Red and Blueshifts in Multi-stranded Coronal Loops: A New Temperature Diagnostic

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ABSTRACT

Based on observations from the EUV Imaging Spectrometer (EIS) on board Hinode, the existence of a broad distribution of blue and red Dopplershifts in active region loops has been revealed: redshifts are predominantly observed in the core of active regions, while blueshifts are observed at the edge of active regions. An other significant observation shows that the distribution of Dopplershifts depends on the peak temperature of formation of spectral lines. Using a nanoflare heating model for multi-stranded coronal loops (Sarkar & Walsh 2008, 2009), we reproduce the above Dopplershift observations using spectral lines covering a broad range of temperature (from 0.25 MK to 5.6 MK). We first show that red- and blueshifts are ubiquitous in all wavelength ranges; redshifts/downflows dominating cool spectral lines (from O v to Si vii) and blueshifts/upflows dominating the hot lines (from Fe xv to Ca xvii). By computing the average Dopplershift, we derive a new temperature diagnostic for coronal loops: the temperature at which the average Dopplershift vanishes is the mean temperature along the coronal loop. In addition, the temperature estimate at the footpoints of the loop when the average Dopplershift vanishes is a lower bound of the temperature along the loop. To compare closely with observations, we thus model typical Hinode/EIS rasters with a spatial resolution of 1", an exposure time of 50s and a step of 3". Even if the raster reproduce the global features of up and downflows along the loop, we show that this type of raster cannot provide information on the heating mechanism. We also discuss the fact that observing a single spectral line can lead to false interpretation of the physical processes at play. For instance, an observed increased in blueshift velocity in the Fe xii channel can indicate a cooling event (decrease of energy input). We also investigate the existence of coronal loops having Dopplershifts of opposite signs which could characterise a unidirectional flow along the loop: about 50% of loops have opposite Dopplershifts at the footpoints for the spectral line closest to the mean temperature of the loop.

Subject headings:

1. Introduction

The coronal heating problem is a long-standing issue in solar physics. It aims at explaining the reason why the solar corona has a mean temperature above 1 MK, while the surface of the Sun has an effective temperature of 5800 K, and also how this high temperature can be maintained during a solar cycle. Hence the solar coronal heating problem is to understand how the thermal energy is continuously and uniformly transported and distributed over a large volume like the corona. One of the favorite model is the heating by small bursts of magnetic energy, the so-called nanoflare heating problem as first mentioned by Parker (1983, 1988); this model explains that the coronal plasma can be heated to high temperatures with a high rate of occurrences of uniformly distributed nanoflares explaining the sustainability of the heating. Parker’s idea has been developed for coronal loops in active regions in which the main source of magnetic energy is located, and with the wealth of observations in different wavelength ranges, which provide strong observational constraints...
By extension, the nanoflare model refers to the heating of loops by a series of energy releases, and does not refer to any particular mechanisms generating these bursts of energy (e.g., magnetic reconnection, wave mode coupling, turbulence). Even if they account for a small fraction of the total coronal heating budget, the understanding of the heating of coronal loops is crucial for solving the global coronal heating problem: loops are well observed in a wide variety of temperature bands and thus their thermodynamical properties are well constrained. The state-of-the-art of this field of research has been reviewed in length by Reale (2010). Despite the large number of loop observations, their nature is still debated: single field line versus multi-stranded flux bundle (e.g., Curtain et al. 2007), isothermal versus multithermal (e.g., Schmelz et al. 2009). In this study, we define a loop as a multistranded flux bundle implying a multithermal plasma. The loop temperature is sustained by a series of small, short releases of energy mimicking the nanoflare model.

Downflows have been commonly observed in quiet-Sun and active regions since Doschek et al. (1976) using Skylab spectroscopic observations. The authors concluded that, for temperatures between 70000 K and 200000 K, the plasma responsible for the downflows was producing more emission in the UV than the plasma responsible for upflows. However, these observations did not shed light on the nature of those Dopplershifts (transient or persistent). Our work is motivated by recent observations of high blueshift patches in active region outskirts reported by del Zanna (2008) and Baker et al. (2009) lasting for several hours. Murray et al. (2010) have simulated the emergence of an active region similar to the one studied by Baker et al. (2011). The authors found that the blueshifts appear in the surrounding of the active region during the expansion phase of the emergence process and are also owed to the presence of a coronal hole interacting with the emerging flux. Baker et al. (2011) showed that the active region exhibits an enhancement of the blueshifts in the Fe XII line at 194 Å prior to the eruption. Hence, the increase in blueshifts has been considered as a precursor of the Coronal Mass Ejection (CME) associated with this active region.

The complex topology of the magnetic field is also a crucial ingredient of the scenario developed by del Zanna et al. (2011) to explain blueshifts observed at the edges of an active region. The authors have combined EUV and radio observations to determine that the blueshifts are occurring at the interface of open and close magnetic field lines, and are sustained by the continuous magnetic reconnection thanks to the growth of the active region. Based on a nanoflare model, our goal is to determine if such a model allows us to show the ubiquitous existence of blueshifts and what are their intrinsic properties at different wavelengths compared to the observations above mentioned. We also rely on the observations by Warren et al. (2011) showing that, within an active region, the amount of blue- and redshifts is strongly dependent on the peak temperature of the spectral line observed. Cooler is the spectral line, redder is the Doppler distribution, and reciprocally, hotter is the spectral line, bluer is the Doppler distribution. Warren et al. (2011) have used the capabilities of Hinode/EIS to obtain simultaneous raster in several EUV spectral lines covering a wide range of coronal temperatures (from Si VII at 0.63 MK to Fe XV at 2.2 MK). The authors found that the Si VII observations of an active region are dominated by redshifts while hotter lines are dominated by blueshifts. It is also worth mentioning that it seems that the Fe XII and Fe XIII lines correspond to a peak in the distribution of blueshifts, and hence less blueshifts are observed at higher temperatures while blueshifts are still dominating the distribution of Dopplershifts in the active region. Similar observations have also been reported by del Zanna (2008) and Tripathi et al. (2009). Flows in moss have also attracted a lot of interest. The moss observed in active regions corresponds supposedly to the emission of hot, core coronal loops at the transition region (Berger et al. 1999; de Pontieu et al. 1999; Martens et al. 2000; Tripathi et al. 2010). In terms of Dopplershifts, the moss is dominated by redshifts for ions from C IV to Fe XIII, that is to say, from the transition region to the corona at 1.78 MK (Tripathi, Mason, and Klimchuk 2012; Winebarger et al. 2013).

