TRACE-derived temperature and emission measure profiles along long-lived coronal loops: the role of filamentation.

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ABSTRACT

In a recent letter (ApJ 517, L155) Lenz et al. have shown the evidence of uniform temperature along steady long coronal loops observed by TRACE in two different passbands (171 Å and 195 Å filters). We propose that such an evidence can be explained by the sub-arcsecond structuring of the loops across the magnetic field lines. In this perspective, we present a model of a bundle of six thin parallel hydrostatic filaments with temperature stratification dictated by detailed energy balance and with temperatures at their apex ranging between 0.8 and 5 MK. If analyzed as a single loop, the bundle would appear isothermal along most of its length.

Subject headings: Sun: corona, Sun: UV radiation, Sun: X-rays

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1. Introduction

The solar X-ray emitting corona entirely consists of independent loop-like bright structures, in which the plasma is confined by the magnetic field (e.g. Vaiana et al. 1973). The coronal loops cover a wide range of sizes and brightness, and make the solar corona highly structured and contrasted in X-rays. Observations at high angular resolution (1") made with the *Transition Region and Coronal Explorer* (*TRACE*, e.g. Handy et al. 1999) show, once again, the high level of structuring of the solar corona, and, in particular, that coronal loops typically consist of several individual filaments, down to the telescope resolution limit. This raises even more questions on the structure, evolution, interaction, turning on, coherence and eventually the heating of the individual filaments (e.g. Proceedings of the Workshop on the Physics of the Solar Corona and Transition Region, 24 - 27 August 1999 Monterey, California, Solar Physics, 1999, in press). In particular, one basic question is how the physical conditions of the several, energetically independent, loop filaments are related to the physical parameters derived from the analysis of TRACE data.

The temperature and density distribution along some loop structures observed by TRACE has been recently investigated by Lenz et al. (1999, hereafter L99). They have selected four relatively isolated loops extending above the solar limb and steady, at least for time intervals of 1-2 hr. The half length of three of the loops (loops a, b, and d) is $L \approx 10^{10}$ cm, and that of the fourth (loop c) is $L \approx 5 \times 10^9$ cm. L99 have analyzed the brightness distribution along each loop by selecting four subimages of each loop (at 1/5, 1/3, 2/3 and 3/3 of the distance from the base to the loop top). Each subimage contains a few hundred to a few thousand pixels and includes the whole loop cross-section.

The temperature and the emission measure (EM) in the regions mentioned above are derived from the 171/195 Å filter ratio and from the 171 Å count rate, respectively, by assuming that all the plasma along the line of sight is at the same temperature and density. L99 find that the filter ratio varies very little along the four loops, therefore concluding that the temperatures profiles are constant along the loops, around 1.3 MK. This finding is at variance from a static, steady-state, non-isothermal loop model (e.g. Serio et al. 1981), uniformly heated and with a temperature of 1.3 MK at the apex: although the temperature profile would be rather flat in the corona according to this model, the observed profile is significantly (and incompatibly) flatter.

By assuming a uniform line-of-sight depth of 10^{10} cm, L99 obtain emission measures increasing from the apex to the base, and ranging between 10^{27} and 10^{28} cm^{-5}. Such profiles are flatter, and at higher density, than predicted by single loop hydrostatic models at that temperature (Serio et al. 1981), and are better described by isothermal loops at T=1.3 MK.

Although aware that the static non-isothermal models used do not take into account possible additional effects, such as non-uniform heating, the presence of flows and mixing, and wave interaction with the background fluid, L99 conclude that "the lack of temperature variation in the EUV loops considered invites speculation that there is a class of such isothermal loops distinct from loops with a temperature maximum at the apex."

This letter revisits this interpretation in light of a more realistic scenario in which the loops detected by TRACE consist of bundles of filaments independent of each other, possibly in different physical conditions, and, in particular, at different temperatures. Each filament may then be described by a distinct non-isothermal loop model. We will show that TRACE diagnostic may actually yield an apparently almost isothermal profile along most of a loop consisting of such a bundle.

We conclude, therefore, that the evidence of isothermal loops shown by TRACE may just be a further signature of the filamentary structure of coronal loops and of the multi-temperature nature of each bundle of filaments across field lines.

