Inclination of large coronal loops observed by TRACE

Fabio Reale*
Dipart. di Scienze Fisiche & Astronomiche, Università di Palermo, Sez. di Astronomia, Piazza del Parlamento 1, I-90134 Palermo, Italy

September 18, 1999

Abstract. A TRACE field of view well inside the solar disk shows very well defined large loops, likely to be very inclined to the solar surface. On the other hand there is little evidence of large loops perpendicular to the solar surface. We show that this does not mean that most large loops have such large inclination but that perpendicular loops are much less visible to TRACE, because of density stratification. We quantitatively evaluate this effect by modeling in detail loops with different inclinations.

Keywords: corona, X-rays

1. Introduction

The high spatial (1 arcsec) and temporal (few seconds) resolution of the Transition Region and Coronal Explorer (TRACE) has put in great evidence the high structuring, filamentation and variability of coronal structures at any scale size. The relatively narrow temperature sensitivity range of the EUV filters, due to their narrow passbands, makes the instrument particularly sensitive also to the thermal fine structuring and variations, therefore further leading TRACE to observe a dynamic and highly contrasted corona.

However the peculiarity of the instrument spectral response with respect to previous wider band telescopes (e.g. Yohkoh/SXT) requires special attention in the analysis and interpretation of the observations. This work analyzes how a simple physical effect, the vertical density stratification, influences the appearance of the overall solar corona as detected by TRACE and how neglecting this effect one may be led to erroneous interpretation of the images.

In particular, TRACE observations with a field of view well inside the solar disk, such as the one of Fig.1, show long coronal loops ($\gtrsim 2 \times 10^{10}$ cm) with a well-defined semicircular (or even elongated) shape. Their shape suggests that such well-defined loops are very inclined to the surface. On the other hand in the same images there is much less evidence of loops perpendicular to the surface, which should appear as foreshortened (or even as straight lines connecting the footpoints

* E-mail: reale@oapa.astropa.unipa.it

at opposite magnetic polarity), due to projection effects. All of this is, of course, somewhat unexpected and may lead to the surprising (and wrong) conclusion that large coronal loops are preferentially very inclined to the solar surface.

Here I show that this is purely an observational selection effect: plasma confined in long loops perpendicular to the solar surface is highly stratified by gravity, and in the upper loop regions its density (and therefore brightness) is so low as to be practically invisible to TRACE; in inclined loops, plasma is less stratified, and, therefore, the loops appear more uniformly bright in the TRACE passband. The presence of density stratification is, of course, not a new effect, but the TRACE sensitivity to a narrow, and relatively cool, range of temperatures has put it into greater evidence with respect to previous observations, so that it deserves some attention and investigation (see also Aschwanden et al. 1999).

In this work this effect is quantitatively investigated by modeling in detail the emission expected in the TRACE 171 Å filter passband from long loops with different inclinations to the solar surface. In Section 2 I describe the approach and modeling, Section 3 shows some results and relevant conclusions are drawn in Section 4.

2. Modeling large coronal loops with different inclinations

The approach consists in modeling the density and temperature distributions of the plasma confined in a set of long coronal loops, assumed steady and static, differing only for their inclination to the solar surface. We can then synthesize and compare the emission along the loops expected in the TRACE passband, in order to have quantitative predictions to match to the observed features.

The largest coronal loops indicated in Fig.1 (total length of the order of $2-6\times10^{10}$ cm) are observed to be steady for a long time (more than 1 hour) and even up to the whole duration of the observation, which is around 3 hours. A characteristic cooling time, which takes into account radiative and conductive cooling times, is the loop entropy decay time τ_S (Serio et al. 1991):

$$\tau_S = 120\frac{L_9}{\sqrt{T_7}} \tag{1}$$

where τ_S is in seconds, L_9 is the loop half-length (10^9 cm), and T_7 the loop maximum temperature (10^7 K). For $L_9 \sim 10-30$ and $T_7 \sim 0.1$, a temperature close to that of maximum TRACE sensitivity 171 Å band, $\tau_S \sim 1-3$ hours. It is therefore reasonable to assume that such long