In Section 2 we describe the nanoflare heating model used to determine the Dopplershifts in hot and warm loops. We describe the different spec-
Fig. 1.— The radiative loss function $Q(T)$ between 10000 K and 10 MK.

neutral lines used to simulate the observed Doppler-shifts (Section 3.1). In Section 3.2, we present the spatial distribution of Doppler-shifts for the different spectral lines. In Section 4, we present a new diagnostic method to estimate the temperature of coronal loops based on multi-spectral observations. In Section 5, we discuss the properties of blue- and redshifts for hot and warm loops as seen by an imaging spectrometer rastering a region of the Sun such as Hinode/EIS. The conclusions are drawn in Section 6. In the Appendices A and B, we describe the effects of changing the observer point of view on the measurements of Doppler-shifts and the temperature diagnostic, and we model the rasters for IRIS and Solar Orbiter/SPICE wavelengths.

2. Multi-stranded model for coronal loops

2.1. Setup of the Model

The corona is a highly conducting medium with a low plasma $\beta$ (ratio of the plasma pressure to the magnetic pressure). Therefore the plasma dynamics occurs along magnetic field lines, and there is no or limited feedback between the magnetic field and thermodynamic parameters. These particular physical conditions justify modelling coronal loops with the hydrodynamic equations projected along the loop and, neglecting perpendicular thermal conduction. Even if magnetic field lines have to satisfy the solenoidal condition, we neglect the variation of the loop radius with height which should occur along a coronal loop with a magnetic field decreasing with height. Despite the increasing number of observations of coronal loops, there is no evidence that the radius or width of a loop increases with height (Watko and Klimchuk 2006; López Fuentes et al. 2006).

A coronal loop is defined as a collection of 128 strands. Each individual strand ($i$) evolves following the time-dependent one-dimensional (1D) hydrodynamic model satisfying mass, momentum, and energy conservation as well as the perfect gas law:

\[
\frac{D\rho_i}{Dt} + \rho_i \frac{\partial v_i}{\partial s} = 0, \quad (1)
\]

\[
\frac{Dp_i}{Dt} = -\frac{\partial \rho_i}{\partial s} + \rho_i g + \rho_i v \frac{\partial^2 v_i}{\partial s^2}, \quad (2)
\]

\[
\rho_i \frac{\gamma}{\gamma - 1} \frac{D\rho_i}{Dt} \left(\frac{\rho_i}{p_i}\right) = \frac{\gamma}{\gamma - 1} \frac{\partial^2 T_i}{\partial s^2} - n_i^2 Q(T_i) + H_i(s,t), \quad (3)
\]

\[
p_i = \frac{R}{\mu} \rho_i T_i, \quad (4)
\]

where $\rho_i$, $p_i$, and $T_i$ are the density, pressure and temperature of the strand $i$ ($i = 1, \ldots, 128$), $v_i$ is the plasma flow along the strand, $s$ is the curvilinear abscissa along the semi-circular loop ($\gamma = 5/3$ and $\mu = 0.6$). The number density $n_i$ (cm$^{-3}$) is $10^{21} \rho_i$ (kg m$^{-3}$). The numerical code is based on the Lagrangian remap method developed by Arber et al. (2001), and further developed for multi-stranded coronal loops by Sarkar & Walsh (2008, 2009).

The geometry of the loop is described by a total length of 100 Mm, a radius of 2 Mm. Assuming that the loop is semi-circular, the height of the loop is thus 32 Mm. The height of the loop is less than the typical pressure scale-height of a coronal plasma at 1 MK justifying the use of a constant gravity, $g$. The 100 Mm loop is divided into two main areas: a transition region (width of 5 Mm) in which the temperature is increasing rapidly and the density decreasing rapidly, and a corona. Therefore the coronal part of the loop has a length of 90 Mm. In addition, there is a chromospheric part at each footpoint of 5 Mm acting as a reservoir of plasma. We consider a total duration of 4 hours 30 min with outputs extracted every 1 s. The Lagrangian remap time-step depends on
Fig. 2.— Distribution of bursts along a single strand (#54) with a minimum energy of $10^{24}$ erg and a uniform heating. Each line segment indicates the duration of the burst, and the color-coding the amount of energy injected.

The energy equation contains three terms on the right hand side: the thermal conduction with $\kappa(T) = \kappa_0 T^{5/2} = 9.2 \times 10^{-7} T^{5/2}$ being a function of the temperature following Spitzer formula, the radiative cooling term where $Q(T)$ is a piecewise function (see Figure 1) adapted from Cook et al. (1989), and the heating source term $H_i(s, t)$. The latter is defined as successive heating bursts with an energy of similar order as a nanoflare. Each strand is subject to 64 bursts which are randomly distributed in time, location, duration, and amount of energy injected: in Figure 2, we plot the distribution of bursts for a chosen strand (for the sake of clarity). In the following, we perform two experiments: (1) with a minimum of energy per bursts of $10^{23}$ erg for a total energy of $5.13 \times 10^{27}$ erg, (2) with a minimum of energy per bursts of $10^{24}$ erg for a total energy of $5.13 \times 10^{28}$ erg. As depicted in Figure 3, the random distribution of bursts along a strand is localised at the footpoint of the strand (fp), uniformly distributed along the strand (uni), or localised at the apex of the strand (ap).

2.2. Thermodynamic Properties of the Loop

The initial temperature is constant in the corona at 1 MK, and linearly decreasing from the bottom of the corona to the top of the chromosphere (10000 K). In Figure 4, we plot the density profile along the loop which describe the initial density as an hydrostatic equilibrium (exponential decay with height with a constant pressure-scale height). The thermodynamic evolution of the loop is defined by the evolution of the density $\rho$ (sum of strand density $\rho_i$) and the temperature $T_{EM}$. The multi-stranded loop is characterised by an emission measure weighted temperature:

$$T_{EM}(s, t) = \frac{\sum_{i=1}^{128} \rho_i^2(s, t) T_i(s, t) dl(s)}{\sum_{i=1}^{128} \rho_i^2(s, t) dl(s)}.$$
The two experiments conducted here lead to two different types of loop differentiated by their thermal properties: (i) a warm loop with a mean temperature of 1.5 MK and an apex temperature of at most 2.2 MK, (ii) a hot loop with a typical temperature around 3 MK for the different heating locations and with an apex temperature of about 4 MK. It is worth noting that our definition of warm and hot loops is independent of the definition currently accepted in the observational framework (see Reale 2010). The time evolution of \(T_{EM}\) for the two loop models and the different heating locations is depicted in Figure 5 along the loop (solid black curves), and at the apex of the loop (light-gray curves). It is remarkable that the temperature reaches an equilibrium value rapidly after the start of the computation. In the following, we will consider that the loop has reached an equilibrium for all models one hour after the beginning of the simulation (solid vertical line in Figure 5). We also note that the loop is filled by the heated plasma at a different rate for both cases: as expected, it takes a much longer time (15–20 minutes) for the warm loop to reach reasonable thermodynamic parameters, compared to less than 10 minutes for the hot loop. There is no significant time delay in achieving an equilibrium between the three different heating locations.