In section 2 we model a loop observed by TRACE as a bundle of thin parallel hydrostatic filaments, synthesize its emission in the relevant TRACE bands and derive its effective temperature and emission measure with the procedures used to analyze real TRACE data. We discuss the results in section 3.

2. The modeling

We consider a loop of half length 5×10^9 cm (corresponding to loop c in L99). The choice of the shortest loop allows us to concentrate on the effects of loop filamentation, without the complication of a strong gravitational stratification expected for the longer loops.

We model the loop as a bundle of parallel, static and hydrostatic filaments. Each filament is assumed to be semicircular and symmetric with respect to the apex, and to lie on a plane perpendicular to the solar surface. Temperature and density stratification is taken into account, according to Serio et al. (1981), by solving numerically the equations for hydrostatic equilibrium and for energy balance among plasma thermal conduction, radiative losses and a heating source assumed uniform along each filament[3].

Table 1 shows the relevant parameters of the model loop filaments, all of the same length and differing for the heating rate. The latter determines the plasma pressure conditions inside each filament (according to the scaling laws of Rosner et al. 1978 and of Serio et al. 1981). We have considered six filaments, with heating rates such that the pressures at the footpoints are logarithmically equispaced and spanning between 0.03 and 10 dyn cm^{-2}. The corresponding filament maximum temperatures span between 0.8 and 5.2 MK. With this choice we sample the plasma conditions typical of non-flaring coronal loops, from quiet to active regions, and relevant for observations with TRACE 171 Å and 195 Å filters.

The computed density and temperature profiles along half of each filament (the other half is symmetric) have been used to synthesize the emission $\mathcal{E}$ per unit optical depth along the filament, in units of Data Number (DN) s^{-1} pix^{-1} cm^{-1}, in the two relevant TRACE passbands, according to:

$$\mathcal{E}(s) = n(s)^2 \; G[T(s)] \tag{1}$$

where s is the coordinate along the filament (cm), n the plasma density (cm^{-3}), T its temperature (K), $G(T)$ the response in each TRACE passband (DN s^{-1} pix^{-1} EM^{-1}), computed with the MEKAL spectral code (Mewe et al. 1995), and shown in Fig. 1. The figure also shows the expected ratio of the emission detected in the 171 Å and 195 Å passbands vs temperature (assuming ionization equilibrium).

The loop-shaped pictures in Fig. 2 show the predicted distributions of the emission in the two TRACE passbands for the six filaments in Table 1, put side-by-side and ordered with pressure (and maximum temperature) increasing inwards. The grey scale (emission per unit optical depth) is saturated at 5×10^{-10} DN s^{-1} pix^{-1} cm^{-1}.

[3] Serio et al. 1981 have shown that non-uniform heating distributions do not change dramatically the model results, and, in particular, the temperature stratification, due to the effectiveness of thermal conduction, unless the heating is very localized.

Such pictures, which assume all filaments to have equal cross-section, provide a general impression of how a thermally structured bundle of filaments would look like in the TRACE passbands. The outermost (and coldest) filament is barely visible in the 171 Å passband, even if most of it is at a temperature not far from the peak of the response, because of its low emission measure, and analogously invisible in the 195 Å passband. In the 171 Å passband the hotter filaments have comparable brightness in the chosen scale, except the hottest one which is clearly brighter, because of its higher emission measure. In the 195 Å passband filament 3 is brighter than filaments 2 and 4, because the temperature of most of its plasma is close to the peak of the filter response. Again, the hottest filament is the brightest one because of its high emission measure.

Fig. 3 shows the ratio of the filtered emission in the 171 Å to the 195 Å passband computed along (half of) each of the six filaments, from the footpoint to the apex, according to Eq. (1). These profiles can be easily understood in terms of the filter ratio curve shown in Fig. 1. Above the lowest 10^9 cm, the ratio is quite high for the coolest models 1 and 2 ($\gg 10$ for model 1), because the temperature along most of them is in the branch below $\log T = 6.2$, and it is much lower than one along most of filament 3 whose temperature is mostly around the ratio minimum occurring at $\log T \approx 6.3$. The temperature of the other hotter models mostly falls in the branch of the ratio curve above $\log T \approx 6.3$, which is more weakly dependent on temperature and with a value ≈ 1. The ratio profile of model 4 has a minimum close to 10^9 cm (corresponding to the minimum at $\log T \approx 6.3$ in the ratio curve of Fig. 1), and then gradually increases to ~ 1 upwards along the loop. For models 5 and 6, the hottest ones, the minimum is more localized and located well below the level of 10^9 cm: above, the ratio is constantly ~ 1.

