The contribution of type II spicules to the transition region radiative output

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Abstract

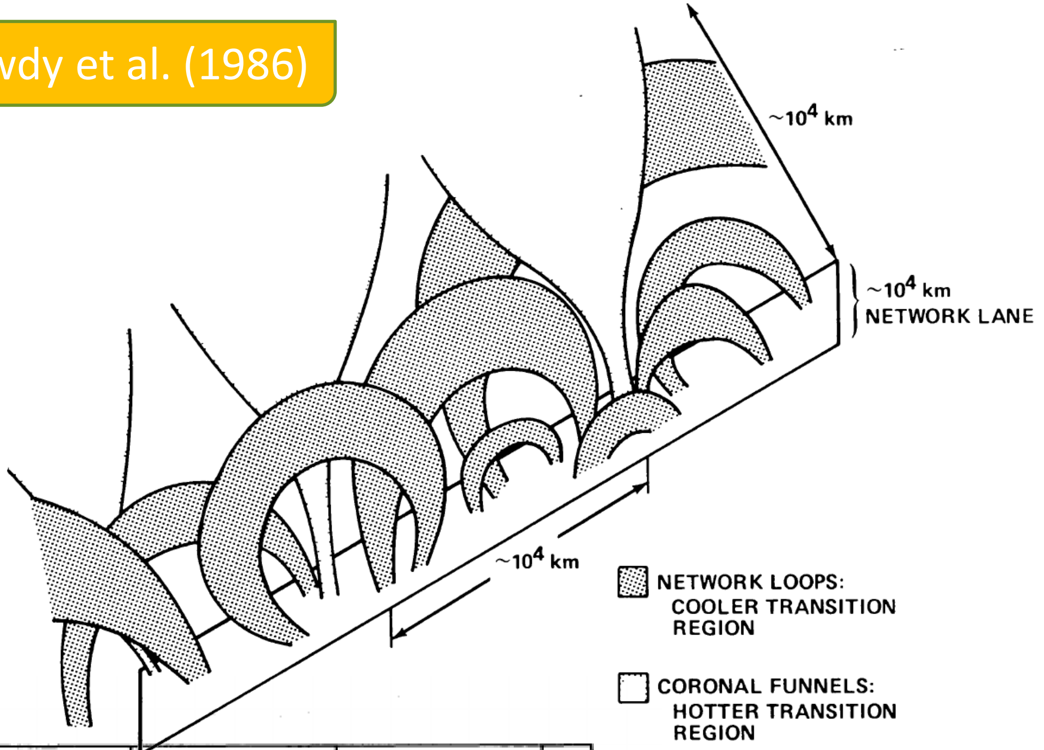
The contribution of spicules, in particular of type II spicules, to the input of mass and energy to the magnetically closed corona is still an actively debated topic. The evidence provided by modern instrumentation (IRIS, for instance) does show that at least type II spicules reach transition region temperatures. We therefore examine the possibility that spicules could be a major contributor to the radiative emission of the transition region below 0.1 MK. We do so by verifying the predictions of a simple "spicule forest" model against available observations. The results of this analysis can provide important clues to the long-standing problem of the source of the radiative emission of the lower transition region

Sources of emission below 0.1 MK : «cool» loops?

In the past 30 or more years, different theories have been proposed and debated to explain the origin of the solar EUV output at temperatures below 0.1 MK. It has long known that the idea that the transition region emission at those temperatures originates from the bases of the hot large-scale coronal loops is not confirmed by the measured differential emission measure (DEM), which is orders of magnitude higher than predicted.

The observed excess emission compared to the predictions of a conduction-dominated TR picture has led, in particular, to the suggestion that much of the TR plasma is confined in relatively small and cool magnetic loops (height < 8 Mm, T < 10^5 K) that are strongly connected to the chromosphere, but are thermally insulated from the corona (Dowdy et al. 1986; Dowdy 1993; Feldman 1983; Feldman et al. 2001).

Fig. 5 from Dowdy et al. (1986)