We plot the profiles of density (Figure 6 top) and temperature (Figure 6 bottom) average over two hours for the two experiments (hot loop in black, warm loop in gray) and for the different heating locations (\(fp\): solid line, \(uni\): dot line, and \(ap\): dashed line). For the hot loop, the density at the loop top decreases from \(3.4 \times 10^{-12} \text{ kg m}^{-3}\) for the \(fp\) heating to \(3.1 \times 10^{-12} \text{ kg m}^{-3}\) for the \(ap\) heating, while the temperature increases from 3.3 MK to 4 MK. As noted by Reale & Peres (2000) in simulating a multi-stranded loop, the \(fp\) heating can mimic a coronal loop with a constant temperature due to the flatness of the temperature profile. The temperature profiles are similar to those modelled by Galsgaard et al. (1999) in a numerical experiment of flux braiding. Although the change in density and temperature is 10—20% between the different heating locations, the observation of coronal loops does not permit a clear identification of the heating source (see e.g., Priest et al. 1998; Mackay et al. 2000; Reale 2002). It is also important to notice the difference in temperature at the apex of the loop depending on the location of the heating deposition: the apex temperature of the hot loop is 3.3 MK for the \(fp\) heating and 4 MK for the \(ap\) heating. This difference results from the small temperature gradients at the apex compared to the coronal footpoints near the transition to chromospheric temperatures, and also from the bidirectional flows generated by the energy deposition which over-heats the loop top.
3. Modelling Synthetic Observations

3.1. Spectral Lines

In order to compare the behavior of the simulated Dopplershifts and the observed ones, we select ten spectral lines with a peak emission temperature \( T_e \) between 250 000 K and 5.6 MK (see Table 1) such as:

- the spectral lines appear in Warren et al. (2011);
- the spectral lines are also in the list of Hinode/EIS spectral lines suggested by Young et al. (2007) to make sure that the selected spectral lines are not too difficult to interpret: for instance, we do not consider the \( \text{Fe} \times i \) line at 188.21 Å studied by Warren et al. (2011) due to its complex blend. Some properties of these spectral lines observed in active regions or quiet-Sun regions can be found in Brown et al. (2008);
- we extend the thermal coverage of the spectral lines, in particular, by adding two relatively cool lines (\( \text{O} \ \text{V} \) and \( \text{Mg} \ \text{V} \)) and two hot lines (\( \text{Ca} \ \text{XV} \) and \( \text{Ca} \ \text{XVII} \)).

Relying on the CHIANTI 6.0 database (Dere et al. 2009), the contribution functions \( C_{sp} \) for each transition are depicted in Figure 7.

![Figure 7](image)

**Fig. 7.**— Contribution functions \( C_{sp} \) for the EUV spectral lines considered in this paper. The temperature range is the same as for the radiative loss function (see Figure 1).

| Spectral Line | Wavelength (Å) | \( T_e \) (log(K)) |
|---------------|----------------|--------------------|
| \( \text{O} \ \text{V} \) | 248.46 | 5.4 |
| \( \text{Mg} \ \text{V} \) | 276.58 | 5.5 |
| \( \text{Si} \ \text{VII} \) | 275.36 | 5.8 |
| \( \text{Fe} \ \text{X} \) | 184.54 | 6.05 |
| \( \text{Fe} \ \text{XII} \) | 195.12 | 6.2 |
| \( \text{Fe} \ \text{XIII} \) | 202.24 | 6.25 |
| \( \text{Fe} \ \text{XIV} \) | 284.16 | 6.35 |
| \( \text{Fe} \ \text{XV} \) | 262.98 | 6.4 |
| \( \text{Ca} \ \text{XV} \) | 200.97 | 6.65 |
| \( \text{Ca} \ \text{XVII} \) | 12.85 | 6.75 |

**Table 1:** Characteristic parameters of the selected spectral lines

![Figure 8](image)

**Fig. 8.**— Statistical and spatial distributions of Dopplershift velocities for the warm loop (\( f_p \) heating) once the equilibrium is established for all 10 wavelengths used in the paper (see Table 1).

3.2. Dopplershift Measurement

In order to compute the Doppler velocity for a given spectral line, we need to proceed in two steps. The first step is to compute the velocity for a given transition with a contribution \( C_{sp} \) using the following equation:

\[
v_{sp}(s, t) = \frac{\sum_{i=1}^{128} \rho_i^2(s, t) v_i(s, t) C_{sp} \ ddll(s)}{\sum_{i=1}^{128} \rho_i^2(s, t) C_{sp} \ ddll(s)}.
\]
The $C_{sp}$ contributions are depicted in Figure 7 for the ten spectral lines used in this paper. The second step is to define the geometry of the loop and in particular the observer point-of-view in order to project the velocity and to obtain the red (downflows) and blue (upflows) Dopplershifts.

There is not a significant difference between the three different heating locations in terms of the analysis of Dopplershifts, thus we are just showing the results for the $fp$ heating as it is the most favorable location for heating the corona: we reckon that the complexity of the magnetic field which can lead to continuous nanoflare occurrence is most likely to be located near the chromosphere (Régnier et al. 2008) making magnetic reconnection and wave mode coupling two mechanisms highly efficient in this region. The apex and uniform heating locations lead to similar conclusions.

In Figure 8, we plot the Dopplershift velocity distribution and their associated spatial distributions in the ten spectral lines described above. The red and blue colors indicate the red and blueshifts respectively. The Dopplershift distributions are plotted between -40 and 40 km $s^{-1}$, while the spatial distributions are scaled between -20 and 20 km $s^{-1}$. It is clear from both types of distributions that there is an obvious behavior for the Dopplershift to be bluer when the temperature of the spectral line increases. Even if not always statistically significant, blue- and redshifts are ubiquitous in all spectral lines. The distribution of Dopplershift is double-peaked for the O V and Si VII lines. The Dopplershift distribution and the Dopplermaps are clearly dominated by redshifts for cool lines from O V to Fe X, while blueshifts start to appear in the Fe XII lines and developed in hotter lines. The maximum of redshift velocity is less than 10 km $s^{-1}$ for all spectral lines except for the Ca XV and Ca XVI lines where the maximum reaches 20 km $s^{-1}$. The tail of the blueshift distribution is getting more and more prominent when the spectral line temperature increases, from a maximum of 10 km $s^{-1}$ in Fe XII to 30 km $s^{-1}$ in Ca XVII.