Our key point is now how such a bundle of filaments would be detected by TRACE if analyzed as a single loop, as in L99. We then sum all the emission profiles shown in Fig. 2, to obtain two single profiles, one for each filter passband. The profile of the ratio of the two resulting emission distributions is shown in Fig. 3 (thick solid line): the ratio is virtually constant (≈ 0.7) along the whole loop except at the very base (below 5×10^8 cm). Of course, such a ratio is determined mostly by the brightest filaments, and in particular model 6, the hottest one, which contributes

30% of the total emission above 10^9 cm in the 171 Å band; the faintest models 1 to 5 contribute to lower the value of the ratio and to make it even more uniform.

The most straightforward interpretation of such a flat ratio profile would be a temperature uniformly distributed along the loop, and in the region around $\log T = 6.1$, i.e. close to the temperature of maximum formation of the 171 Å and 195 Å lines, if one restricts the range of possible temperatures to be in the monotonic branch of the filter ratio curve around $\log T = 6.1$. The temperature distribution, shown in Fig. 4, is flat for $s \geq 5 \times 10^8$ cm, and around 1.4 MK, i.e. very close to value obtained by L99 for the four loops they have analized.

From the ratio of the expected emission to the value of the response function at the given temperature, by assuming a line-of-sight depth of 10^{10} cm, as done in L99, one obtains the distribution of the emission measure shown in Fig. 4. The region of interest, which can be compared to the results of L99, is the one above 10^9 cm: in such 4/5 of the loop the emission measure spans between $\approx 4 \times 10^{28}$ cm^{-5} and $\approx 4 \times 10^{27}$ cm^{-5}. For loop c L99 report quite a flat profile, with a value around 5×10^{27} cm^{-5}. The EM profiles shown in Fig. 4 are not flat above 10^9 cm, but such profiles are obtained in the assumption of a constant line-of-sight depth. This may not be entirely realistic, as mentioned also in L99, and a smaller depth due to a thinning of the loop near and at the chromosphere cannot be excluded (a factor of two may be easily in agreement with observations). If the shrinking is not very fast, this should not affect significantly the model results, obtained in the assumption of a constant cross-section. Note that the choice of the depth cannot influence the key effect on the filter ratio discussed in this letter, since it depends on the combination of the several filaments emission, all six equally influenced by the depth value.

3. Discussion

Base on the indication of isothermal loops, observed by TRACE, L99 conjecture the possibility of a new class of isothermal loops, distinct from the non-isothermal hydrostatic loops.

The problem of the interpretation of the evidence of large isothermal loops, although at temperatures lower than those in L99, and probably in physical conditions very different from those in L99 (Brekke et al. 1997), have already been faced by Peres & Orlando (1996) and Peres (1997), who propose that such loops may be non-steady and strongly dynamic.

On the other hand, in the course of modeling a loop ignition observed by TRACE, Reale et al. (1999) have found that the temperature profile of a model loop of total length 10^{10} cm and heated at one footpoint becomes relatively flat after a few thousand seconds. Since evidence for isothermality is invariably found in all loops analyzed in L99, one wonders whether the phenomena discussed by Reale et al. (1999) may be so common. Reale et al. (1999) themselves have found that the loop they study is certainly not activated by heat deposition at one footpoint, but more likely higher in corona. In the same work it is shown that relatively flat temperature profiles are obtained if the heating is high for a short time and then decaying slowly. However, such a possibility, as well as the non-steadiness proposed for large cool loops, seems unlikely for the TRACE loops analyzed by L99, since they are observed to be steady for times longer than the loop characteristic cooling times.