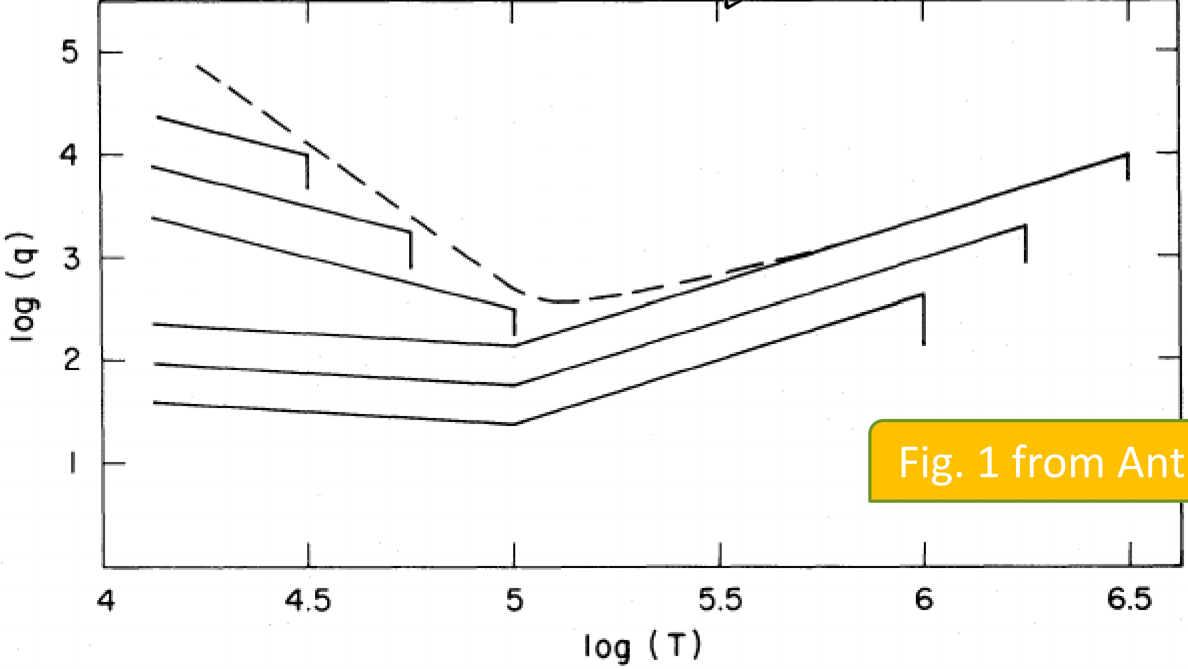


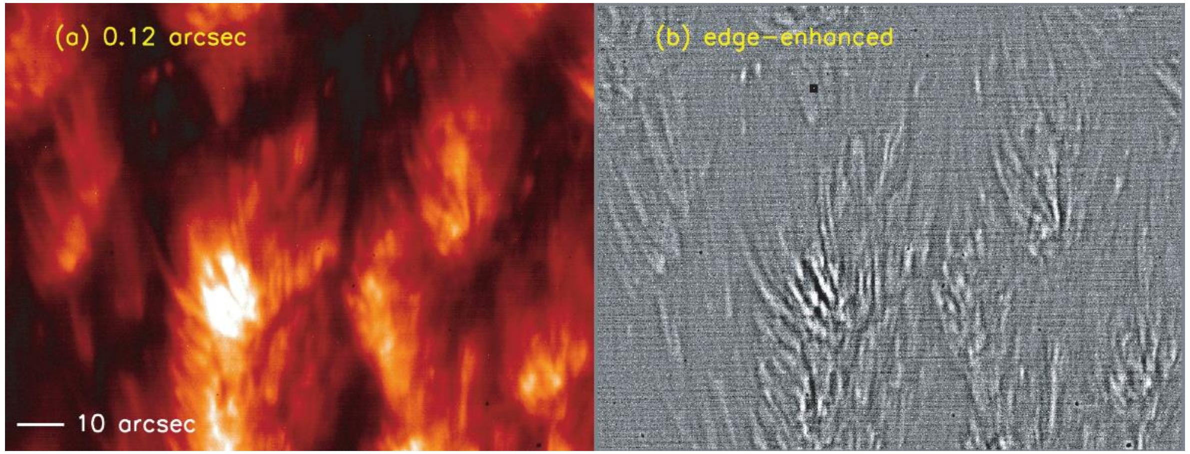
Fig. 1 from Antiochos & Noci (1986)

Sources of emission below 0.1 MK: «cool» loops?

The existence of this class of magnetic loops, predicted for decades, remains far from being established. From the observational point of view, they are indeed very difficult to observe.

There have nevertheless been observation hinting to structures that could be identified with such cool structures. Whether these observed structures are numerous enough to justify the solar EUV output below 0.1 MK, at least in the quiet Sun, is still far from clear.

Fig. 2 from Patsourakos et al. (2007):
VAULT data (Ly-α)



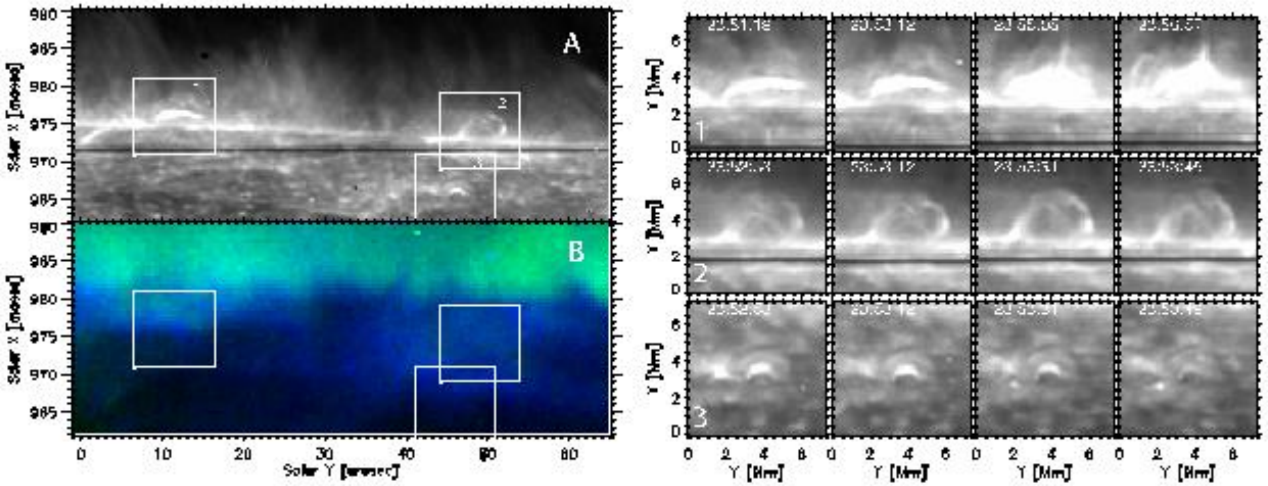


Fig. 1 from Hansteen et al. (2014):
IRIS data

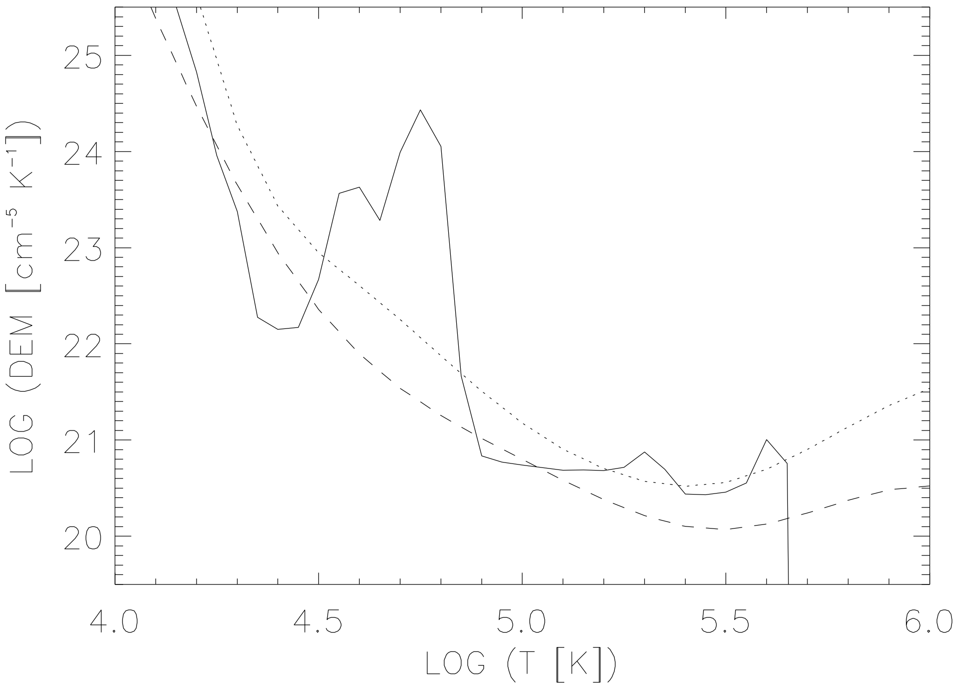
Sources of emission below 0.1 MK: «cool» loops?

From a theoretical point of view, it has very early pointed out that the properties of cool loops, even their existence and stability, depend on the details of the plasma radiative losses (Hood & Priest 1979, Antiochos & Noci 1986). This has been confirmed by subsequent numerical studies (Cally & Robb 1991, Sasso et al. 2012, 2015).

In particular, the optically thick losses due to the Ly-α line makes more difficult the existence of stable structures below 3 10^4 K. As a result, average DEMs from reasonable ensembles of such structures exhibit shapes significantly different from the observation.

It is however possible that «metatable» structures, when averaged over time, could reproduce the observed DEM of the quiet Sun. However, it is not clear whether such structures can be identified with the observed features recently observed.

Fig. 8 from Sasso et al. (2015): Average DEM from an ensemble of static cool loops, compared with observed quiet-Sun DEMs (dashed and dotted lines).