In Figure 9, we plot, for the hot loop, the same quantities as in Figure 8. The Dopplershift distributions show a double-peak distribution from the O V line to the Fe XII line. As in the warm loop case, blueshifts and redshifts are ubiquitous at all wavelengths. For the cooler lines (below Fe XIII), the blueshifts are located in the top part of the loop (between -20 and 20 Mm), while for hotter lines (from Fe XV to Ca XVII) the blueshifts are located at the footpoints. The maximum velocity in absolute value oscillates between 6 km $s^{-1}$ and 30 km $s^{-1}$. However, the maximum of the blueshift velocity as in the Ca XVII line can be greater than 40 km $s^{-1}$, while the maximum of the redshift velocity (Mg V line) is about 30 km $s^{-1}$. The maximum redshift velocity is less than 10 km $s^{-1}$ except for the Mg V and Si VII lines in which it reaches about 30 km $s^{-1}$.

It is common to define “evaporation” in a plasma as a rapid increase of temperature and decrease in density, and “condensation” in a plasma...
as a rapid decrease of temperature and increase in density. Those two main thermodynamic effects are responsible for the blue- and redshifts observed in coronal loops located near the footpoints of the loop. The redshifts (downward motions) in cool spectral lines characterise the plasma condensation flowing from coronal temperature to chromospheric temperature. The blueshifts (upward motions) in hot spectral lines characterise the plasma evaporation of chromospheric material into the coronal medium.

4. Temperature Diagnostic

4.1. Hot vs Warm Loop

We now compare the properties of the hot and warm loops in terms of Dopplershift distribution. In Figure 10, we plot the amount of blue and redshifts for the ten wavelengths sorted by increasing temperature $T_e$ and for the three heating models ($fp$, uni, and ap). The statistics of Dopplershifts along the whole loop (Figure 10 top row) show that blueshifts (and redshifts) are ubiquitous in all wavelengths, and also that the cooler lines exhibit redder Dopplershifts than the hotter lines as mentioned in the previous section. In addition, we notice that there is a strong increase in the percentage of blueshifts for the Fe X line for the warm loop (left) and for the Fe XV line for the hot loop (right). Similarly, there is a maximum of blueshifts at about 80% in the Ca lines for the hot loop, while this maximum is for the Fe XV and Fe XVI line for the warm loop. The warm loop distribution of blueshift decreases above the Fe XVI line. The maximum of blueshifts is located near the maximum temperature of the loop. Those two significant points indicate that the distribution of blueshifts is strongly influenced by the temperature of the loop: the distribution of blueshifts is similar for both hot and warm loop with the center of the distribution corresponding to the maximum temperature of the loop. In Figure 11, we also plot the contribution of the footpoints (middle row) and the apex (bottom row). The Dopplershifts at the footpoints are only redshifts for cool lines and abruptly increase to 80-90% from the Fe XV line for the hot loop and from Fe X line for the warm loop. The footpoint distribution peaks for the Fe XVI line for the hot loop and for the Fe XII line for the warm loop. The peak of the footpoint distribution corresponds to the mean temperature of the loop. The Dopplershift distribution at the apex of the loop (bottom row) is relatively flat at about 40-45% of blueshifts.

It is foreseen that the temperature of a loop can be estimated by studying the distribution of blue and redshifts along a loop or even just at the footpoint. Therefore multi-wavelength spectroscopic observations of a selected set of spectral lines covering a broad range of temperature can provide a good estimate of the mean and/or maximum temperature of a coronal loop. This study also shows that the estimated temperature depends on the section of the loop that is observed: the observation of the footpoints will provide a mean temperature while observing the entire loop will provide the maximum of temperature.

Fig. 11.— For the warm loop: (top row) average Dopplershift along the loop (left) and at the footpoint (right), and (bottom row) average redshifts (positive) and blueshifts (negative) along the loop (left) and at the footpoints (right).

Fig. 12.— Same as Figure 11 for the hot loop.
Fig. 13.— (Left) Average Dopplershifts at the footpoint of the warm (blue) and hot (red) loops ($fp$ heating), and the average Dopplershift values (black curve) obtained by Tripathi et al. (2009); (Right) Percentage of blueshift at the footpoint (solid) and along the loop (dash) for the warm (blue) and hot (red) cases. The dashed black lines indicate the crossing of the curves with the vanishing average Dopplershift or the 50% level.

In Figure 11 for the warm loop and Figure 12 for the hot loop, we plot the average Dopplershift velocity (top row) for the entire loop (left) and at the footpoints (right), as well as the mean positive and negative Dopplershift velocities (bottom row) for the entire loop (left) and at the footpoints (right). We plot the average value at the footpoints as this is often the quantity which can be derived from the observations. By comparing the three different heating locations ($fp$, $un$ and $ap$), there is no obvious changes for the hot loop from one heating model to the other; there is a slight discrepancy between the model for hot lines (from Fe xvi to Ca xvii). While for the warm loop, the discrepancy between the models is stronger for hot lines of about 5 km s$^{-1}$. For the hot loop, the average Dopplershift vanishes at about the Fe xv line for the loop and between the Fe xiii and Fe xv lines for the footpoints. Similarly for the warm loop, the average Dopplershift vanishes at about the Fe x line for the loop and between the Si vii and Fe x lines for the footpoints. Therefore the location where the average Dopplershift vanishes depends strongly on the temperature of the loop. The evolution of the average positive and negative Dopplershifts is consistent with the evolution of the width of the Dopplershift distributions as depicted in Figures 9 and 8. For the average velocity above the Fe xvi, the contribution of the footpoints is large with a maximum of -30 km s$^{-1}$ for blueshift and 11 km s$^{-1}$ for redshift in the Ca xvii line. For the warm loop (Figure 11 bottom row), the distribution is shifted towards lower temperatures, and the distribution at the footpoint exhibits a maximum average redshift in the Ca xv line at 12 km s$^{-1}$ while the average blueshift reaches -20 km s$^{-1}$.

Tripathi et al. (2009) have studied two areas observed by Hinode/EIS and thus have computed the average Dopplershift in these regions. They show that the average Doppler velocity decreases with increasing temperature (with the exception of a Fe xiv line). In their examples, the average Dopplershift vanishes for a temperature between the Si vii and Fe xii line. Thus following our model these regions will correspond to warm loops. Tripathi et al. (2009) also noticed that, based on the emission measure loci method, the temperature of the observed loops is between 0.8 and 1.5 MK consistent with our study detailed above.

4.2. Tool for temperature diagnostic

Using the analysis performed in the previous Section, we develop a new tool to approximate the temperature of a coronal loop which can be used in conjunction with observations.