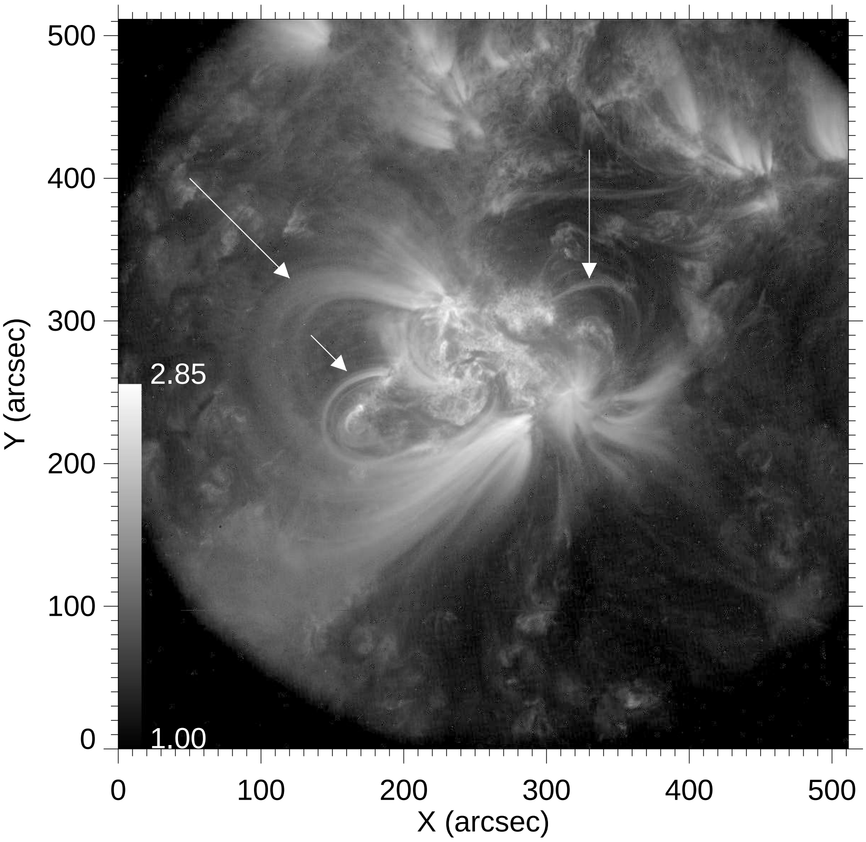

Figure 1. This TRACE field of view taken in the 171 Å band, is well within the solar disk (center at X=-492.8" Y=253.9"), and is 1024 × 1024 pixels of size 0.5", taken at 13:54:17 UT of June 26, 1999 (see also Reale et al. 1999). The exposure time is 23 sec and the brightness scale units are log Data Number (DN). The arrows indicate large loops which appear almost semicircular and therefore are likely very inclined to the solar surface.

structures are steady and stable at least for a time of the order of the characteristic radiative and cooling times, and to model the plasma confined in them as in hydrostatic conditions.

For our modeling we also assume that the loops are semicircular, uniformly heated and symmetric with respect to the apex. The assumption of a uniform heating distribution may be somewhat unjustified (see Reale et al. 1999), but it has been proven that moderate deviations from uniformity are unimportant, due to the effectiveness of thermal conduction which rapidly redistributes the temperature along the magnetic field lines (Serio et al. 1981).

We model the plasma distribution inside the loops according to the single-loop/single-fluid one-dimensional static model of Serio et al. (1981): gravity, radiative losses, thermal conduction and an external heating source are included. The model includes temperature stratification due to the detailed energy balance among the terms mentioned above. Recently flat profiles of TRACE 171/195 filter ratio measured along most of the length of some selected loops has been interpreted as evidence for isothermal loops (Lenz et al. 1999). However, it has also been shown (Reale & Peres 1999, see also Lenz et al. in this issue) that flat filter ratio profiles (with similar filter ratio values) are yielded if each analized loop consists of a bundle of hydrostatic non-isothermal threads, with at least one being at relatively high maximum temperature (~ 3 MK). For this reason I believe that a thermally stratified atmosphere still describes realistically the plasma confined inside loops observed by TRACE.