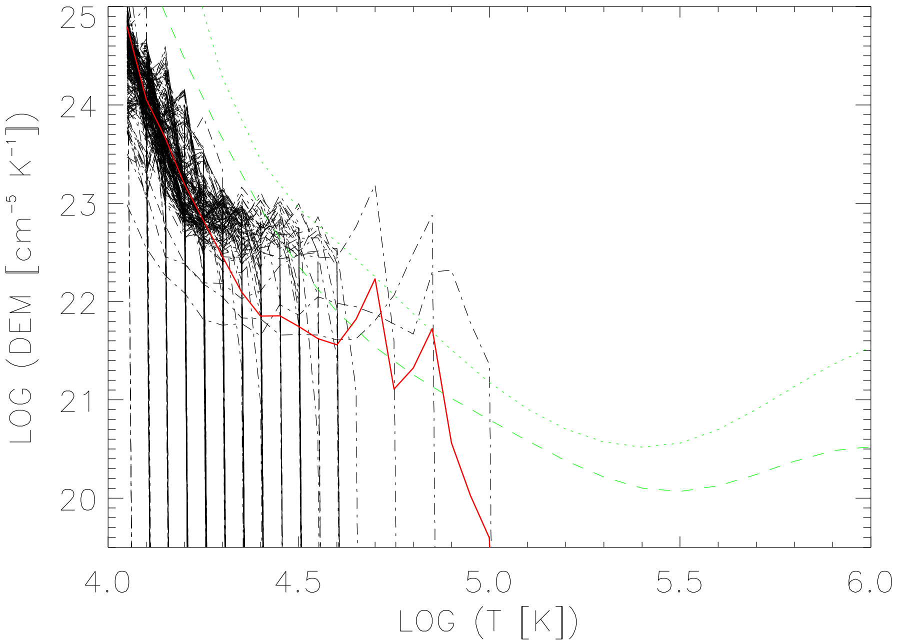


Fig. 9 from Sasso et al. (2015): Average DEM (red) from an ensemble of transient cool loops, compared with observed quiet-Sun DEMs (dashed and dotted lines).

Sources of excess emission below 0.1 K: spicules?

While the so-called cool loops remain elusive structures, spicules on the other hand are ubiquitous and their properties are becoming more and more accurately characterized.

The emphasis of studies on spicules, in particular on Type II spicules, is often on their connection with the corona. Here instead we want to examine their connection with the chromosphere and the lower transition region below 0.1 MK.

In fact, we want to determine to what extent the EUV output in the lower transition region of the quiet Sun can be attributed to spicules.

To do so, we compare the observed average off-limb emission with the contribution from an ensemble of spicules.

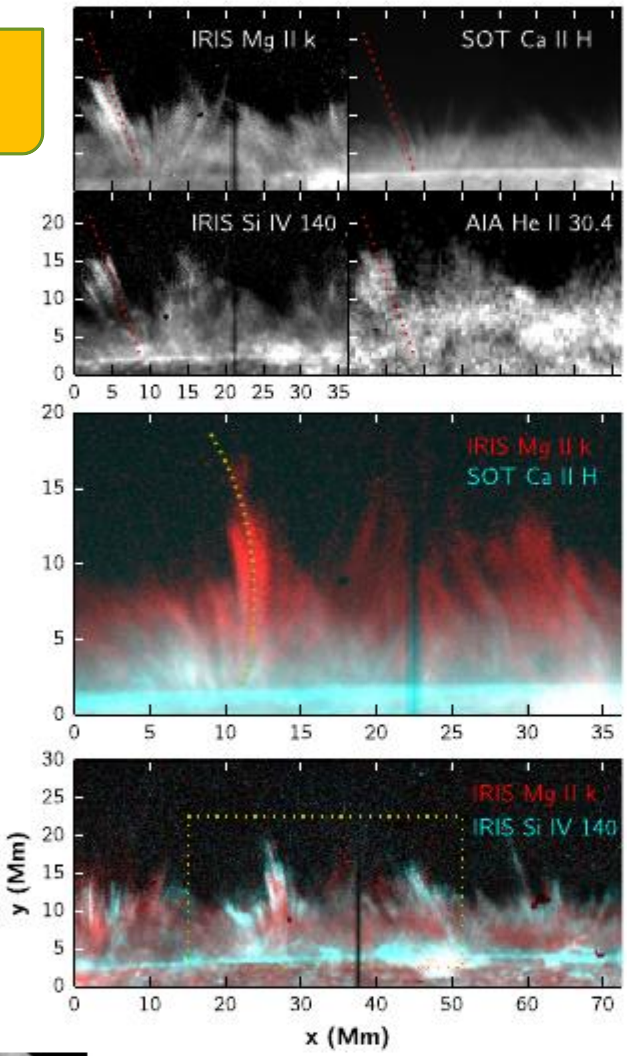


Fig. 1 from Pereira et al. (2014)