The modeling illustrated in the present work shows that a bundle of conventional (Serio et al. 1981) non-isothermal and uniformly-heated static filaments with apex temperatures ranging between 0.8 and 5 MK, observed by TRACE in the 171 Å and 195 Å passbands, if analyzed as a single loop, would appear as an isothermal loop with a filter ratio typical of ~ 1.4 MK and with emission measures in rough agreement with the observed ones.

We have obtained this result by selecting a bundle of six loop filaments with base pressure logarithmically equispaced, simply summing their emission with equal weights. One may wonder how the results are influenced by this particular (although unbiased) choice of the parameters; indeed we obtain very similar results with a different choice of the pressures, provided that hot filaments are included. The fundamental result is therefore quite robust. Observations in all three TRACE filters may provide further constraints on the thermal structure of the loop bundle. However a more conclusive word may require future instruments with even higher spatial resolution, so as to better resolve the single filaments and to obtain enough signal-to-noise ratio from each of them.

The key result obtained here crucially depends on the major role played by the hottest components of the bundle: a) their temperature is mostly in the region in which the 171/195 filter ratio is weakly dependent on temperature, thus yielding a flat filter ratio profile along more than 4/5 of the length and showing a dip (corresponding to the dip in the filter ratio curve around $\log T = 6.3$) only very close to the footpoints; b) their emission measure is high and contributes significantly to the total emission in the TRACE band even though their temperature is not close to the peak of the filter response. For such hot filaments, and, in general, for all loops with $6.3 < \log T < 7$, the temperature diagnostics offered by TRACE two-filter observations should be taken with care, due to the non-monotonic and weak dependence of the 171/195 filter ratio on the temperature in that range.

Our conclusion is that the isothermal profiles obtained by L99 could be a consequence of the high structuring of the observed loops across the magnetic field lines, i.e. "filamentation", and, likely, an indication of the presence of high temperature threads (~ 5 MK). The TRACE images, indeed also those in L99, show a high level of loop filamentation.

This result of course needs further support by future observation and analysis, possibly in coordination with other instruments with spectral capabilities, such as those on board SOHO.

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Table 1: Parameters of the model loop filaments

Model	Base pressure (dyn cm^{-2})	T_{max} (MK)	Heating (10^{-3} erg cm^{-3} s^{-1})	Apex density (10^{9} cm^{-3})
1	0.03	0.8	0.01	0.05
2	0.1	1.1	0.04	0.15
3	0.3	1.6	0.15	0.4
4	1	2.4	0.6	1.1
5	3	3.5	2.6	2.5
6	10	5.2	10	5.9

