Quantifying the role of spicules in the lower transition region

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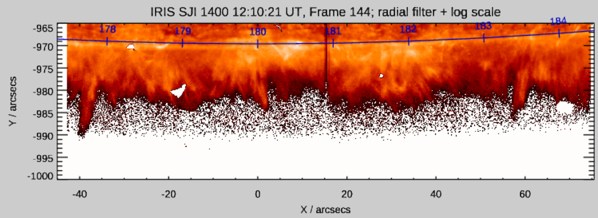
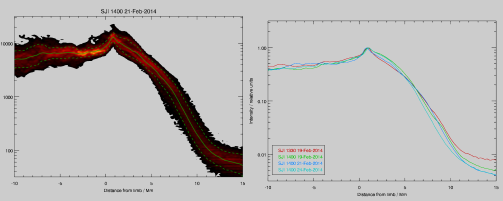
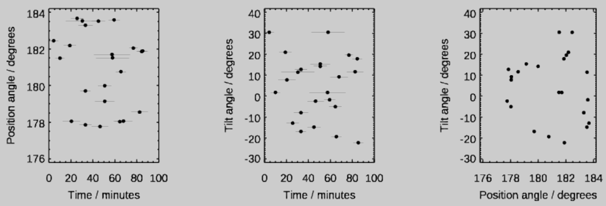
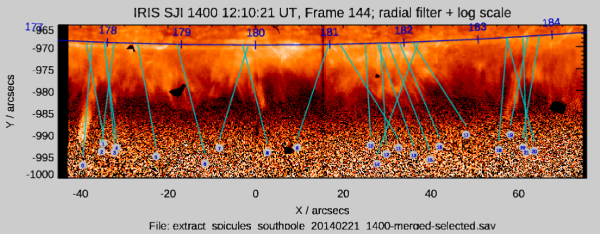
Despite decades of active study, we do not yet have a satisfactory model of the source of the radiative output of the lower transition region (T < 10^5 K). On the other hand, it is now well established that at least type II spicules do reach transition region temperatures. It is therefore natural to assume that spicules may contribute significantly to the observed transition region emission.
We present here results of an analysis of IRIS data providing a quantitative assessment of the fraction of the transition region output below 10^5 K due to spicules.
In particular, we combine off-limb measurements of isolated spicules with a geometric model to simulate the average radial profile of Si IV emission. We then compare the synthetic off-limb emission thus obtained against the observed radial profile.



We analyzed the following IRIS slit-jaw data sets taken on 2011: February 19 (SJI 1330, 1400), 21 (SJI 1400), and 24 (SJI 1400). From each set of slit-jaw images, we built a 2-D histogram of off-limb intensities, computing the mean and standard deviation of intensities at each height above the limb. These mean values do not change significantly over the three dates. The aim is to investigate whether it is possible to reproduce the mean off-limb intensity profile in the 1400 and 1330 SJI bands by assuming that all the off-limb solar emission in those bands is due to (type II) spicules.



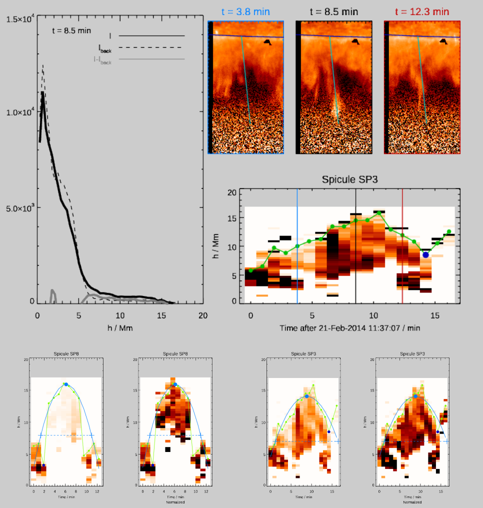




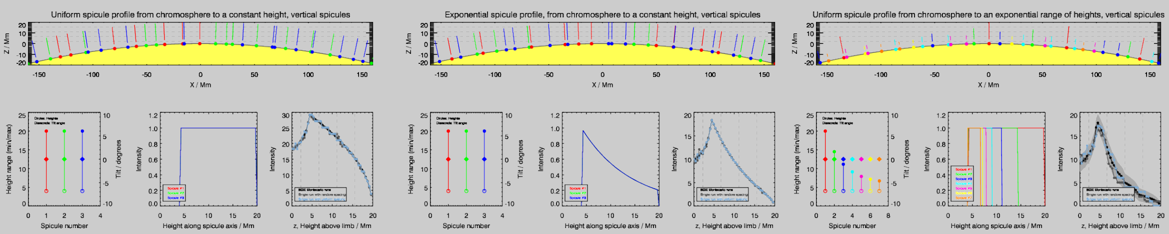
We visually identified a number of spicules in each data set. The intensity profile of the selected spicules was estimated over a "virtual slit" drawn along the axis of the spicule. We thus obtained for each spicule *s* an intensity profile as function of length and time, $I_s(h,t)$.