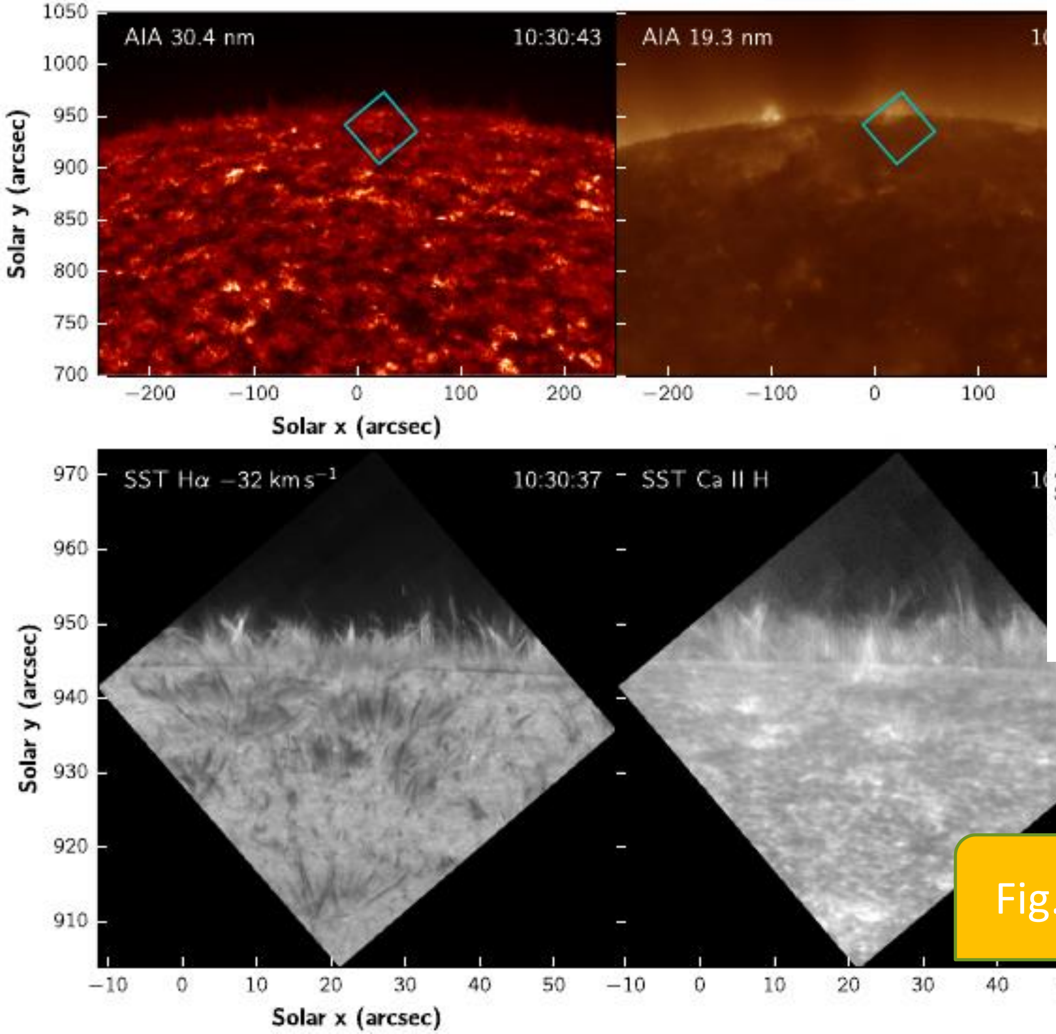
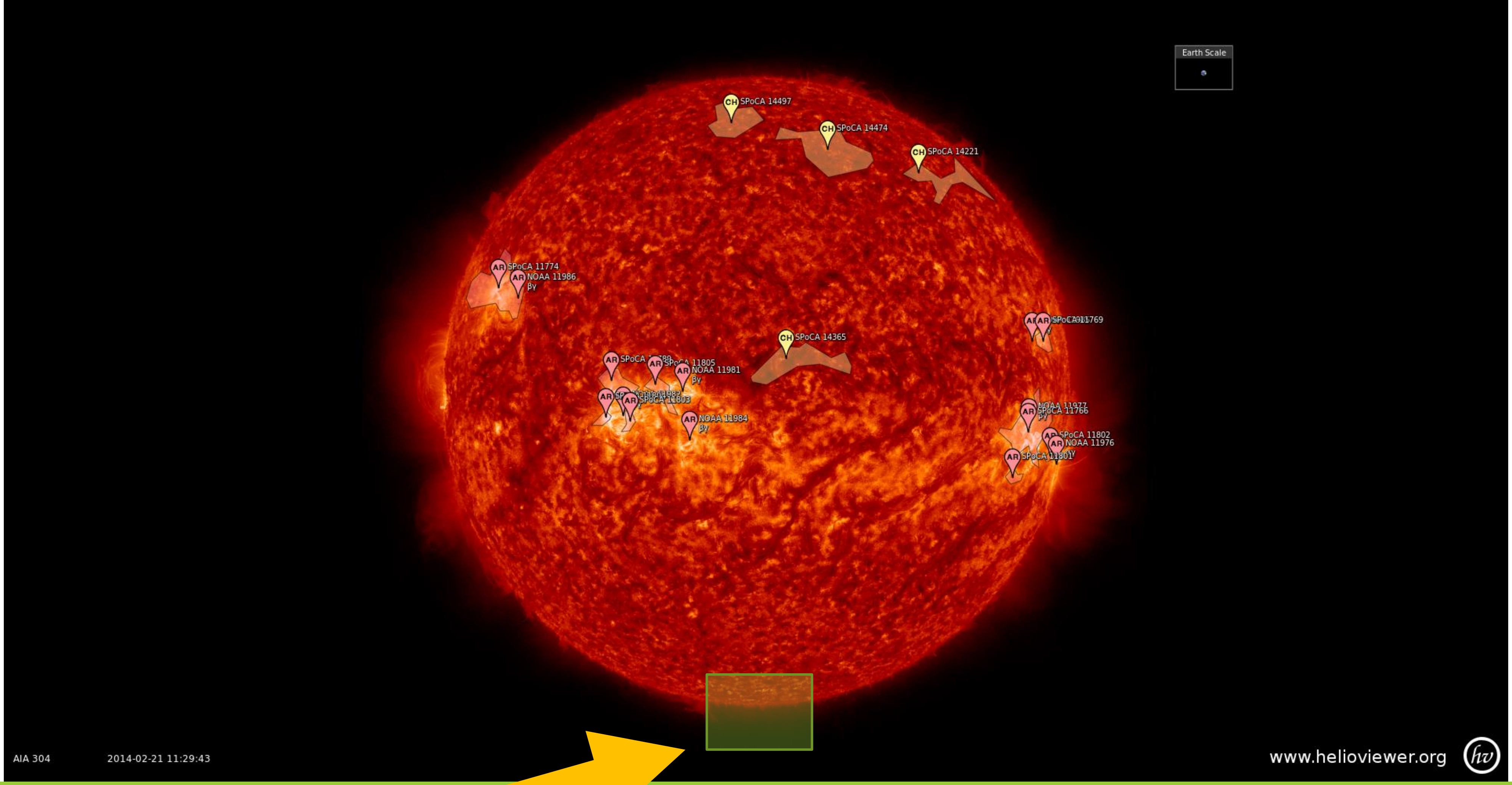
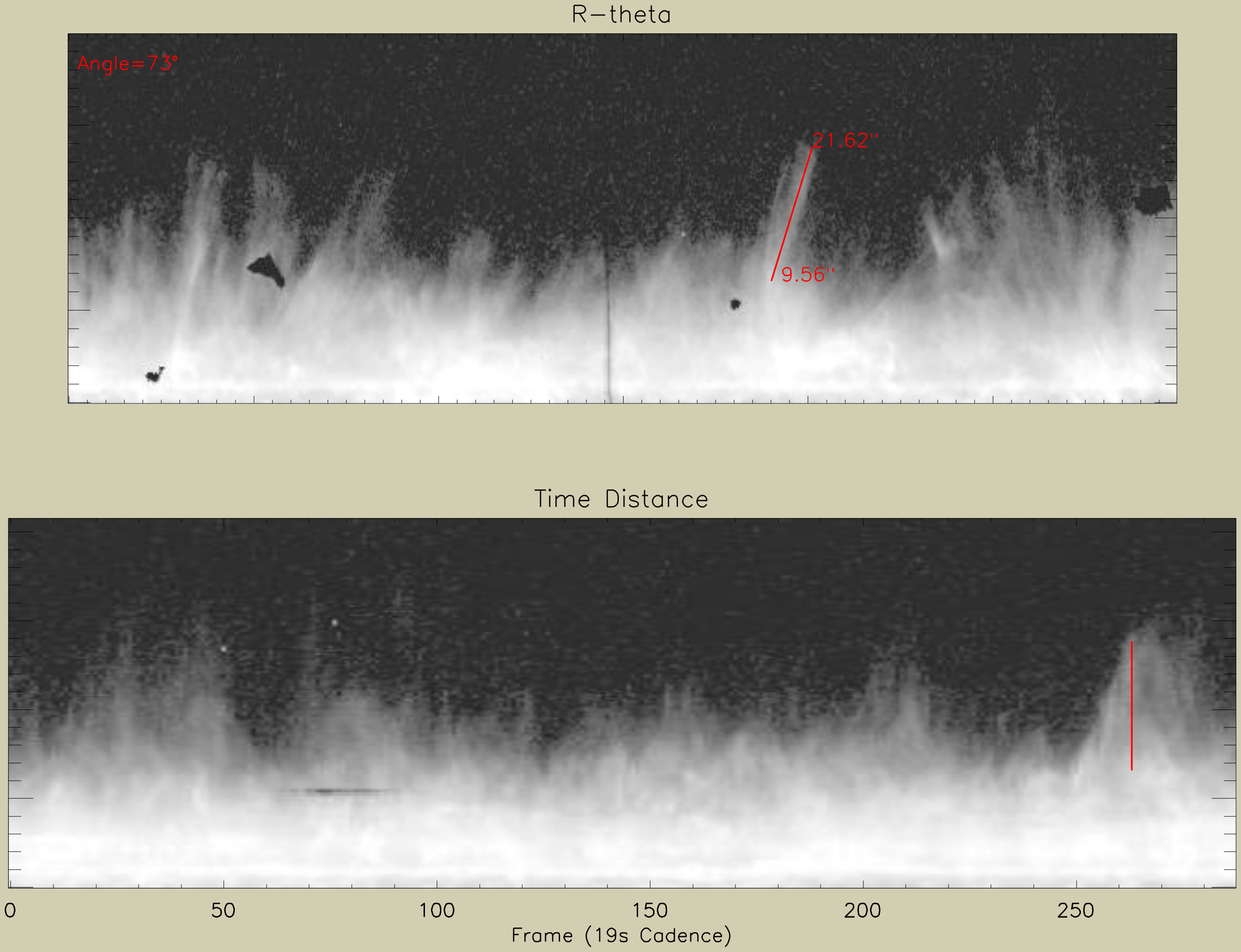


