FULL TITLE
*ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION***
NAMES OF EDITORS

Solar spicules near and at the limb, observed from *Hinode*

Alphonse C. Sterling[1] & Ronald L. Moore

NASA/MSFC, Huntsville, Alabama, USA
[1] Currently at JAXA/ISAS, Sagamihara, Kanagawa, Japan

Abstract. Solar spicules appear as narrow jets emanating from the chromosphere and extending into the corona. They have been observed for over a hundred years, mainly in chromospheric spectral lines such as H-alpha. Because they are at the limit of visibility of ground-based instruments, their nature has long been a puzzle. In recent years however, vast progress has been made in understanding them both theoretically and observationally, as spicule studies have undergone a revolution because of the superior resolution and time cadence of ground-based and space-based instruments. Even more rapid progress is currently underway, due to the Solar Optical Telescope (SOT) instrument on the *Hinode* spacecraft. Here we present observations of spicules from *Hinode* SOT, as seen near the limb with the Ca II filtergraph.

1. Introduction

Solar spicules appear as ubiquitous small-scale ($\sim 10''$) jets of material extending from the chromosphere into the corona. A more detailed definition of them is difficult, and often quite inconsistent (see discussions in Sterling 2000). However they are defined, the views we have from the *Hinode* satellite are revolutionizing our understanding of them beyond the "traditional" spicules described in the solar literature over much of the last century (e.g., Beckers 1968, 1972). Spicules are near, and in some cases probably beyond, the spatial resolution limits of ground-based telescopes. *Hinode*'s Solar Optical Telescope (SOT) can observe spicules with a clarity and consistency hitherto impossible from the ground (De Pontieu et al. 2007a,b; Suematsu et al. 2008).

We have been examining spicules near and at the solar limb using SOT Ca II images. By using very-high-cadence data, and applying to those data image enhancement techniques based on the SOT Ca filter's point spread function (PSF), we are able to glimpse some details of activity at the base of some spicules, and we can also follow the detailed evolution of some spicules when viewed beyond the limb. The spicule features we see have high velocity (50 - 120 km s^{-1}) and generally fade from view without showing indications of falling, and therefore resemble the features referred to as "Type II" spicules by De Pontieu et al. (2007a).

2. Data and Method

Our data are from a high-cadence run of SOT Ca II observations, with images about every 10 sec. We observed a region in the north polar coronal hole on 2007 July 25, near 07:00 UT. We processed the images by approximately deconvolving the effects of the telescope's PSF for the SOT Ca filter. We do this by convolving the images with the inverse of the PSF, where the PSF was determined by C. E. DeForest during an eclipse seen from *Hinode* during January 2007, using the process described in DeForest et al. (2009) with $\epsilon = 0.03$. For the SOT case the PSF was derived from images of the lunar limb acquired during a *Hinode* eclipse, and assumes azimuthal symmetry in the scattering component (DeForest 2010). The resulting PSF is circularly symmetric.

Briefly, we can understand the deconvolution process we use as follows. If we call a theoretical "perfect" image being observed by a telescope I_p, then the actual observed image is modulated by the telescope's PSF, P, so that the actual observed image, I_o, is

$$I_o = I_p \circ P,$$

where $\circ$ denotes the convolution operation. So the theoretical perfect image is given by

$$I_p = I_o \circ P^{-1},$$

where P^{-1} is the inverse of the PSF. There are however several limitations on how accurately the theoretical perfect image can be reproduced, including the accuracy to which the PSF has been determined. There are also some limitations on the Fourier components used in the inversion process; see DeForest et al. (2009) for a discussion. Additionally, what we discuss here is the simplest theoretical case of noiseless images; DeForest et al. (2009) also discuss the more general case where noise is included. Despite these caveats however, DeForest et al. (2009) found the images resulting from applying the deconvolution to be very satisfactory.

The result of convolving our SOT images with the inverse PSF is that our images are sharpened over the non-processed images. We are also however able to see the features of all of our primary results in the original (non-deconvolved) images, albeit with somewhat less clarity. Therefore we are certain that our PSF-deconvolution processing procedure has not introduced artificial results into our analysis.

3. Outline of Results

The most prominent aspect of the images just inside the solar limb is the presence of ubiquitous bright features of size $\sim 1''$, some of which show apparent fast (few tens km s^{-1}) horizontal or near-horizontal motions low in the atmosphere. We call these features "Ca II brightenings," and they are likely what are variously called"H_{2V} grains," "K_{2V} grains," or "K_{2V} bright points" (e.g., Sivaraman et al. (2000), Nindos & Zirin (1998), and de Wijn et al. (2008), and see Rutten & Uitenbroek (1991) for discussions of earlier works).

