SYNTHESISED RADIATIVE EMISSION FROM A NANOFLARE HEATED ELEMENTAL SOLAR LOOP

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ABSTRACT

We have carried out a numerical experiment to determine the observational consequences for TRACE and SolarB-EIS of a heating event on the spatial, temporal and energy scales characterised by the traditional nanoflare model of Parker (1988). The radiative emission accompanying such an event has been synthesised for the TRACE 171 and 195 Å filters, and the long and short wavelength bands of EIS, assuming an ionisation balance for the emitting plasma both in and out of equilibrium.

We find substantial departures from the equilibrium balance for each of the ions that emit important spectral lines in the sensitivity range of both instruments and conclude that a nanoflare-like heating event would be extremely difficult, if not impossible, to observe directly. However, a more easily observable signature of nanoflare heating emerges when the plasma begins to cool by heat conduction.

We demonstrate the unreliability of the broad- and narrow-band filter ratio method, commonly used to determine the plasma temperature, when the ionisation balance is not in equilibrium and show that the temperature can be dramatically underestimated.

Finally, we emphasise the importance of high cadence and enhanced spectral resolution, at the expense of spatial resolution if need be, which may allow a rapid temperature increase to be followed and Doppler shifts caused by the symmetric jets predicted to be driven by small-scale heating events to be observed.

Key words: corona; hydrodynamics; radiation.

1. INTRODUCTION

One of the outstanding problems in solar physics, despite decades of study, is the identification of the mechanism(s)\(^{(1)}\) by which the corona of the Sun is heated to temperatures several orders of magnitude greater than the surface temperature. This is not a trivial problem as many solar observing missions have revealed additional layers of complexity, which have often served to confuse rather than enlighten. However, the enormous repository of data provided by SOHO, combined with extensive analysis, has provided new physical interpretations of solar atmosphere phenomena and constraints for theoretical models, giving cause for optimism that the correct path is being followed towards an eventual solution of the coronal heating problem.

A general consensus has emerged that the heating mechanism is likely to be transient and associated with the coronal magnetic field. This possibility led Parker (1988) to propose that the corona is heated by a ‘swarm of nanoflares’ - small-scale magnetic reconnection events between coronal field lines (see also Cargill, 1994).

Given a transient heating mechanism, it is reasonable to suppose that it should have a characteristic signature in the coronal EUV and X-ray emission. In general, the intensity of a spectral line increases with temperature until ionisation to a higher charge state takes place, whereupon the intensity decreases. Therefore, one may look to observations in the hope of recognising such a signature and identifying it with a particular mechanism. For example: enhanced emission (provided density increases can be ruled out) due to increasing temperature; or reduced emission due to ionisation to higher charge states.

Unfortunately, matters are not so straightforward and no such signatures have been convincingly observed. A transient heating mechanism brings with it an intrinsic set of difficulties, not least of which is the response of the coronal ion population.

In a quasi-static, steady-state plasma of coronal temperature and density the ionisation balance is expected to reach equilibrium on time-scales of several tens of seconds. Pre-SOHO observations tended (though not exclusively) to support the view that much of the corona existed in this state and thus interpretations of observations, and modelling studies, generally assumed an equilibrium ionisation balance. Solar flares were, of course, a notable exception, though when faced with the difficulties of a non-equilibrium ionisation balance both observers and modellers mostly opted for the equilibrium assumption citing the high density of the flaring plasma as justification.

Recent observations of the solar atmosphere, such as those provided by the instruments aboard SOHO (CDS, EIT and SUMER), Yohkoh and TRACE, have revealed a strongly dynamic component to the coronal activity and much of the plasma appears to be far from quasi-static and steady-state. The advent of substantially increased computing power and the development of a new computational code, HYDRAD, allowed the authors to inves-
tigate the nature of the ionisation balance in the light of these observations for a variety of solar events (Bradshaw & Mason, 2003a; Bradshaw & Mason, 2003b; and Bradshaw et al., 2004).

The work of the authors presented in the cited papers shows that not only is a non-equilibrium ionisation balance inevitable in coronal plasma subject to a transient event (both heating AND cooling), but that it also has a profound effect upon its radiative emission.