Fig. 1 from Pereira et al. (2016)



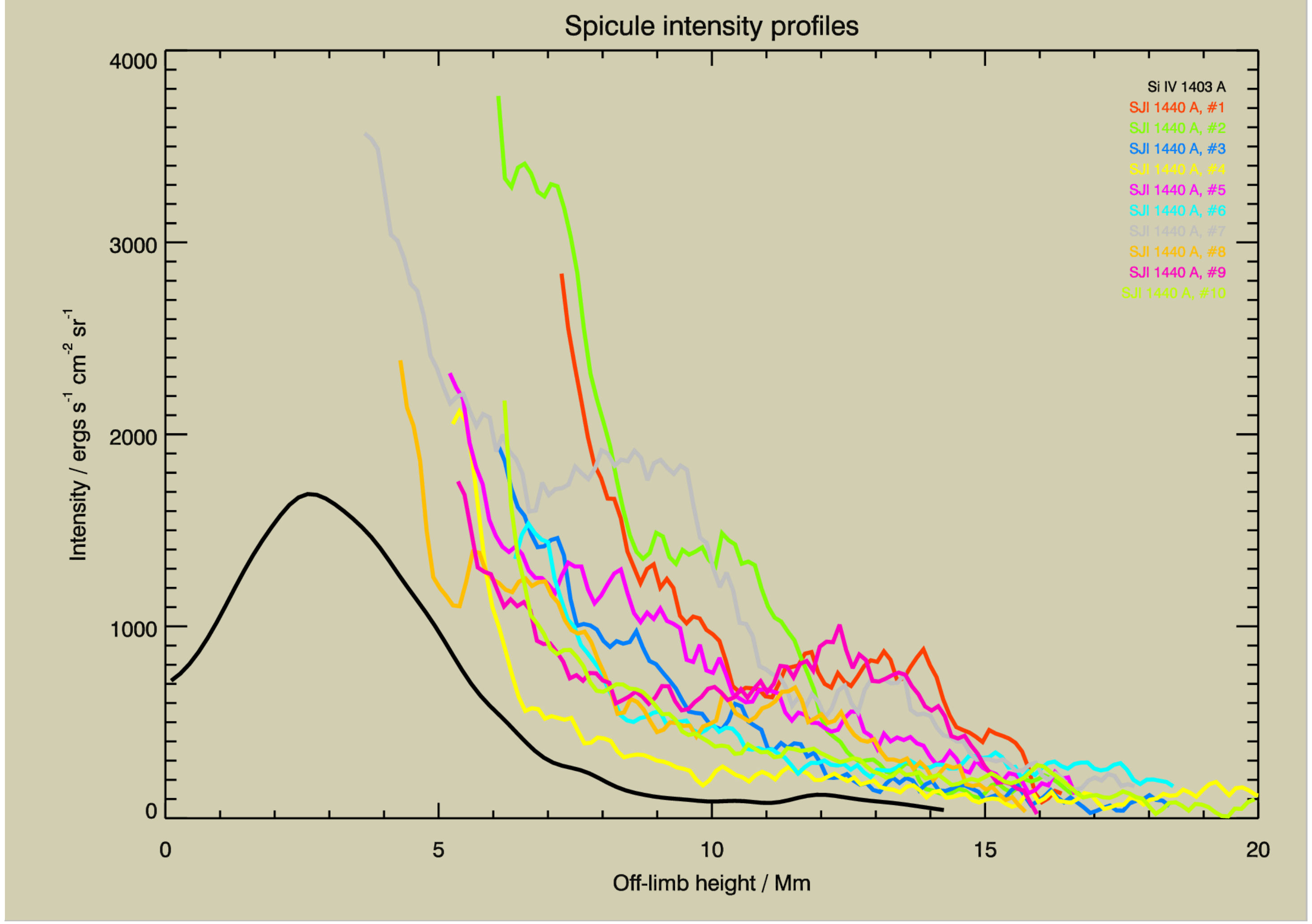
The data sets

For a preliminary analysis, we chose well known data sets which include both IRIS spectra and slit-jaw images. The main data set we have considered was taken on 21-02-2014 at the S pole. For this data set we analyzed slit-jaw images in the 1400 Å band. The same region of the Sun was also observed on 19-02-2014. From the latter data set we also analyzed IRIS spectra, in particular we determined the mean intensity of the Si IV 1403 Å line as function of height above the limb.