It appears that the evolution of the average Dopplershift at the footpoints with increasing temperature (see Figure 13 left) intersects the zero-value Dopplershift at approximately the mean temperature of the loop. In Figure 13 left, we plot the average Dopplershift curves for the warm (blue) and hot (red). The estimated temperatures (indicated by the vertical dash lines) are $T_{\text{warm}} = 1.35$ MK, and $T_{\text{hot}} = 2.45$ MK, which have to be compared to the temperatures mentioned in Section 2.2 i.e., $T_{\text{mean}}^{\text{warm}} = 1.5$ MK, and $T_{\text{mean}}^{\text{hot}} = 3$ MK. It is worth noting that our estimate of the temperatures relies on piecewise linear interpolation between consecutive points, which, in this case, tends to give a lower value of the mean temperature. To confirm our temperature diagnostic, we also plot the results obtained by Tripathi et al. (2009) as a black solid curve in Figure 13 left for the footpoints of coronal loop using the Hinode/EIS spectrometer. The estimated temperature of the coronal loop is $T = 923000$ K.
Using an EM loci method, Tripathi et al. (2009) have estimated that the temperature of coronal loops in the observed region is between 800000 K and 1.5 MK depending on the height of the loop. Therefore, the method proposed above is a good approximation of the mean temperature of coronal loops. However, the temperature diagnostic can only be performed from a series of spectral lines covering a broad range of temperature.

We also notice that the mean temperature of the loop can be estimated from the percentage of blueshifts at the footpoint or along a coronal loop. In Figure 13 right, we plot the percentage of blueshift as a function of temperature for the warm (blue) and hot (red) cases computed at the footpoint of the loop (solid curve) and along the loop (dash curve). The 50% level of blueshift crosses the different curves at an approximation of the mean temperature similar to the average Dopplershifts at the footpoints (see Figure 13 left). That is to say, \( T_{\text{warm}} = 1.4 \) MK, and \( T_{\text{hot}} = 2.5 \) MK. However, the percentage of blueshifts is not a quantity accessible with the current observations due to the spatial resolution of the instruments. One possible proxy will be the variation in time of the Dopplershift at a given location assuming that the loop is stable, and considering that the exposure time is small (typically of the order of 1–2 s).

5. Discussion

5.1. Simulated Hinode/EIS Raster

5.1.1. Modelled Loop at EIS Spatial and Time Scales

To compare our simulation results with the Hinode/EIS observations, we first construct a raster in a similar way to EIS. We here raster the loop assuming that the loop is observed from the top. In these simulated observations, the 100 Mm semi-circular loop correspond to a loop of 80 Mm. We resample the simulated loop in order to obtain a pixel size of 1″ and an exposure time of 50 s. We neglect the CCD camera reading time. We simulate the observations by Warren et al. (2011) by constructing a raster with a 3″ step between successive observations. The stepping is introduced to speed up the scanning of the region. As mentioned in Warren et al. (2011), the EIS raster takes about 52 minutes for scanning a length of 180″ (about 130 Mm). For our simulated loop of 80 Mm long in the corona, it will take about 30 min. The data are then interpolated between two consecutive exposure time as in Warren et al. (2011). The resulting rasters for each spectral lines are shown in Figure 14 for the warm loop, and in Figure 15 for the hot loop. In both Figures 14 and 15 we construct two consecutive rasters. The first raster starts at \( t = 3600 \) s and lasts for 30 min, so the second one starts at \( t = 5400 \) s for the same duration. The Dopplershift distribution depends on the time the raster has started. For instance, while the cool lines exhibit only redshifts for the first raster (Figure 14 left), the second raster (Figure 15 right) evidence blueshifts in the Mg v and Si vii lines. The distributions are...
smooth due to the interpolation between consecutive exposure times. Qualitatively, the rasters indicate the same behavior as the modelled loop: redshift dominated for cool lines below Fe xii and Fe xv for the warm and hot loop respectively, and blueshift dominated above Fe xii and Fe xv for the warm and hot loop respectively. The strong blue and redshifts are located at the footpoints of the loop owe to a combined effect of high density and integration along the line-of-sight. There is no symmetry between the two footpoints of the loop because of the randomness of the nanoflare heating deposition.

Warren et al. (2011) reported Hinode/EIS observations of two different active regions with a broad temperature coverage from Si vii to Fe xv (nine different lines). Both observations show evidence of temperature dependence of the downflow and upflow regions: downflows (redshifts) are dominating cool lines such as the Si vii, while upflows (blueshifts) dominate the hot lines (from Fe xi to Fe xv). Their first observation (see Figure 3 of Warren et al. 2011) shows a clear sudden increase of the blueshift in the Fe xi line, while their second observation (see Figure 4 of Warren et al. 2011) shows an increase in the Fe x line. According to the above results for the multistranded model (see Figures 15 and 14), we can complement Warren et al. (2011) article by concluding that the active region loops are warm loops with a characteristic temperature at the apex of about 2 MK, and that the overall temperature of the first active region is larger than the temperature of the second active region.

5.1.2. Comparing Different Types of Observations

We now compare the typical Hinode/EIS raster with a 3” step with two other possible observations: (i) the instantaneous observation with an exposure time of 50 s, (ii) the dense raster without the stepping of 3” (consecutive 50 s exposures). The latter raster takes about 2 hours to be completed. The corresponding rasters are depicted in Figure 16 for the warm loop and in Figure 17 for the hot loop. All three types of observations are reproducing the main features of the Dopplershifts: (i) cool spectral lines dominated by redshifts and hot spectral lines by blueshifts, (ii) the blueshifts in hot lines are located at the footpoints, (iii) the warm and hot loops have a blueshift distribution dependent on their characteristic temperature. However, the Dopplershift distribution for the instantaneous observation (left) is smooth owe to the continuity of the different physical quantity at a given time, the distribution of 3” step raster is also smooth due to the interpolation, while the distribution of the 1” continuous raster is patchy due to the different times of observations and the bursty nature of the heating mechanism (and the possible occurrence of shocks). Thus, only a series of instantaneous observations or the dense raster with sufficient time and spatial resolutions evidence the nature of the heating mechanism along the loop.

Fig. 16.— Dopplershift for simulated Hinode/EIS along the warm loop with a 1″ resolution and a 50 s exposure time, (left) instantaneous observations (no raster), (middle) raster of duration \(\approx\) 2 hours, (right) raster with a 3″ step and of duration about 30 minutes.