In particular, Bradshaw & Mason (2003b) presented a plausible explanation for the fact that no nanoflares of the type posited by Parker (1988), or similar small-scale heating events, have been directly observed. The non-equilibrium ionisation balance that is shown to arise as a consequence of nanoflare heating strongly attenuates the change in the radiative emission that one would expect to observe if the balance remained in equilibrium.

In the current paper we build upon these results and present additional work in which we have developed a forward-modelling approach to comparing observations and model data by synthesising the emission observable by the TRACE 171 and 195 Å filters, and the long and short wavelength bands of EIS, assuming an ionisation balance both in and out of equilibrium. We will show that the heating event remains all but invisible to observing instruments when the ionisation balance departs from equilibrium, even those instruments with relatively narrow bands of wavelength sensitivity.

Forward-modelling is a powerful technique, which allows models to predict the emission that instruments should observe and thus facilitates direct comparisons with actual observational data, rather than deriving properties such as temperatures and densities from observational data for comparison with models. The latter method is subject to its own inherent uncertainties, making comparisons all the more fraught with difficulties, while the forward-modelling method by definition predicts observational consequences for specific physical processes.

In §2, brief details of the numerical experiment are given; in §3, we present our results; and in §4, our conclusions, with recommendations for the future in terms of observing missions and theoretical modelling.

2. NUMERICAL EXPERIMENT

The numerical simulations are precisely those presented in Bradshaw & Mason (2003b). However, in brief, we used HYDRAD to simulate a nanoflare with the characteristic properties described by Parker (1988) by applying a perturbation to the energy equation and following the evolution of the plasma. We adopted the following analytical form for the perturbation:

\[ E_H = E_{H0} \exp \left( \frac{s - s_0}{s_H} \right) \sin \frac{t - t_0}{\tau_H} \]

(1)

\[ E_{H0} \text{ and } E_{H0} \text{ are the background heat input required to maintain the initial atmosphere and the maximum transient heat input. The exponential term describes the spatial distribution of heat, where } s_0 \text{ and } s_H \text{ are the location of maximum heating and the heating scale length (or e-folding length). The sinusoidal term describes the transient behaviour of the heating pulse, where } t_0 \text{ and } \tau_H \text{ are the onset time and the period (i.e. the time taken for it to rise, reach its maximum and decay).} \]

We chose the following values for the parameters of the heating function:

\[ E_{H0} = 2.4 \times 10^{-4} \text{ erg cm}^{-3} \text{ s}^{-1}, \]
\[ E_{H0} = 0.1 \text{ erg cm}^{-3} \text{ s}^{-1}, \]
\[ s_0 = 4 \times 10^9 \text{ cm}, \]
\[ s_H = 1 \times 10^8 \text{ cm}, \]
\[ t_0 = 0 \text{ s}, \]
\[ \tau_H = 30 \text{ s}. \]

The above parameter values describe a heating pulse delivered symmetrically about the loop apex, with a maximum heat input of 0.1 erg cm\(^{-3}\) s\(^{-1}\), a spatial scale of 2 \times 10^9 cm (2000 km or about 3") and a period of 30 s. Only one pulse was delivered to the loop in each simulation and so only constant background heating remained after 30 s. The total amount of heat delivered to the loop was about 10^6 erg cm\(^{-2}\).

HYDRAD solves the system of hydrodynamic equations cast in conservative form simultaneously and self-consistently with the time-dependent ionisation balance equations (by coupling them to the radiation term of the energy equation) on an adaptive computational grid. It runs in single- and multi-processor environments.
3. RESULTS

We carried out two numerical experiments: one assuming an equilibrium ionisation balance; and the other allowing a full non-equilibrium treatment of the ionisation balance.

The emission detectable by the TRACE 171 and 195 Å filters, and by the long and short wavelength bands of EIS, was synthesised using our forward-modelling code; the temperatures, densities and ion populations from both simulations; and the instrument response functions shown in Fig. 1. The EIS response functions calculated by the authors and employed here are preliminary, as the performance of the instrument is likely to differ somewhat from expectations when it becomes operational.