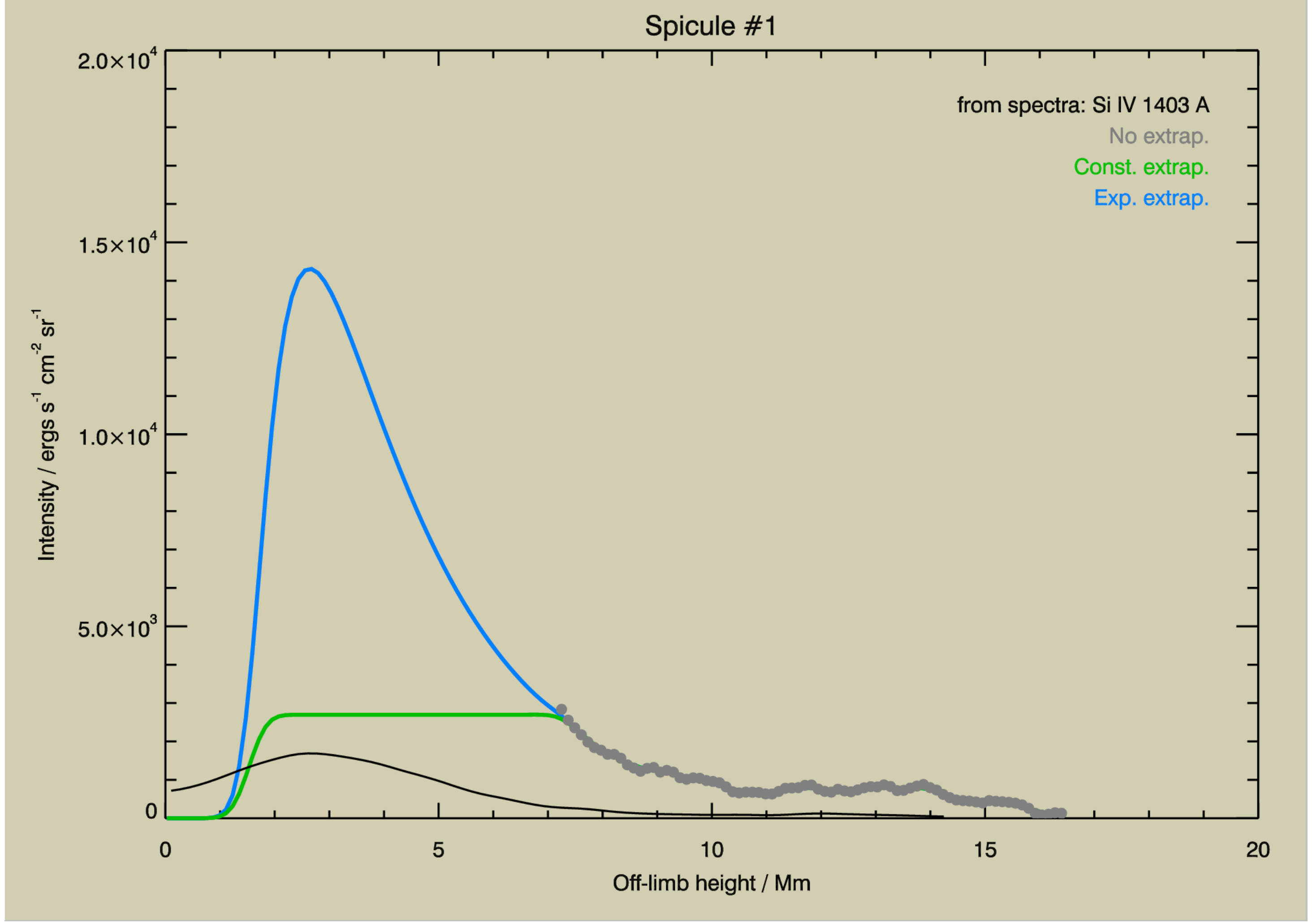
Observed off-limb spicule intensity profiles

For the IRIS SJI 1400 Å dataset from 21-02-2014, images were coaligned to within 0.04" accuracy; the limb was then fitted to determine the helioprojective coordinates: this allowed the determination of the polar coordinates (radius, azimuth). These polar coordinates were used to visually identify spicule candidates. We selected the 10 events which reached the highest heights with subjective assessment of linearity and continuity of structure. At the time of peak extension, we extracted the intensity along the spicule using a “virtual” slit that is linear but is not necessarily vertical. The vertical range of the extracted intensities is determined by where we could see an intensity enhancement at the top and the point where we could see other transient structures superposed at the base. The intensities have been calibrated using IRIS_GET_RESPONSE V004.



Intensity profiles of a set of representative spicules

The intensity profiles for the 10 representative spicules are shown in this figure. The mean intensity in the Si IV 1403 Å line of a spicule observed in spectra from the 19-02-2014 data set is also shown for comparison (black curve).

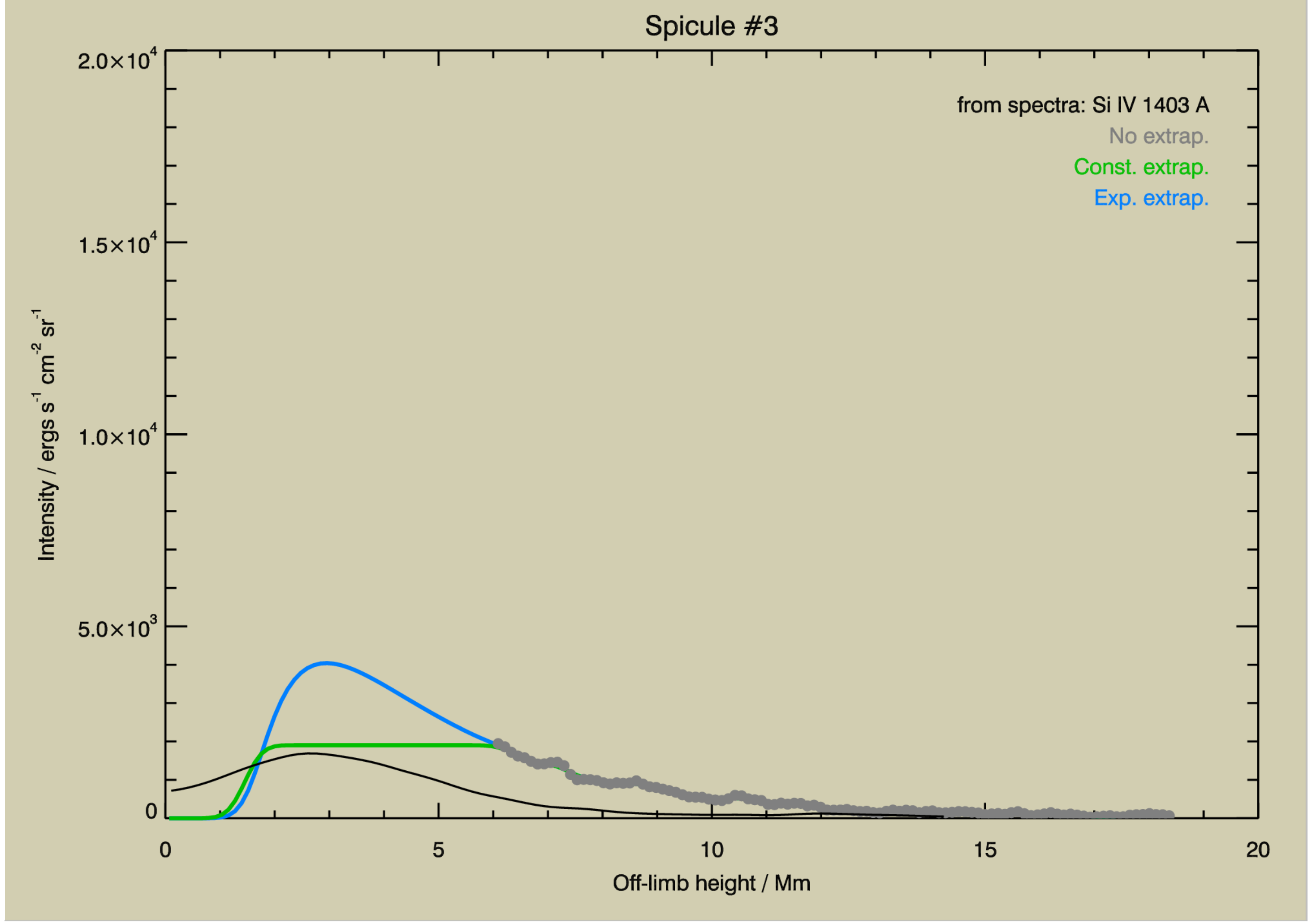


Extrapolating the profiles down to the chromosphere

The measured spicule profiles from slit-jaw images start from about 6-8 Mm above the limb. In order to estimate the contribution of spicules at lower heights, we extrapolated the observed spicule profiles either by a constant value or by a function with the form:

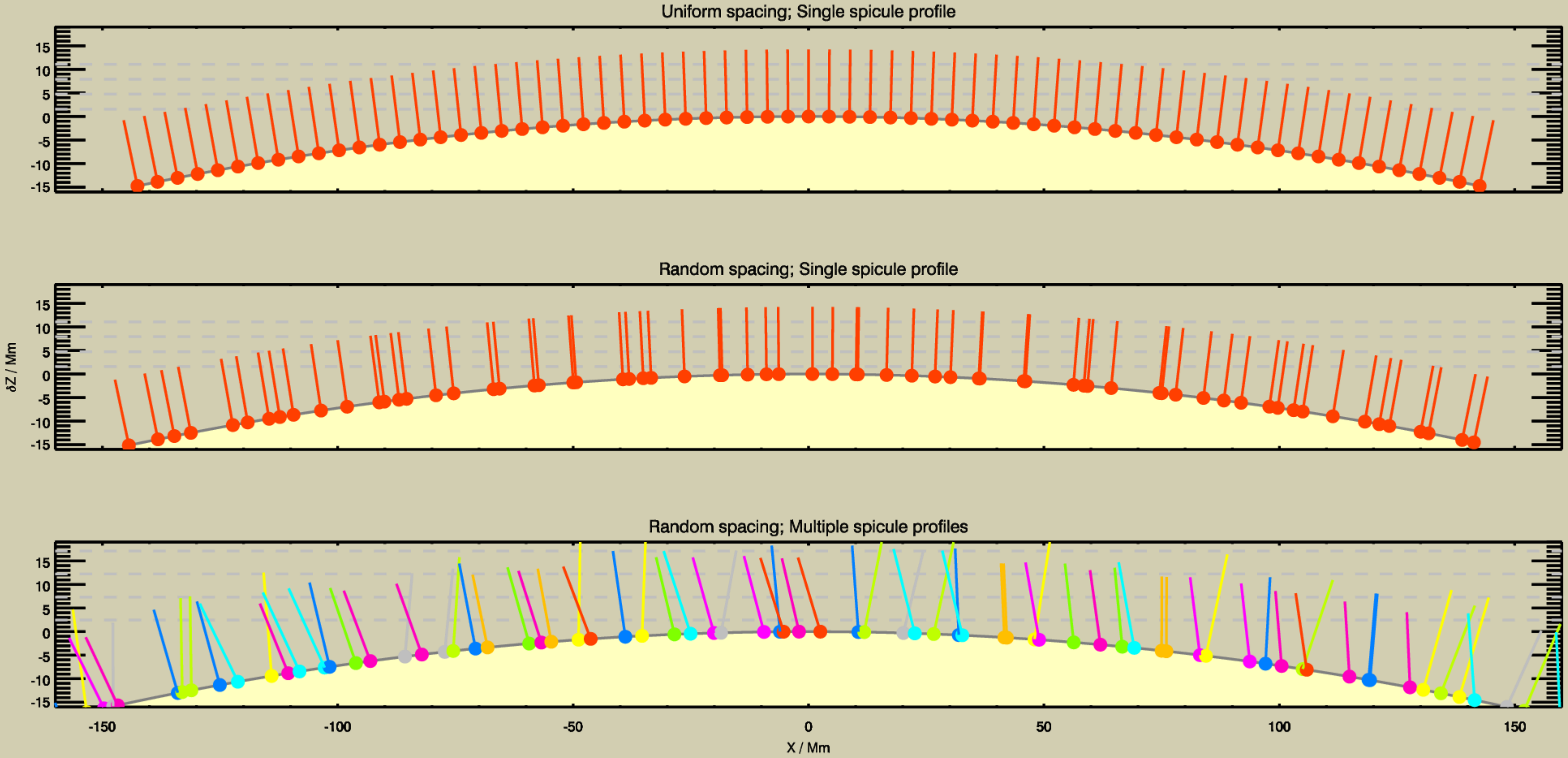
$f(h) = A \exp[-\alpha (h-h_0)] \{1-\exp[-k \alpha (h-h_0)]\}$

(«exponential» extrapolation), where k and h_0 are given parameters (k=3 and h_0=1.5 Mm) and α and A are determined by fitting the data.



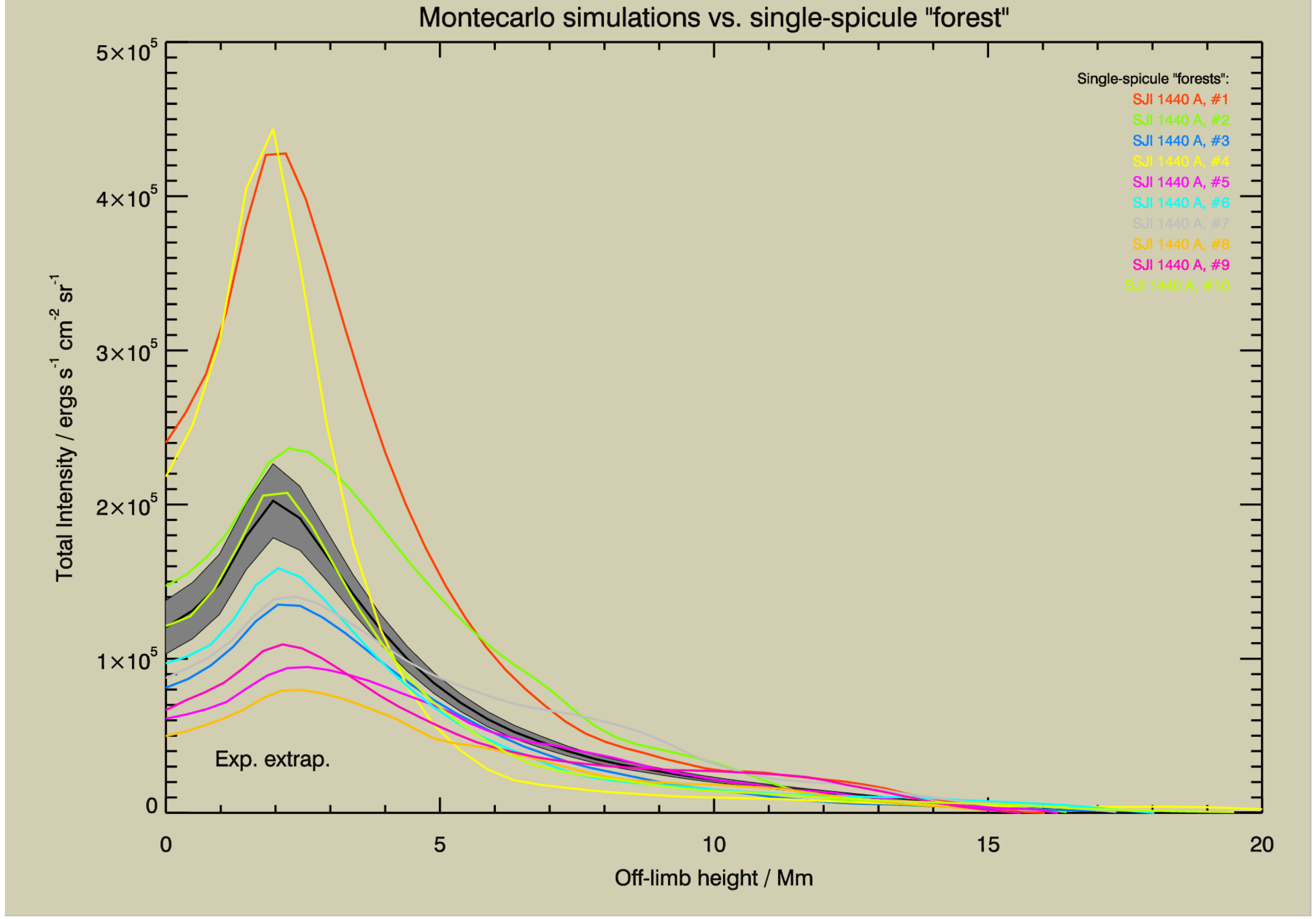
Extrapolating the profiles down to the chromosphere