We consider two loop half-lengths $L/2 = 1 \times 10^{10}$ and 3×10^{10} cm and, for each length, six values of the pressure at the base of the loop, corresponding to maximum temperatures (Rosner et al. 1978) from 0.8 MK to 1.9 MK (0.8, 1.0, 1.2, 1.4, 1.6, 1.9 MK for vertical loops), and to pressure scale heights between 4×10^9 cm and 10^{10} cm.

For each loop length and maximum temperature, the plasma density and temperature distribution along the loop is computed for four inclination angles: 90°, 30°, 10°, 5° with respect to the solar surface, i.e. from a perpendicular loop to a practically horizontal one (if one takes into account the effect of the solar surface curvature). Temperature differences between loops with the same base pressure but inclined by 90° and by 5° are below 10%.

Although the loop model is not isothermal, the high efficiency of thermal conduction in corona makes the temperature profile rather flat along each loop (Serio et al. 1981): the temperature drops by no more than 20% in 70% of the loop length from the loop apex, in any of the selected models.

From the density and temperature distribution the emission along each modelled loop is synthesized in the TRACE 171 Å filter passband according to:

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

where s is the field line coordinate, $G(T)$ is the plasma emissivity per unit emission measure folded with the instrument spectral response in the 171 Å band. $G(T)$ has been computed by using the MEKAL spectral code (Mewe et al. 1995).

3. Results

Fig.2 shows the distributions of brightness in the 171 Å filter passband along loops with half-lengths 10^{10} cm and 3×10^{10} cm differing only for their inclination to the solar surface, obtained according to the present modeling. The emission of the footpoints is saturated to 2 and 0.1 10^{-10} DN s^{-1} pix^{-1} cm^{-1} respectively. Each loop-shaped picture of Fig.2 consists of a bundle of loop threads of plasma at different maximum temperature (see section 2). This representation allows us to show how the loops would realistically appear to the observer and to put the effect of the different inclinations in the correct perspective.

If we look at the perpendicular loops (90°) in Fig.2, the apex of all of the filaments composing them for both lengths is very faint because above the pressure scale height the plasma density (and therefore the emission measure) is low, much lower than close to the footpoints. Such high brightness contrast footpoints/apex is further enhanced when observing the loop projected on the solar disk. Therefore long vertical loops can be hardly identified in TRACE observations on the solar disk: only their legs are visible.

Inclined loops (30° to 5°) extend all below the pressure scale height, and they are more uniformly filled with plasma: Fig.2 clearly shows that within the solar disk they will appear to TRACE more uniformly bright than the "vertical" loops, and, therefore, as proper loop-like structures when projected on the solar disk (only little deformed by projection on the disk). Although the TRACE 171 Å filter response has quite a narrow temperature sensitivity range (e.g. Lenz et al. 1999), the strong brightness stratification in the less inclined loops is mostly due to the density stratification, rather than to the temperature variations along the loop ($< 20\%$). The effect of temperature vs filter temperature response can be inferred in Fig.2 by comparing threads at the same inclination and differing only for the base pressure (and therefore also for the maximum temperature).

4. Conclusions

Modeling loops of various inclinations to the solar surface shows that all segments of long coronal loops lying almost parallel to the solar surface are expected to be visible in the TRACE passband: the loops will therefore appear as proper loop-like structures when observed inside the disk. However the upper parts of loops perpendicular to the solar surface have been shown to be too faint to be visible in disk