A critical step in the measurement lies in the estimation of the background intensity. This was accomplished with two different methods:
1) Another "virtual slit" was considered on the side of the spicule axis: in every frame, the intensity of that "side" (or "background") slit was used to estimate the background.
2) On a subset of spicules, at each time step we estimated the intensity above the top of the spicule. Since the majority of the spicules we measured exhibit a rising and a falling phase, this method allowed us to estimate the average background over the entire lifetime of the feature.

We verified that the two methods yield similar results. We then systematically applied the first method to all our measurements.
The plots to the left show the set of spicules identified in the data set of February 21st, 2011. The plots to the right show an example of a "virtual slit" measurement of a spicule: the slit-jaw images at three times during the evolution of the spicule are show together with the position of the virtual slit (green line). The time-distance diagram for that spicule is shown below those images. The intensity profile, the estimated background, and the residual intensity are also shown for the time of maximum elongation of the spicule. Finally, the time-distance diagrams of two more spicules are shown to the right, together with an estimate of the maximum height reached by the spicule as a function of time (green dots and lines) and its quadratic fit (blue curve).



The next step is to utilize the collection of all the measured spicule profiles, $I_s(h,t)$, to estimate the off-limb solar emission at 1400 Å (or 1330 Å), $I_{SJI}(h)$.
We assumed that spicules are distributed nearly uniformly over the solar surface with a mean spacing *L*. With this assumption, we can compute the off-limb emission integrated over the line of sight cutting through a given set of spicules: the "spicule forest" model. We show here three idealized cases (figures to the right) demonstrating the effects of some of the most important parameters in this problem. For each case, we followed a Monte Carlo approach by computing the result of a large number of random spatial distributions with the same mean spacing *L*, in order to compute the mean and the standard deviation of the resulting off-limb intensity as a function of height.
1) The first case is a population of identical spicules with an intensity profile constant with height. The result is a relatively shallow fall-off of intensity with height up to a cut-off point corresponding approximately to the maximum height of the spicules.
2) The second case is similar to the previous one, except that the intensity profile of each spicule falls off exponentially with height. The resulting off-limb fall-off of intensities also is approximately exponential.
3) The third case considers a populations of spicules with a constant intensity profile as a function of height, but with an exponential distribution of their maximum height. The result is similar to case #2, but with a larger standard deviation of the intensities.

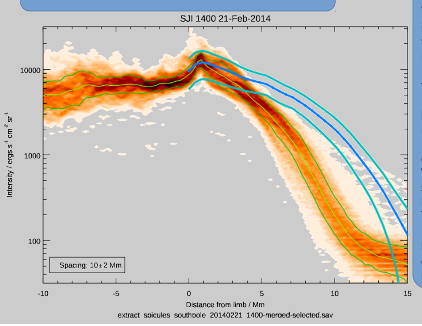


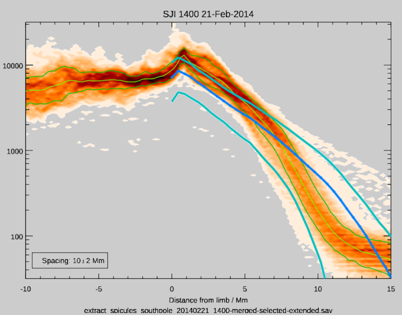
We then applied this "spicule forest" model to the set of measured spicule profiles, $I_s(h,t)$, and compared the resulting intensities to the measured intensity distributions obtained from the constant height slices discussed above.

More specifically, each spicule *s* is measured over a set of N_s time steps, thus obtaining a set of N_s intensity profiles, $I_s(h,t_i)$, $i=1,\ldots,N_s$. The full set of these intensity profiles for all the *N* measured spicules constitutes a data base of $M=\Sigma_{s=1,N} N_s$ intensity profiles. We treat each of these intensity profiles independently and then randomly reshuffle this set distributing it along the line of sight with the mean spacing *L*. This procedure is equivalent to distributing each of the *N* spicules over the surface with a probability proportional to N_s, i.e. to their lifetime, and then to picking the intensity profile of each of the instances of the same spicule at a random phase of its evolution. The procedure is then repeated a large number of times to obtain a Monte Carlo simulation of the predicted off-limb intensity from the input set of *N* spicules.

The figure to the left shows the result. Clearly, the off-limb fall-off is too shallow compared with the observations. However, the measurements of spicule profiles with this method are severely limited at lower altitudes above the limb. It is reasonable to assume that we have missed either the lower part of the majority of spicules or a large number of smaller spicules hardly distinguishable over the near-limb "haze".
In both cases, the hypothesis that all the lower transition region emission (and thus the corresponding off-limb emission) is due to spicules, can still be considered plausible.
We tested the second possibility by adding to the population of measured spicules three sets obtained by using the same spicule measurements and scaling the lengths along the spicule axis by the factors 0.62, 0.4, and 0.25, to mimick an exponential distribution of spicule sizes.
The result of this exercise is shown in the plot on the right.

In conclusion, we showed that under reasonable assumptions, it is possible describe the off-limb solar emission at the wavelengths of 1400 and 1330 Å by a "spicule forest" model, despite the limitations of the method so far employed to measure individual spicules.





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