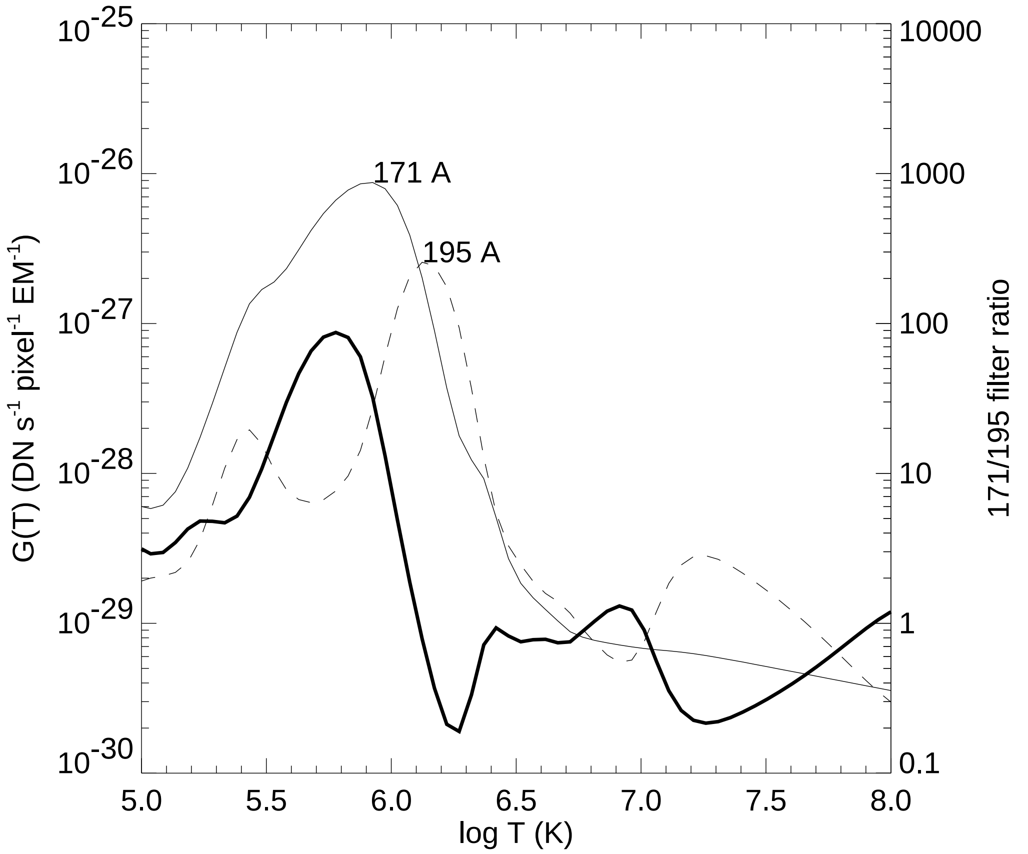

Fig. 1.— TRACE response of 171 Å (solid) and 195 Å (dashed) passbands (EM is in units of cm^{-5}), and filter ratio (thick solid) of the 171 Å and 195 Å passbands vs temperature of the emitting plasma volume.

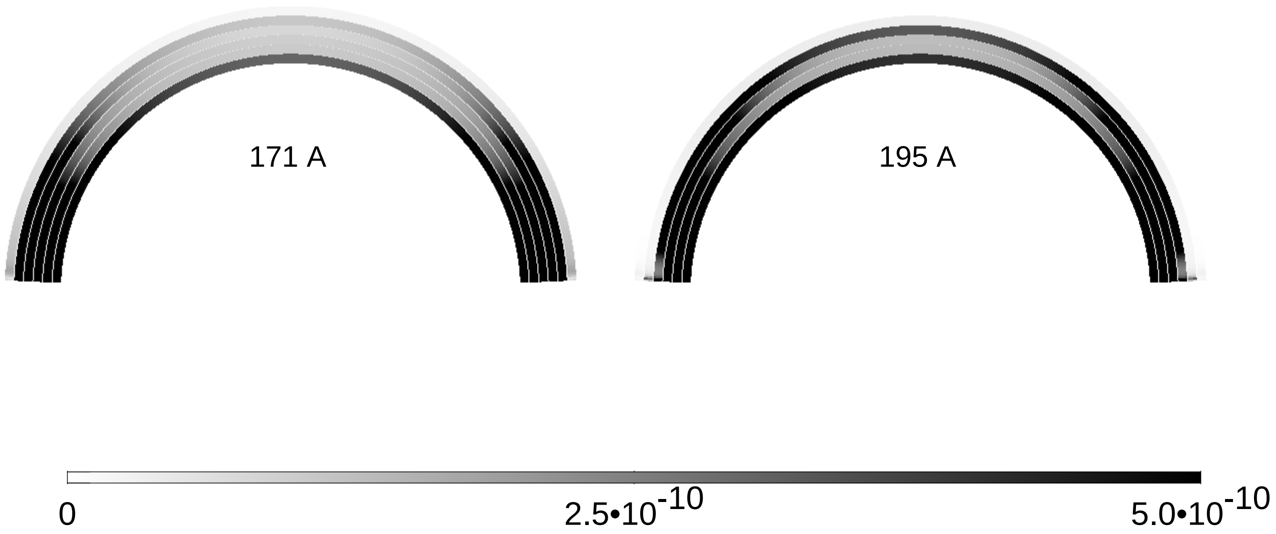

Fig. 2.— The loop-shaped structures show the distribution of the emission per unit volume in the TRACE 171 Å and 195 Å passbands, synthesized from the six model loops in Table 1, ordered with pressure (and maximum temperature) increasing inwards. The grey scale (emission per unit optical depth) is saturated at 5×10^{-10} DN s^{-1} pix^{-1} cm^{-1}.

