OBSERVATIONAL SIGNATURES OF NANOFLARE HEATING

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Abstract

During the past few years it has been suggested that the solar corona results from the superposition of a large number of tiny impulsive energy-release events, which have come to be known as "nanoflares". However, these events have not yet been observed; moreover, it remains to be shown theoretically that the repetitive occurrence of nanoflares can eventually build up a plasma at typical coronal densities and temperatures. The purpose of this work is to describe the temporal evolution of the plasma in a rigid, originally cool and nearly empty coronal flux tube with footpoints rooted in the chromosphere, when the flux tube is subject to the sporadic release of typical nanoflare energies. To this end, by analytically integrating the partial differential equations for mass, momentum, and energy conservation over the loop's spatial coordinate, we have developed a simple model involving only the spatial averages of the plasma thermodynamic variables. The model allows us to show how the repeated occurrence of low energy events in loops of different sizes eventually builds up a higher density, high temperature plasma - i.e., a nanoflare-heated corona. The observational consequences of our modeling, as well as future work in this area, are also discussed.

1. Introduction

The coronal heating mechanism, whose nature has been debated over the past 40 years, has not yet been unambiguously identified. Neither theories nor observations have yet been able to provide uncontroversial clues that could help us settle this long-standing problem. Recently Parker (1988) has advocated the hypothesis of a corona heated by a myriad of tiny impulsive energy release events. Because a typical event is envisaged as corresponding to an energy of order 10^{-9} of the energy of the largest flares, they are referred to as "nanoflares". With minor differences, a similar mechanism had been proposed in the past by various authors (Gold, 1964; Levine, 1974; Glencross, 1975; Heyvaerts and Priest, 1984). Possibly the reason why a nanoflare-heated corona has not been popular in the past is the lack of observational evidence for these events: the detection of an energy release on the order of 10^{24} ergs was, and still is, beyond the capabilities of current instrumentation. However, over the past 10 years there have been a number of observations either of small events (see, e.g., Lin et al., 1984; Porter et al., 1984; Dere et al., 1989) or of variability in small loops (Haisch et al., 1988) and in Bright Points (Habbal and Withbroe, 1981; Habbal, 1991). These observations have generated renewed interest in the nanoflare heating mechanism, on the grounds that such events might represent the high-energy tail of the hypothesized nanoflare family and that the variability phenomena might be ascribed to an unresolved population of mini-events flickering on and off, giving rise to the observed intensity fluctuations.

The increased interest in nanoflares as a potential heating mechanism has recently spawned a number of papers dealing with different aspects of this admittedly ill-defined phenomenon. In the following section, we first briefly summarize the model we have developed to describe the temporal behavior of nanoflare-heated plasma confined in a coronal magnetic flux tube; then we show how the repeated occurrence of low energy events in an originally cold, low density loop rapidly establishes a high temperature plasma at typical coronal densities (Kopp and Poletto, 1993). In Section 3 we discuss the recent literature on this subject, in an effort to define the observational and theoretical works which are badly needed to put the nanoflare heating hypothesis on a more solid basis.

2. The Model

One of the issues which had not been explored until recently is the ability to establish a hot, solar-type corona via the repeated occurrence of nanoflares: it had to be demonstrated that the interplay of radiative losses, thermal conduction, chromospheric evaporation, and gravitational settling, could in fact act to build up a quasi-steady hot coronal plasma in the presence of sporadic nanoflare energy releases. Sophisticated hydrocodes, such as those commonly used to predict the behavior of flaring loops, might of course be used for this purpose. However, these codes do not provide the most efficient means for calculating the effects of multiple events occurring over long time intervals on a single loop. Moreover, the spatial details of these calculations should be somehow averaged, in order that the code predictions may be compared with available data; the latter consists of the combined radiative output from many unresolved loops contained within a single resolution element (pixel) of the instrument.

In order to answer this question -fundamental for the credibility of the nanoflare mechanism- we have developed a simple model which includes all of the basic physical processes of the more sophisticated models but describes only the *time variation of the spatially averaged properties* of the loop plasma. This approach leads to a great mathematical simplification: the plasma behavior, which would otherwise be calculated by integrating the partial differential equations for mass, momentum, and energy conservation, is now given by the time-integral of a system of total differential equations. We refer the reader to Kopp and Poletto (1993) for a detailed explanation of the modeling technique.