Fig. 2 shows the evolution of the plasma temperature, velocity, pressure and density during the first 20 s of the nanoflare, at which time the apex temperature reaches a maximum of about $3 \times 10^6$ K (double its initial value). The resulting increase in pressure at the apex drives a flow, associated with a conduction front, toward each footpoint. Since the flows are only about $1.5 \times 10^6$ cm s$^{-1}$ (15 km s$^{-1}$) only a very small amount of material is ejected from the apex region and is not sufficient to noticeably dim the apex emission.

One important point to note is that SOHO-CDS does not have sufficient spectral resolution to unambiguously resolve Doppler shifts at these velocities, which is one possible explanation for the fact that the ‘plasma jets’ predicted to be associated with nanoflares have not been observed.

After 20 s the apex plasma begins to cool by conduction and the loop plasma gradually returns to its hydrostatic equilibrium configuration.

3.1 Synthesised Emission Observable by TRACE

Fig. 3 and Fig. 4 show the synthesised emission in the TRACE 171 and 195 Å filters. The brighter regions have been intentionally saturated in order to emphasise the difference between the equilibrium and non-equilibrium ionisation balance results.

It is immediately clear that a non-equilibrium ionisation balance has dramatic consequences for the observed emission. When the apex plasma reaches its peak temperature, at 20 s, the associated emission calculated assuming an equilibrium balance is negligible in both filters and one would expect to observe a dark ‘blob’ of plasma as a signature of the heating event.

However, when the time-dependence of the ionisation balance is accounted for it is evident that the observed emission during the first 20 s remains unchanged, despite a factor of 2 increase in the plasma temperature. In fact, the emission only begins to vary after about 30 s, which is well into the conductive cooling phase, and even then it is doubtful whether it is sufficient to be clearly discernible from the ambient coronal emission.

At this point we emphasise that the observational problem is not one of temporal or spatial resolution. TRACE should be equal to the task of temporally resolving events on time-scales of a few seconds and it’s spatial resolution of 1” is more than sufficient to resolve the 3” scale of the simulated nanoflare.
Figure 4. Synthesised emission in the TRACE 195 Å filter for an equilibrium (bottom) and non-equilibrium (top) ionisation balance during the first 60 s of evolution. White represents the strongest emission and black represents no emission.

Figure 6. Predicted TRACE 195 / 171 Å filter ratio along the loop (footpoint to apex) at $t = 0$ s.

3.2 Filter Ratio Measurements of Plasma Temperature

We now present a word of warning with regard to using the popular filter ratio method to determine the temperature of a relatively tenuous, optically-thin plasma, such as the solar corona, when it is subject to a small-scale heating event (such as a nanoflare).

Fig. 5 shows theoretical TRACE 195 / 171 Å filter ratio curves. They are sensitive functions of temperature. The differences between the curves highlight the importance of using carefully selected and up-to-date atomic data.

Fe VIII emits important lines in the TRACE 195 Å range which are not accounted for in CHIANTI v2 (Landi et al., 1999), thus explaining the significant departure from the CHIANTI v4.01 (Young et al., 2003) curve below $10^6$ K. Using the CHIANTI v2 filter ratio curve would result in the underestimation of the plasma temperature below $10^6$ K. The data pertaining to the higher temperature lines has also been improved and updated in the later versions of CHIANTI.

The choice of ionisation balance is also seen to have a major effect. The curve calculated with the Arnaud & Rothenflug (1985) balance is markedly different to the curve calculated with the Mazzotta et al. (1998) balance. Finally, the filter ratio is multi-valued over a reasonably narrow interval in the temperature range of interest ($10^6 - 10^{6.4}$ K), which leads to further uncertainty in the derived temperature (Testa et al., 2002).

The difficulties with the filter ratio method described above are substantial enough. However, a non-equilibrium ionisation balance compounds the problems further. Fig. 6 shows the predicted filter ratio along the model loop at $t = 0$ s. At the apex the value of the filter ratio is 3, which, using the solid line in Fig. 5, corresponds to a temperature of $\approx 1.5 \times 10^6$ K. Thus, the apex temperature at $t = 0$ s in Fig. 2 is recovered.
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Figure 7. Predicted TRACE 195 / 171 Å filter ratio along the loop at \( t = 10 \) s for the non-equilibrium ionisation balance.