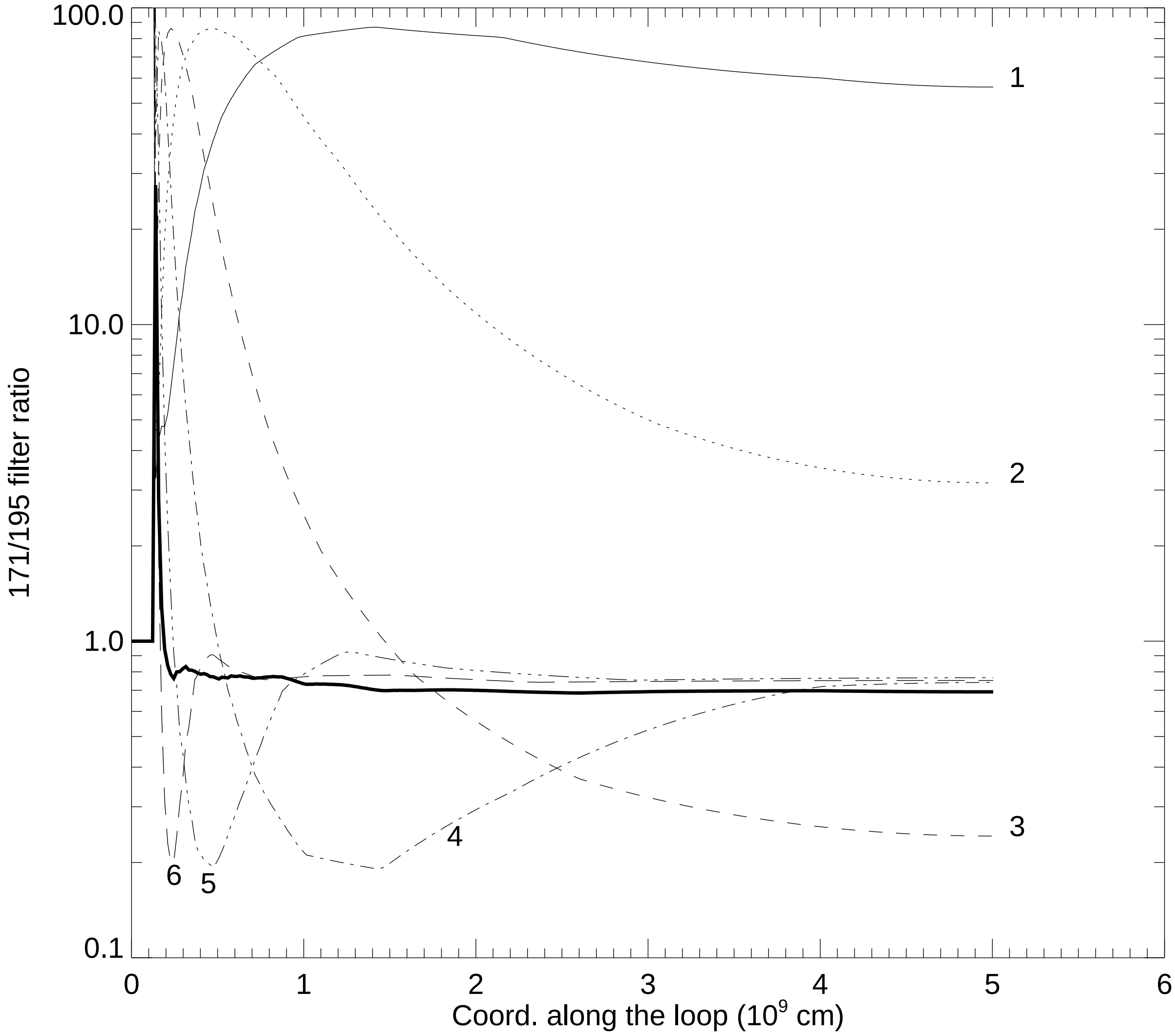

Fig. 3.— Ratio of the of the 171 Å to the 195 Å passband expected emission computed along each of the six model loops in Table 1 (thin lines). The ratio obtained by merging the six loops into a single loop, i.e. by summing the emission of the loops is also shown (thick solid line).