Fig. 17.— Same as in Figure 16 for the hot loop.
5.2. A Mechanism for Blueshift Increase

Recently, Baker et al. [2011] have observed the increase in the upflow velocity in an active region prior to a CME. The authors have interpreted this increase in the Fe XII line as a precursor of the eruption. They claim that the increase is due to the continuous expansion/emergence of the active region leading to the interaction between the expanding magnetic field and the nearby coronal hole magnetic field. These interpretations have been confirmed by simulated flux emergence from the bottom of the convection zone to the corona, and by making close comparison between the model and the observations (Murray et al. 2010; Harra et al. 2011). Based on our nanoflare model of hot and warm loops having the same geometrical properties, we are able to give another possible interpretation to the increase of upflows in a single wavelength range. In Figure 18, we plot the Dopplershift distributions for a hot loop (solid line) and a warm loop (dashed line) in the Fe XII line, and for the \( f_p \) heating. The increase of the upflow velocity can be explained by a cooling of the loop keeping the loop length constant: the decrease of the amount of energy injected in the warm loop model being 10 times less than the energy input for the hot loop model. Our study also shows that the tomographic or multi-thermal observations of a loop is required to better understand the thermodynamical properties of the observed loop, and also to analysis its time evolution.

Furthermore, del Zanna et al. [2011] supported the conclusions of Baker et al. [2011] by studying the relationship between persistent blueshifts in active regions, metric radio noise storms and the magnetic topology of the coronal magnetic field. They conclude that the continuous growth of the active region is sustaining a steady reconnection rate across separatrix surfaces. The magnetic reconnection occurs between open field lines in the outskirts of the active region and closed loops in the core. As their conclusions are also based on very few spectroscopic observations to derive the Dopplershift distribution (mostly in a Fe XII line), the viable mechanism that the authors described can certainly applied to some field lines but surely not to all closed field lines. The multistranded model suggests that the existence and evolution of blueshifts for closed loops is controlled by the amount of energy input: the fan field lines which are blueshifted in the Fe XII lines are warm loops, while the core field lines which are still redshifted in the Fe XII are hot loops. The latter is confirmed by the X-rays observations (see Figure 3 in del Zanna et al. [2011]).

In terms of modelling, Bradshaw et al. [2011] have modelled the possible interchange-reconnection model which can explain the increase of blueshifts in coronal loops. Based on a 1D hydrostatic model, the authors justify the interchange-reconnection by the increase of blueshift velocities with the increase of the ionisation of iron lines with typical blueshift velocities of 10 km s\(^{-1}\) for Fe X and Fe XII, 20 km s\(^{-1}\) for Fe XIV, and 40-50 km s\(^{-1}\) for Fe XVI. These characteristic velocities are similar to the one obtained for the warm loop modelled with the multi-stranded model of a single close loop with footpoint heating (see Figure 8).

By modelling a warm and hot loop, we thus showed that there are alternative mechanisms to the observed increased in blueshifts in the Fe XII line. However, the estimated Dopplershifts from our model do not reproduce the large Dopplershift velocity reported in del Zanna et al. [2011] and Baker et al. [2011]. Nevertheless, we would like to issue a warning in the physical interpretation of Dopplershifts using a single spectral line; several spectral lines covering a broad range of temperature are required to understand the physics happening within coronal loops.
Fig. 19.— Occurrence (in percentage) of coronal loop having the opposite Dopplershift (blue or red) at the footpoints for all spectral lines. The percentage is computed for the warm (gray) and hot (dark) loops and for all three heating locations.

5.3. Blue and Redshifted Footpoints

Using the capabilities of Hinode/EIS combined with magnetic field extrapolations, Boutry et al. (2012) have shown that mass flows can be observed in large-scale loops connecting two distant active regions: one footpoint being blueshifted, the other one being redshifted. From the simulated Hinode/EIS rasters, we deduced that loops with a blue and a redshifted footpoint can be observed. In Figure 19, we plot the percentage of loops with an opposite sign of Dopplershift at footpoints for the warm (gray) and hot (dark) loop models and also for the three different locations of heating (fp: solid line, uni: dotted line, ap: dash line). As for the statistical study of Dopplershifts in Section 5.2, the percentage of loops with footpoints of opposite Dopplershifts depends on the spectral line and on the mean temperature of the loop: about 50% of loops have opposite Dopplershifts in the Fe X line for the warm loop and in the Fe XV line for the hot loop. The peak in percentage appears for the same spectral line for each source of heating. None or only a small amount of loops (< 5%) has opposite Dopplershifts for spectral lines cooler than the mean temperature of the loop, whilst the percentage stays above 10% for spectral lines hotter than the mean temperature (Fe XII for the warm loop and Ca XV for the hot loop). The change in percentage between a uniformly and footpoint heated loop is small which makes both heating locations difficult to distinguish, whilst, for appropriate spectral lines, the percentage for the apex heated loop is significant (more than a factor of two less).

6. Conclusions

We have complemented the work of Sarkar & Walsh (2008, 2009) regarding the thermodynamic properties of coronal loops defined a collection of strands. We have computed the physical properties of a 100 Mm loop with two different energy inputs with a particular focus on the Dopplershifts distribution for different spectral lines. The recent Hinode/EIS observations have put forward the existence of both blueshift and redshift velocities in active region loops (del Zanna 2008; Warren et al. 2011), the amount of Dopplershifts depending on the peak temperature of the observed spectral line. The multistranded coronal loop model has reproduced the main observed features: (1) red and blueshifts exist in active region loops of realistic length (100 Mm); (2) the amount of red and blueshifts depends on the peak temperature of the observed spectral line: cooler lines being redder, hotter lines being bluer; (3) the amount of red and blueshifts depends on the mean/average temperature of the loop (as an amalgamation of strands). These properties are now well-known for coronal loops and have been reproduced with other numerical experiments (see, for instance, Taroyan and Bradshaw 2014).