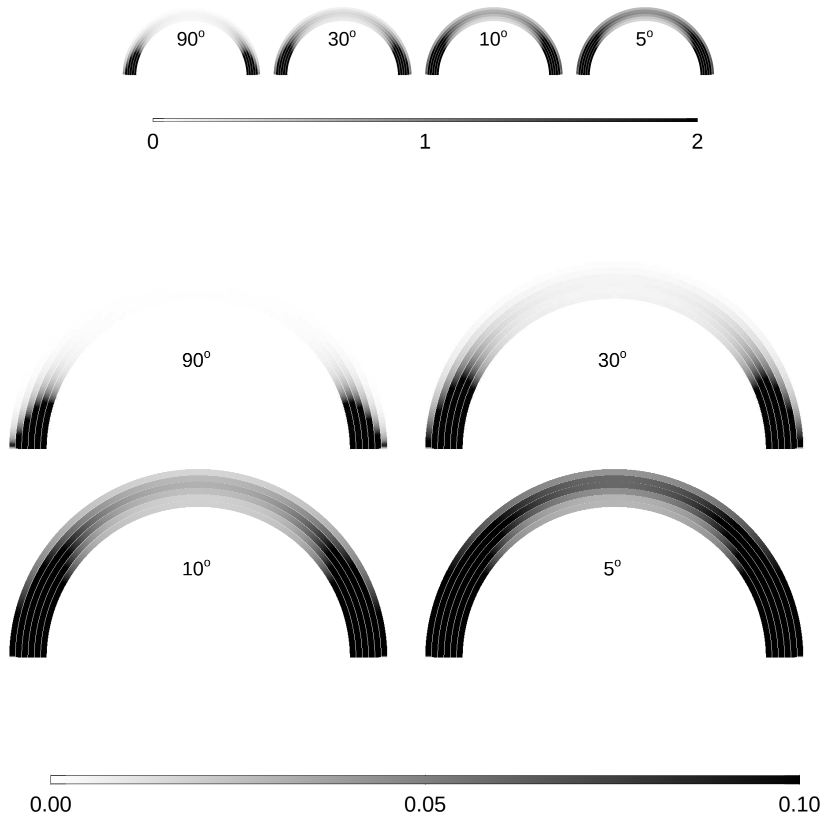

Figure 2. Modelled distribution of brightness (10^{-10} DN s^{-1} pix^{-1} cm^{-1}) in the 171 Å filter passband along loops (the pictures are scaled in size) with half-lengths 10^{10} cm (*upper panel*) and 3×10^{10} cm (*lower panel*) scale) and the labelled inclinations, from perpendicular (90°) to almost parallel (5°) to the solar surface. Each thread is a loop with a different maximum temperature from 0.85 MK (external) to 1.9 MK (internal). Brightness scales are shown below the loops.

observations. This effect is mainly due to the different plasma density stratification.

Complex loop systems consisting of bundles of many loops with any inclination, and sharing the same footpoints, may then appear in TRACE disk observations with a characteristic (single or double) *horseshoe* shape (instead of a uniformly bright bundle), because only loops very inclined to the solar surface are wholly visible, while only the footpoints of the nearly vertical loops are bright (see also Aschwanden et al. 2000). This effect should be taken into proper account in systematic analyses of coronal loops systems observed by TRACE.

Acknowledgements

The author acknowledges support from Ministero dell'Università e della Ricerca Scientifica e Tecnologica and Agenzia Spaziale Italiana.

References

Aschwanden M.J., Newmark J. S., Delaboudiniere J.-P., Neupert W.N., Klimchuk J.A., Allen Gary G., Portier-Fozzani F., Zucker A., *ApJ* 515:842-867, 1999.

Aschwanden M.J., et al., *ApJ* 531 (March 1 issue), 2000.

Lenz D. D., DeLuca E. E., Golub L., Rosner R., Bookbinder J. A., *ApJL* 517:L155, 1999.

Mewe, R., Kaastra, J. S., Liedhal, D. A., *Legacy* 6:16,1995

Reale F., Peres G., Serio S., DeLuca E.E., Golub L., *ApJ* submitted, 1999.

Reale F., Peres G., *ApJL* in press, 1999.

Rosner R., Tucker W., Vaiana G. S., *ApJ* 220:643, 1978.

Serio S., Peres G., Vaiana G. S., Golub L., Rosner R., *ApJ* 243:288, 1981

Serio S., Reale F., Jakimiec J., Sylwester B., Sylwester J. *A&A* 241:197, 1991.