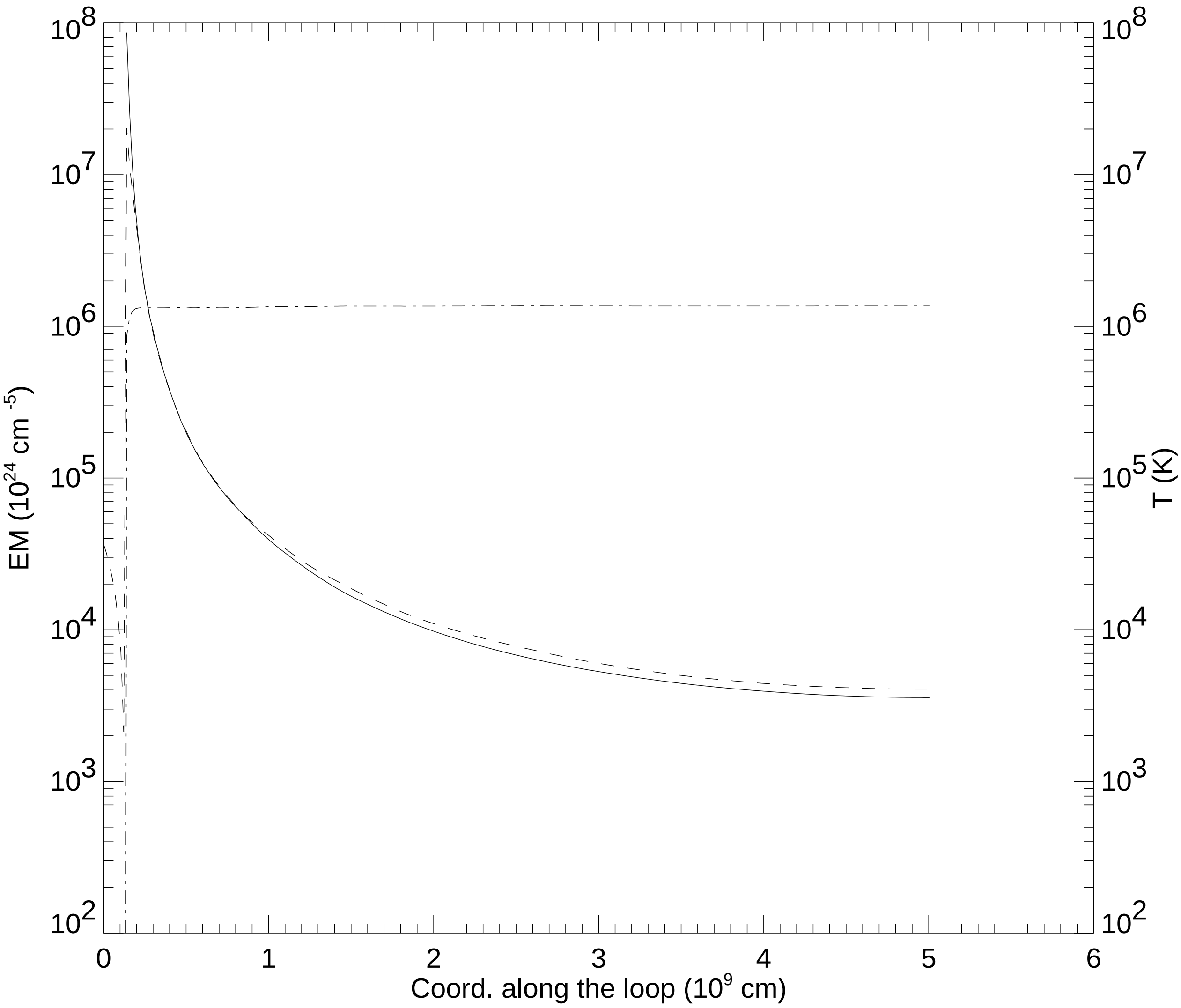

Fig. 4.— Temperature (dashed-dotted line) and emission measure profiles along the bundle of six filaments (Table 1); we have summed the synthesized emission of all six filaments in the 171 Å and 195 Å passbands and used the monotonic branch of the filter ratio curve around $\log T = 6.1$. The solid line shows the emission measure profile derived, as in L99, using a constant G(T) value of 2×10^{-27} DN s^{-1} pix^{-1} EM^{-1} for the 171 Å passband; the dashed line shows the analogous result using the G(T) proper.