In addition, the 1D multistranded hydrodynamic model offers more information on the spatial and temporal evolution of heated coronal loops, and thus on the physical processes at play. The comparison between the multistranded model and modelled observations leads to the following physical interpretations:

- redshifts in the cooler spectral lines evidence the condensation of the plasma mostly located near the footpoints of the loop: dense plasma cooling;
- blueshifts in the hotter spectral lines is a signature of the evaporation of the plasma: hot plasma evacuate towards less dense regions;
- the coexistence of condensation and evaporation for the entire coronal loop is owed to the multistrandedness nature of the loop.
More importantly for future analysis of multi-spectral observations, this study suggests that it is possible to estimate the mean/average temperature of a coronal loop: the transition from redshift-dominated loop to blueshift-dominated loop gives an estimate of the mean temperature of the coronal loop. As an example, we refer to the study by Li et al. (2014) of two flare loops observed by SDO/AIA and Hinode/EIS. The authors measured the Dopplershifts at both footpoints of two coronal loops related to the flaring process. The Hinode/EIS lines used in their study are Fe x at 184.54 Å (log(T)=6.0), Fe xii at 192.39 Å (log(T)=6.09), Fe xiii at 202.04 Å (log(T)=6.17), and Fe xv at 284.16 Å (log(T)=6.3). From their Figure 2 showing the average Dopplershifts for the spectral lines mentioned above, we can derive from the temperature diagnostic that (assuming a view from the top of the loop):

- the first set of loops has a temperature close to 1 MK for the first half an hour of the observation as the average Dopplershift in all spectral lines is negative;

- the first set of loops is then heated to a temperature above 2 MK for about 1h45min for the northern footpoints and for about 15min for the southern footpoints;

- the second set of loops shows a very different behaviour: the heating of the loop is seen as less and less blueshift-dominated curve for the northern footpoints; whilst the southern footpoints exhibit two consecutive heating events.

- the ordering of the spectral lines is consistent with a top view of the loops for the northern footpoints of both sets of loops; whilst the ordering for the southern footpoints is characteristic of an highly inclined field (see Appendix A).

Our temperature diagnostic allows us to deduce the same properties of the loop plasma than Li et al. (2014). The temperature diagnostic from average Dopplershift measured along the loop or at the footpoints is thus a robust diagnostic of the temperature of the loop. As a study case, the active region moss is observed to be dominated by redshift velocities for spectral lines of peak temperature less than 1.78 MK (Fe xiii) according to Tripathi, Mason, and Klimchuk (2012) and Winebarger et al. (2014). From the temperature diagnostic detailed above, we then conclude that the temperature of the coronal loop associated with moss is above 1.78 MK, which is consistent with the moss being the transition counter of hot core active region loops (Martens et al. 2000; Tripathi et al. 2010).

By studying the Dopplershift velocities, we have also shown that the cooling of a coronal loops can explain the increase of blueshifts observed in active regions. Even if this is an unlikely mechanism, this adds the difficulty of making definitive conclusion from single spectral line observation. And thus we claim that multi-spectral analysis should become the norm for spectroscopic studies.

It is anticipated that the temperature diagnostic can be applied to IRIS and Solar Orbiter/SPICE observations. As notice in Appendix B, the temperature diagnostic will be useful for coronal loops having a temperature less than 1 MK due to the limitation in the spectral lines selected.

Knowing that the coronal loop temperature can be derived using multi-spectral observations in the frame of this multi-stranded model, the future work will be to produce temperature maps within active regions as well as further estimate of the energy release. The temperature diagnostic will fail at locations where the heating mechanism is different than the impulsive release of energy considered in this paper. Therefore, the multi-stranded hydrodynamic model can give us more information on the plausible heating mechanisms at play in active regions.

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A. Viewing Angle Effects

In Section 3.2, we studied the distributions of Dopplershifts when looking at the loop from the top. We now study the distributions when the observer’s direction is making an angle of 20°, 45° and 70° with respect to the vertical direction. In Figures 20, 21 and 22 we plot the Dopplershifts distributions for the ten selected spectral lines.

![Fig. 20.— Distribution of Dopplershift velocities for the hot loop (fp heating) once the equilibrium is established for wavelengths from O V to Ca XVII (see Table 1). The observer direction makes an angle of 20° with respect to the vertical direction.](image)

Comparing the distributions of Dopplershifts for the different viewing angles, we clearly see the increase of blueshifts for spectral lines with increasing peak temperature for angles between 0° and 45°, while this behaviour is not obvious for a viewing angle of 70°. The peak of the distribution of blueshifts is shifted towards larger values when the angle increases: for instance, from about 0 to -2 km s^{-1} for the Fe XII line. Whilst the distribution of redshifts is flattened to reach a more uniform velocity distribution.

In Figure 23 top, we plot the percentage of blueshifts and redshifts regardless of their actual values for the three different viewing angles. As for the distribution, there is a clear increase of the amount of blueshift with the peak temperature of spectral lines for viewing angles between 0° and 45°, while the amount of Dopplershifts is getting more and more evenly distributed with the percentage of blueshift and redshift being around 50% for all the spectral lines.

In Figure 23 bottom, we test our temperature against the change in viewing angle. We thus plot the average Dopplershift for a given spectral line or temperature. The temperature diagnostic that we have defined states that a vanishing average Dopplershift marks the temperature of the modelled coronal loop. The average temperature of the modelled loops is indicated by the dash lines. For a viewing angle of 20°,
the curves of average Dopplershift are similar to those for a viewing angle of 0° (see Figure 13 left). The temperature diagnostic at 30° provides the same temperature as the diagnostic at 0°. For a viewing angle of 45°, the average Dopplershift has been significantly reduced even if the curve has kept the same shape. The average Dopplershift is below 0.5 km s\(^{-1}\) in absolute value. In addition the vanishing average Dopplershift is for a temperature of 1.25 MK for the warm loop and 2.24 MK for the hot loop. This implies a change of about 8% in the estimated temperature of the loops. For a viewing angle of 70°, the curves of average Dopplershift are reversed with a dominant blueshift velocity for the low peak temperature spectral lines. Nevertheless, the temperature diagnostic at 70° is similar to the diagnostic at 0°.

From this analysis of the behaviour of Dopplershifts as a function of the viewing angle, we conclude that our temperature diagnostic is robust for a wide range of viewing angles; however, a moderate viewing angle (like 45°) leads to an increase of the errors on the estimated temperature. On the observational point-of-view, we note that the average Dopplershift for a viewing angle of 45° is small (< 0.5 km s\(^{-1}\)), and thus difficult to observe with the current instrumentation.

### B. Simulated IRIS and Solar Orbiter/SPICE observations

We apply the Dopplershift and temperature analysis to a selection of spectral lines, which could be observed by two spectrographs: the Interface Region Imaging Spectrograph (IRIS), and the SPectral Imaging of the Coronal Environment (SPICE) instrument on board Solar Orbiter.
Fig. 22.— Same as Fig. 20 for an angle of 70° with respect to the vertical direction.

Table 2: Characteristic parameters of the selected spectral lines

| Instrument       | Spectral Line | Wavelength (Å) | $\tau$ |
|------------------|---------------|----------------|-------|
| **IRIS**         | Mg ii         | 2803.53        |       |
|                  | C ii          | 1334.53        |       |
|                  | Si iv         | 1402.77        |       |
|                  | O iv          | 1401.16        |       |
|                  | Fe xii        | 1349.4         | 5.15  |
| **Solar Orbiter/SPICE** | C ii    | 1037.01        | 5.8   |
|                  | O iii         | 703.85         | 6.0   |
|                  | O iv          | 790.20         | 5.15  |
|                  | N iv          | 765.15         | 6.0   |
|                  | O vi          | 1031.91        | 6.3   |
|                  | Ne viii       | 770.41         | 5.8   |
|                  | Mg ix         | 706.06         | 6.0   |
|                  | Si xii        | 499.41         | 6.3   |
Fig. 23.— Distribution of Doppler shift velocities for the warm loop ($fp$ heating) once the equilibrium is established for all 10 wavelengths used in the paper (see Table 1).

