation(7) is negligibly small for higher values of α, i.e., greater than the critical value 2. Then the flare driven coronal luminosity becomes

$$L_f = \frac{k}{\alpha - 2}(P_{min})^{2-\alpha} \tag{8}$$

where k is another normalization constant. Here $\alpha < 2$, L_f is dominated by the large events and for small flares cannot account for coronal heating. However, if the statistics of nanoflares is such that $\alpha > 2$, then L_f is dominated by small events. The generation rate of nanoflare over the whole solar surface can be obtained by integrating the power law distribution equation (2) over the entire range of energy limits

$$R = \int_{E_{min}}^{E_{max}} \frac{dN}{dE} dE = \frac{A}{\alpha - 1} (E_{min})^{1-\alpha}. \quad (9)$$

For mathematical simplicity under limiting conditions of nanoflares the maximum energy is not taken into account. We take the nanoflare generation rate in terms of generation of heating agents is given in table I (Kopp et al. 1993).

Table 1. Nanoflare numerical estimations

Semi length L (cm)	Base area a (cm^2)	Number of agents	Average birth rate (s^{-1})
1 x 10^8	6.283x10^{14}	9.80x10^7	0.0042
2 x 10^8	2.531x10^{15}	2.45x10^7	0.0168
5 x 10^8	1.571x10^{16}	3.92x10^6	0.1047
1 x 10^9	6.283x10^{16}	9.80x10^5	0.4189

The nanoflare birth rate per flux tube R_f can be defined as

$$R_f = \frac{R}{N_f} \quad (10)$$

where N_f is the total number of flux tubes on the solar surface and it depends on the base area of the loop in the corona. From equations (9) and (10) we get

$$R_f = \frac{A}{N_f(\alpha - 1)} (E_{min})^{1-\alpha}. \quad (11)$$

From the table it is clear that the rates of nanoflare per flux tube is seen to increase rapidly with loop size and corresponding to it the heating agents decrease. For smaller number of flux tubes which correspond to the larger nanoflare birth rate of nanoflare agents which provide an average coronal heating rate by nanoflares.

2.2 *Estimation of coronal radiation*

For the critical value of power law index 2.0 the observed frequency f in terms of energy becomes

$$f = f_0 E^{-2} \quad (12)$$

where f_0 is the cut off value and numerically about 746. By applying the similar treatment to multiply by E and integrate over the entire energy ranges E_{min} to E_{max} in equation (12) yields

$$R_c = f_0 \int_{E_{min}}^{E_{max}} E^{-2} E dE = f_0 \; ln \frac{E_{max}}{E_{min}}. \tag{13}$$

Analytically, by introducing the values of minimum and maximum energies (E_{min} = 5 x 10^{23} and E_{max} = 5 x 10^{26} ergs) to get

$$R_c = 5.16 \text{ x } 10^4 \text{ erg } cm^{-2}\ s^{-1}.$$

The theoretical value of coronal radiation is very near the observed value of coronal radiation 4.5 x 10^5 erg $cm^{-2}s^{-1}$ reported by (Krucker and Benz 1998). Under the energy limits the power law will tend to have most of the energy deposited in nanoflares and due to lower density of corona dissipate their energy in it.

3. Discussion and conclusions

We consider coronal heating by nanoflare in the lower energy population of a broad spectrum of flare like events. An adjacent group of nanoflares is responsible for coronal heating in terms of heating agents. However, individual nanoflare cannot be resolved observationally, with the present day instrumentation. The broad energy spectrum of heating events via nanoflares creates an ensemble of heating agents of various sizes (see Fig.1). Not enough statistics on such phenomena is available with high temporal resolution and continuous observations can help to constrain the flare physics and the mechanisms of coronal heating. However, estimated amount of the coronal radiation 5.16 x 10^4 erg $cm^{-2}s^{-1}$ is very near the observed value 4.5 x 10^5 erg $cm^{-2}s^{-1}$.

Acknowledgements

It is a pleasure to acknowledge the kind hospitality of Prof. N. K. Dadhich, (Director) Inter University Center for Astronomy and Astrophysics (IUCAA), Pune. We are thankful to Dr. B.N. Dwivedi for helpful coments. This work is supported by IUCAA and we acknowledge the co-operation of M.B.Govt. P.G. College authority. Thankfully acknowledge UGC, New Delhi for partial support through minor research project 2002 No. F6 **-** 117/2002 (MRP/NRC).

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