Even a simple model, however, requires the specification of a number of observational parameters. How many nanoflares occur per unit time? What is their energy distribution? What is the size distribution of coronal loops? Unfortunately, not all of these questions can be answered at present. The number of nanoflares per unit time can be inferred from the coronal energy requirement. For the case of the quiet corona, Withbroe and Noyes (1977) estimated an energy input of $\approx 10^6$ $erg\ cm^{-2}\ s^{-1}$. The nanoflare energy distribution, on the other hand, is an issue currently under debate (Hudson, 1991) - although it is widely believed that the distribution is represented by a power law. Keeping with recent estimates (Porter et al., 1993), we here choose an exponent of 2.2 for the power-law exponent (Poletto and Kopp, 1994). For the sake of simplicity, and for lack of adequate information, we have assumed that the corona is entirely made up of loops of the same size: this is kept as a free parameter in our simulations. On this basis we have been able to show that a random temporal sequence of nanoflares, distributed randomly in energy according to the afore-mentioned power law, is capable of establishing and maintaining typical coronal values of density and temperature on a loop which was originally cool and nearly empty of plasma. This conclusion remains true regardless of the assumed loop size. *If* nanoflares exist, *if* there is a sufficient number of them, and *if* their energy distribution is given by a power law with the *right* exponent, nanoflares are a viable means to heat the solar corona.

3. Discussion and Conclusions

As mentioned above, we have analyzed the case of the quiet solar corona. An analogous work has been recently published by Cargill (1993), who examined the implications of the nanoflare hypothesis for the case of the active corona. Cargill's work focusses on the observational consequences of nanoflare heating and predicts a lower filling factor for the quiet corona than for the active corona. By observationally determining these filling factors, the upcoming SOHO mission might be able to test this prediction.

A different type of observational test of the nanoflare heating hypothesis has recently been made by Shimizu (1994). Yohkoh/SXT images have revealed transient flare-like active region brightenings (Shimizu et al., 1992) that are suggestive of nanoflares. Shimizu used the data to examine whether these transient brightenings represent enough energy to account for the required coronal heating. This kind of analysis can be pursued further, by comparing the observed X-ray emission against that predicted by the nanoflare heating model for different power-law energy distributions and for different loop size distributions. However, whenever many loops are imaged simultaneously within a single pixel, one has also to take into account that the emission from each loop will be smeared over the entire pixel and thus may appear as a smaller energy release than that which actually occurred; alternatively, the emission may simply become lost in a fluctuating background, whose base level is determined by the frequency of occurrence and energy distribution of the nanoflare population. Shimizu's approach is surely worth additional work, both on present and future (SOHO) data. Moreover, any information on the loop-size distribution (see, e. g., Martens and Gómez, 1992) and the exponent of the power-law flare energy distribution may have a large impact on the credibility of the nanoflare hypothesis.

The extension of the nanoflare heating hypothesis from the solar corona to stellar coronae has not been worked out yet, although on both theoretical (Parker, 1993) and observational grounds (Butler et al., 1986) we may expect this mechanism to operate on dMe and possibly all late-type stars. However, the same paucity of data which currently prevents an observational test of the nanoflare hypothesis for the Sun, postpones analogous considerations for stellar coronae beyond the foreseeable future. Still, it may be worth developing models of nanoflare-heated coronae for late-type stars, if only to check whether the nanoflare mechanism can explain these as well as the corona of the Sun.

A topic possibly related to nanoflare heated plasmas, is that of the release of energy in "normal" flares. Traditionally, flares have been interpreted as a manifestation of the release of magnetic energy stored in a large-scale structure. However, this view has recently been challenged and an alternative hypothesis has been advanced (see, e.g., Lu and Hamilton, 1991; Zirker and Cleveland, 1993a,b). According to this suggestion, flares occur because of a chain reaction which involves many small-scale sites: in this "avalanche" model, a small-scale event creates a disturbance that propagates close-by, triggering further energy releases. According to Zirker and Cleveland, twisting and braiding of field lines are responsible for the energy release processes: in particular, twisting of magnetic fields may produce the steady heating of active regions, while fieldline braiding may lead to the sporadic large energy release which occurs in flares. A unified view of quasi-steady hot plasmas and rapidly evolving phenomena, like flares, is certainly appealing, although at the present time, as the authors point out, their suggestion yields results not in complete agreement with observations.

This cursory review of open questions in the hypothesized nanoflare heating mechanism shows that it is an area now thriving with new ideas and badly in need of new observational material. The onus is clearly upon us to develop the nanoflare scenario up to a point where it may either provide the long-sought answer to the coronal heating puzzle or give rise to an entirely different picture.

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