Here we show another example of extrapolated profiles for one of the representative spicules. As a comparison, we also show the intensity profile from the spectra.



The model: a «forest» of spicules

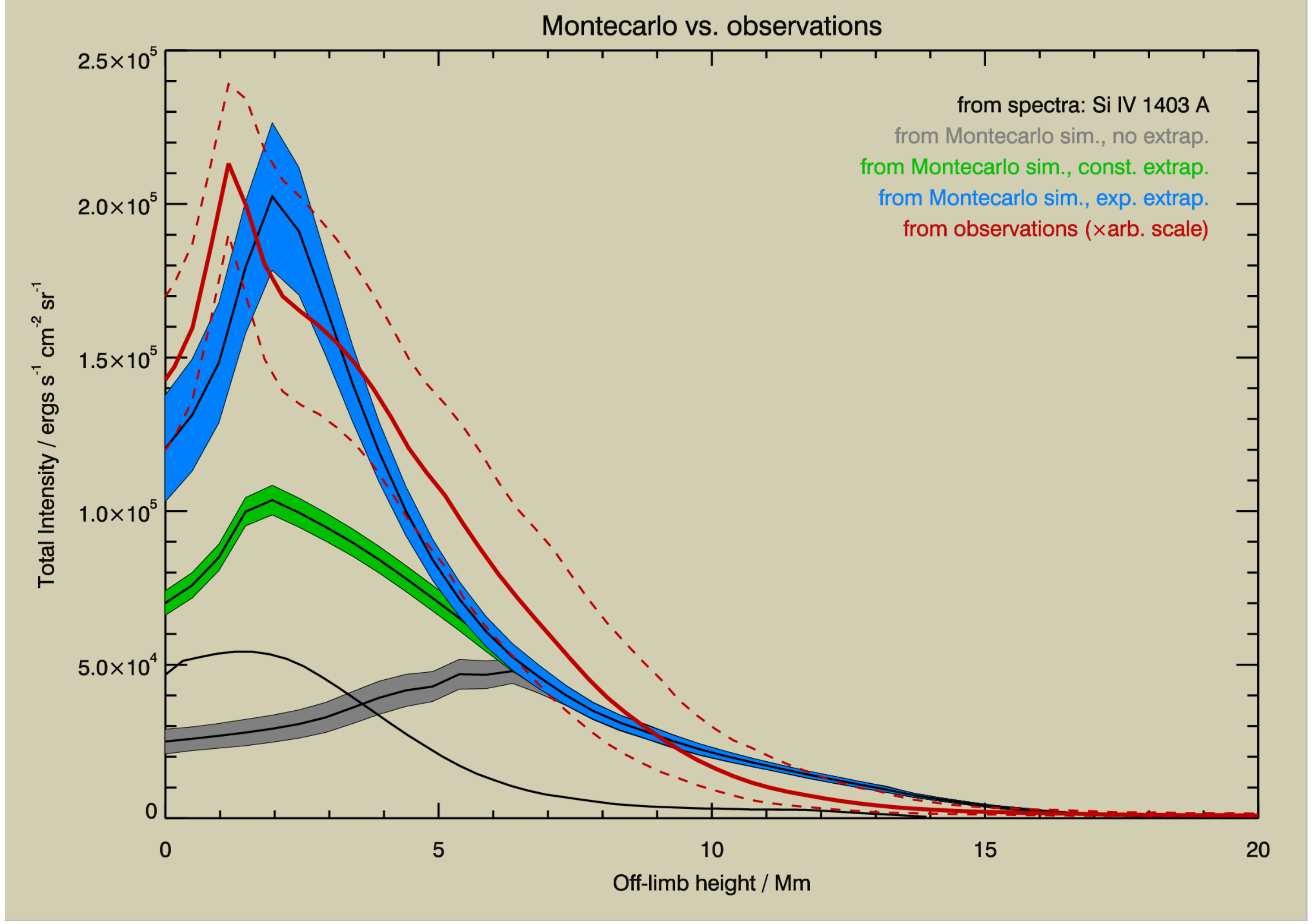
Once we determined the off-limb intensity profile of a set of 10 representative spicules, we then computed the total emission seen along the line of sight at different heights above the limb due to a distribution of such spicules over the solar surface («spicule forest» model). The simplest variant of this model is to take a single spicule profile and distribute it over the solar surface with a constant spacing. We then considered the case of random spacing with an average value *L* and a standard deviation *δL*. We finally considered the case of an ensemble of spicules picked at random from the representative set of 10 observed spicules and randomly spaced (bottom panel).



Montecarlo simulations vs. single-spicule «forests»

For each spicule profile, it is possible to construct a total intensity profile as function of height above the limb by assuming a set of randomly spaced identical spicules (cf. middle panel of the previous slide). These profiles – in the case of exponential extrapolation - are shown as color lines in the plot above.

To add more realism to the model, we consider the case of randomly picked and randomly spaced spicule profiles (cf. bottom panel of the previous slide). We can then create a Montecarlo simulation by repeating this calculation for a large number of times. The average and standard deviation of all the instances of the «forest» model is shown as a grey shaded area.



The calculated total intensity profiles vs. observations

The results of these Montecarlo simulations of a «spicule forest» model for the three extrapolation cases we have considered are compared here to the average off-limb intensity of the slit-jaw data from 19-02-2014 (similare values are obtained for the 21-02-2014 data set). We have added an arbitrary scale to the off-limb profile since in this context we are mainly interested in the general shape of the off-limb fall-off of intensity.

Summary

The sources of the EUV radiative output from the so-called lower transition region (plasma below 0.1 MK) are still in large part unidentified.

We propose an approach to check whether the bulk of such emission is due to spicules, in particular to Type II spicules. A preliminary analysis following this approach shows that the observed off-limb emission below 0.1 MK could indeed be reproduced by a simple model of a «forest» of Type II spicules.

Work is in progress to improve this analysis in several respects. Among the things to be done:

- ❑ Reduce the need for extrapolating spicule intensities at low heights.
- ❑ Remove the background from the profiles of individual spicules.
- ❑ Add spicule time dependence.
- ❑ Repeat this analysis in other structures of the solar surface (e.g.: coronal holes).