We have two main findings regarding spicules. First, we have several specific examples where we can see ejections of spicule-like features just inside the disk, and in those cases there are Ca II brightenings at or near the bases of the ejected spicules. Moreover, frequently in these cases the spicules originate from where two or more Ca II brightenings *appear* to come together, or even collide or coalesce, and then disappear (fade). Whether these motions and behaviour of the Ca II brightenings are real or apparent, and whether this applies to the majority of spicules, are all still outstanding questions.

Our second main findings is in regard to the later evolution of spicules, when seen beyond the solar limb. In at least several cases, we have identified what appears to be a splitting of the spicules. That is, the spicules rise as a single jet, but they then either split into two or more fainter spicules, or they expand to wider spicules, as they fade. The apparent splitting or expansion occurs with velocities of a few tens km s^{-1}. Suematsu et al. (2008) has talked about multi-threaded spicules, while even earlier Tanaka (1974) discussed multi-thread mottles, and we may be observing the same type of features here.

4. Discussion

Our observations are near the limit of what we can see in the images and in movies constructed from those images. And moreover with the current processing techniques, the spicules against the disk are still rather faint, and because of dynamic range limitations it is often difficult to trace spicules from their source location on the disk to over the limb. So for example, we have not yet unambiguously identified an individual spicule where we can both see it originating on the disk, and later splitting or expanding after it extends beyond the limb. There are also complicating effects of observing near the solar limb, for example the difficulty of measuring velocities of the Ca II brightenings, and the line-of-sight issue that makes it difficult to be certain when we are observing a single splitting spicule instead of a superposition of different spicules. Because of these difficulties, our initial observations should be verified with follow-up studies before considering detailed eruption mechanisms.

One particular mechanism however which so far has not received much attention but which might be consistent with our observations here is that describing spicules as miniature magnetic eruptions (Moore et al. 1977; Moore 1989, 1990, 2001). That is, spicules could be like “standard” solar eruptions that produce flares and CMEs, but on a much smaller spatial and temporal scale. By analogy, the Ca II brightenings' apparent motions and collisions at the bases of the spicules could be the counterpart to the inflation of pre-eruption arcades prior to large magnetic eruptions (e.g., Sterling et al. 2007), or the heating of the flare loops themselves when the CME is being ejected. Also, CMEs expand as they leave the Sun (e.g., Hirayama 1974), and the analog could be the apparent splitting or expansion of spicules that we observe.

Images, movies, and full details of our findings from this investigation are presented in Sterling, Moore, & DeForest (2010).

Acknowledgments. We thank C. E. DeForest for useful clarifications of the image enhancement procedure. A.C.S. and R.L.M. were supported by funding from NASA's Science Mission Directorate through the Solar Physics Supporting Research and Technology Program and the Heliophysics Guest Investigator Program. *Hinode* is a Japanese mission developed and launched by

ISAS/JAXA, collaborating with NAOJ as a domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway).

References

Beckers, J. M. 1968, Solar Phys., 3, 367
Beckers, J. M. 1972, ARA&A, 10, 73
DeForest, C. E., Martens, P. C. H., & Wills-Davey, M. J. 2009, ApJ, 690, 1264
DeForest, C. E. 2010, private communication.
De Pontieu, B., et al. 2007a, PASJ, 59, S655
De Pontieu, B. et al. 2007b, Science, 318, 1574.
de Wijn, et al. 2008, ApJ, 684, 1469
Hirayama, T. 1974, Solar Phys., 34, 323
Moore, R. L. 1989, in Solar System Plasma Physics, ed. J. H. Waite, J. L. Burch, & R. L. Moore (Washington, DC: AGU), 1
Moore, R. L. 1990, Memorie della Societa Astronommica Italiana, 61(2), 317
Moore, R. 2001, in Encyclopedia of Astronomy and Astrophysics, ed. P. Murdin (Bristol: Inst. of Phys. Publ.), 2691
Moore, R. L., Tang, F. Bohlin, J. D., & Golub, L. 1977, ApJ, 218, 286
Nindos, A., & Zirin, H. 1998, Solar Phys., 179, 253
Rutten, R. J., & Uitenbroek, H. 1991, Solar Phys., 134, 15
Sivaraman, K. R., Gupta, S. S., Livingston, W. C., Dame, L., Kalkofen, W., Keller, C. U., Smartt, R., & Hasan, S. S. 2000, A&A, 363, 279
Sterling, A. C. 2000, Solar Phys., 196, 79
Sterling, A. C., Harra, L. K., & Moore, R. L. 2007, ApJ, 669, 1359
Sterling, A. C., Moore, R. L., & DeForest, C. E. 2010, ApJ, 714, L1
Suematsu, Y., et al. 2008, ASP Conference Series, 397, 27S
Tanaka, K. 1974, IAUS, 56, 239