Figure 8. Synthesised emission in the EIS 170 - 210 Å filter for an equilibrium (bottom) and non-equilibrium (top) ionisation balance during the first 60 s of evolution. White represents the strongest emission and black represents no emission.

3.3 Synthesised Emission Observable by SolarB-EIS

Fig. 8 and Fig. 9 show the synthesised emission in the EIS 170 - 210 and 250 - 290 Å filters. Again, it is clear from Fig. 8 that even EIS may not be able to directly observe a nanoflare or similar small-scale heating event, despite its ability to resolve individual spectral lines at high cadence (a few seconds) and with high spatial resolution (2'). The synthesised emission calculated using the non-equilibrium ionisation balance shows that any detectable signature of the heat input is unlikely to be observed until the onset of conductive cooling.

However, the synthesised emission in Fig. 9 offers some hope. The 250 - 290 Å wavelength band contains a strong line from Fe XV at 284 Å and it appears that if there is a sufficient population of Fe XV at the onset of heating then these ions will emit with increasing intensity as the temperature rises. Though Fe XV is quickly depleted in equilibrium by ionisation to higher charge states, as evidenced by the dark 'blob' corresponding to a lack of emission, it remains reasonably abundant when departures from equilibrium are accounted for and thus a brightening at 284 Å could be observed throughout the heating phase.

At this point we mention the fact that TRACE also possesses a filter sensitive to spectral lines in the region of 284 Å though it has been under-utilised to-date in order to conserve bandwidth and improve cadence for the more commonly used 171 and 195 Å filters.

It may be fruitful to search the TRACE data archives for evidence of small-scale heating in the available 284 Å observations, although as pointed out above the detectable signature depends upon the initial abundance of Fe XV. In a cooler initial plasma there may be no detectable signature at all because the delay in ionisation to Fe XV from lower charge states means that it will be severely depleted.
when the plasma reaches the temperature of peak Fe XV abundance in equilibrium.

4. CONCLUSIONS AND RECOMMENDATIONS

We have demonstrated the inescapable physical fact that the ionisation balance of a tenuous, optically-thin plasma, such as the solar corona, depart substantially from equilibrium even for a relatively modest heating event, with dramatic consequences for the observable emission.

Our simulations based upon the standard nanoflare model proposed by Parker (1988) have shown that a non-equilibrium ionisation balance makes direct observations of the heating extremely difficult, if not impossible, to obtain.

One lesson to be learned from these results is that even arbitrary increases in spatial and temporal resolution are of no help, since TRACE in particular should be well able to observe a heating event on the scales adopted here.

We have shown that filter ratios are an unreliable method for determining the temperature when the rate of temperature increase exceeds the rate of ionisation. Ratios of spectral lines emitted by the same ion, with temperature (and density) sensitivity, are necessary to remove the difficulties associated with the ionisation balance. The rates of excitation and decay are greater than those of ionisation and recombination, therefore temperature measurements using line ratios may better be able to keep up with the evolving plasma.

Consequently, the future lies in instruments with high cadence and enhanced spectroscopic resolution, hence increased wavelength and temperature discrimination.

However, this assumes that the statistical equilibrium equations governing the populations of energy levels are valid and, of course, in a rapidly evolving plasma this may also not be the case. Time-dependent energy level populations require the solution of the time-dependent statistical population equations, which increases the computational demands by several orders of magnitude.

On the positive side we have shown that one may hope to observe signatures of the heating at the onset of conductive cooling and also by observing at wavelength ranges corresponding to higher temperature emission. Furthermore, the spectral resolution of EIS should easily be capable of resolving Doppler shifts corresponding to velocities below 10 km s\(^{-1}\) and thus provides the possibility of finally observing the symmetric jets, at coronal temperatures, predicted by nanoflare models, which would be extremely strong evidence in their favour.

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