B.1. IRIS

IRIS is a multi-channel UV imaging spectrograph dedicated to the study of structures and events in the chromosphere and transition region (De Pontieu et al. 2014). The pixel size is one-sixth of arcsecond along the slit and one-third of arcsecond wide. In Table 2, we list the IRIS spectral lines that are analysed here. This selection includes spectral lines with a characteristic temperature between log($T$) = 4.2 and log($T$) = 5.15 from Mg ii h to O iv, as well as an Fe xii line above 1 MK. The contribution functions for each ion are plotted in Figure 24, top. In Figures 25 and 26, we plot the statistical distribution of Dopplershifts (top row) once the equilibrium is reached, and the time evolution of Dopplershifts along the loop (bottom row) for both the warm and hot modelled coronal loop. The distributions of Dopplershifts are mostly double-peaked with the highest peak being close to zero or blueshifted and the secondary peak being redshifted. The noticeable exceptions are for the Fe xii distribution for the warm loop which is dominated by blueshifts (with a small contribution of redshifts), and the Mg ii h distribution for the hot loop also dominated by blueshifts. The hot loop is also characterized by larger redshift velocities (up to 20 km s$^{-1}$) for C ii, Si iv and O iv than the warm loop.

The Fe xii ion is common to IRIS and Hinode/EIS; however, these are two different transitions with different wavelength: the contribution function of the 195.12Å Fe xii peaks at -23.5 (log scale), while the 1349.4Å line peaks at -27.5. Despite the different atomic transitions, the Dopplershift distributions are almost identical (similar peak velocity, width of the distribution, spatial distribution) for both the warm and hot loops.

To construct the rasters, we assume that the pixels are square and of size $1/3''$. The rasters are compact,
and with an exposure time of 1s and starting at \( t = 3600 \) s and lasts for 4 min. In Figure 27 we plot the simulated IRIS rasters for the warm (left) and hot (right) loops. For the warm loop, the Dopplershifts at the footpoints are dominated by redshifts except for the Fe XII line. Characteristic values of the velocity are between -4 km s\(^{-1}\) and 4 km s\(^{-1}\). The raster for the hot loop leads to the same comments except for the Mg ii line for which the Dopplershifts at the footpoints are dominated by blueshifts. For these rasters, it is worth noting that the Dopplershift velocity is small (\(|v_{sp}| < 2 \) km s\(^{-1}\)), and thus certainly not measurable with current instrumentation, with the exception of the footpoints of the hot loop in C II, Si IV and O IV which can reach a Dopplershift velocity above 4 km s\(^{-1}\) in absolute value.

![Fig. 25.— Distribution of Dopplershift velocities for the warm loop (fp heating) for the five selected IRIS wavelengths: (top row) statistical distribution from 1 hour of the computation, (bottom row) spatial and temporal distribution of Dopplershifts. Red-shifts (resp. blue-shifts) are positive (resp. negative) velocities.](image)

### B.2. Solar Orbiter/SPICE

Solar Orbiter is a collaborative mission between ESA and NASA probing the Sun’s atmosphere as close as 0.28 AU. The Solar Orbiter payload includes in situ and remote sensing instruments (Müller et al. 2013). Here we consider the Spectral Imaging of the Coronal Environment (SPICE) which is an EUV imaging spectrograph remotely characterizing the plasma properties of the chromosphere and corona. We have selected eight spectral lines observed by Solar Orbiter/SPICE (see Table 2) covering chromospheric and coronal temperatures. In Figures 28 and 29, the statistical, spatial and temporal distributions of Dopplershifts are expected following our study of the Hinode/EIS simulations: the cool lines are dominated by redshifts, and hot lines dominated by blueshifts. The cool lines are also double-peaked showing an excess of redshifts around 5 km s\(^{-1}\).

In Figure 30, we plot the simulated rasters for the selected Solar Orbiter/SPICE spectral lines and for
Fig. 26.— Same as Fig. 25 for the hot loop.

the warm (left) and hot (right) loop. The rasters are compact rasters with an exposure time of 4 s and a pixel size of 1’. The duration of the rasters is 320 s starting at \( t = 3600 \) s.

The \( \text{C} \, \text{II} \) and \( \text{O} \, \text{IV} \) ions are common to \textit{IRIS} and \textit{Solar Orbiter}/SPICE.

B.3. Temperature diagnostic

For the warm and hot loops, the temperature diagnostic for our selection of spectral lines is inaccurate for two main reasons: (i) there is a poor coverage of high temperature spectral lines (no line above the \( \text{Fe XII} \) line at 1349.4 Å, and (ii) the linear interpolation between the \( \text{O IV} \) at \( \log(T) = 5.15 \) and the \( \text{Fe XII} \) at \( \log(T) = 6.2 \). However, the temperature diagnostic tools will be appropriate for cool loops at a temperature typically around \( \log(T) = 5.15 \). Note that we did not consider the \( \text{Fe XXIII} \) line at 1079 Å as the peak temperature of the contribution function is above 10 MK (upper limit of the radiative loss function in Figure 1). In Figure 31 left, it is possible to estimate the temperature of the warm loop at \( \log(T) = 6.0 \) when the average Dopplershift vanishes. It is about 25% less than the temperature estimated with \textit{Hinode}/EIS spectral lines.
Fig. 27.— Compact IRIS rasters with 1/3” pixel size and 1 s exposure time for the warm (left) and hot (right) loops.
Fig. 28.— Same as Fig. 25 for the selected Solar Orbiter/SPICE wavelengths (see Table 2).
Fig. 29.— Same as Fig. 28 for the hot loop.
Fig. 30.— Compact Solar Orbiter/SPICE rasters with 1” pixel size and 4 s exposure time for the warm loop (left) and the hot loop (right).
Fig. 31.— Temperature diagnostic for the warm (blue) and hot (red) loops for IRIS (solid lines) and Solar Orbiter/SPICE (dashed lines): (left) average Dopplershift at the footpoints, (right) percentage of blueshifts at the footpoints. The vertical dashed lines indicate the temperatures estimated using the Hinode/EIS spectral lines: log(T) = 6.13 and log(T) = 6.39.