Title: Solar Polar Spicules Observed with Hinode

Author: Alphonse C. Sterling, Ronald L. Moore, Craig E. DeForest

Abstract:

We examine solar polar region spicules using high-cadence Ca II data from the Solar Optical Telescope (SOT) on the Hinode spacecraft. We sharpened the images by convolving them with the inverse-point-spread function of the SOT Ca II filter, and we are able to see some of the spicules originating on the disk just inside the limb. Bright points are frequently at the root of the disk spicules. These ``Ca II brightenings" scuttle around at ~few x 10 km/s, live for ~100 sec, and may be what are variously known as ``H_{2V} grains," ``K_{2V} grains," or "K_{2V} bright points." When viewed extending over the limb, some of the spicules appear to expand horizontally or spit into two or more components, with the horizontal expansion or splitting velocities reaching ~50 km/s. This work was funded by NASA's Science Mission Directorate through the Living With a Star Targeted Research and Technology Program, the Supporting Research and Program, the Heliospheric Guest Investigator Program, and the Hinode project.

Solar Polar Spicules Observed with *Hinode*

Alphonse C. Sterling[1] **and Ronald L. Moore**

NASA/MSFC/NSSTC, Huntsville, Alabama, USA

and

Craig E. DeForest

Southwest Research Institute, Boulder, Colorado, USA

[1] **Currently at: JAXA/ISAS, Sagamihara, Japan**

Overview

We examine solar polar region spicules using high-cadence Ca II data from the Solar Optical Telescope (SOT) on the Hinode spacecraft. We sharpened the images by convolving them with the inverse-point-spread function of the SOT Ca II filter, and we are able to see some of the spicules originating on the disk just inside the limb. Bright points are frequently at the root of the disk spicules. These "Ca II brightenings" scuttle around at few x 10 km/s, live for $\sim$ 100 sec, and may be what are variously known as "H_{2V} grains," "K_{2V} grains," or "K_{2V} bright points." When viewed extending over the limb, some of the spicules appear to expand horizontally or spit into two or more components, with the horizontal expansion or splitting velocities reaching $\sim$ 50 km s^{-1}. A full report of this work appears in Sterling, Moore, & DeForest (2010).

This work was funded by NASA's Science Mission Directorate through the Living With a Star Targeted Research and Technology Program, the Supporting Research and Program, the Heliospheric Guest Investigator Program, and the Hinode project.

The Data

We assembled a 70-min long movie of Ca II images from the *Hinode* Solar Optical Telescope (SOT), taken at the north solar limb on 2007 July 25. During this period the cadence was very high, at 10 sec. We selected a $30'' \times 30''$ sub-FOV from the SOT images for detailed analysis.

The images making up the movie were convolved with an inverse point spread function (PSF) for the SOT broad band filter. This function was provided by one of us (CED), and was produced by the method described in DeForest et al. (2009), with $\epsilon = 0.03$. The PSF itself is circularly symmetric, and was derived by DeForest by hand-fitting the falloff curve of brightness inside the lunar limb during the 2007 January eclipse. Employing this convolution improves contrast and small-feature detectability in the SOT images. In particular it improves visibility of the roots of some spicules on the disk just inside the limb.

Overall Appearance

There is an overall "haze" extending from the solar surface up to ~ 6000 km ($8''$), that may itself be largely or totally composed of spicules. Projected on this are thin, discrete, dynamic spicule features. Figure 1a shows the full field of view of our study, and the haze of the spicules.

In the movie constructed from the images, one obvious spicule dynamic is their lateral swaying, which De Pontieu et al. (2007a) interpreted as a response to Alfvén waves. There is also a strong upward motion apparent in the spicules themselves, with downward motion not obvious; rather, most of the spicules appear to fade rather than fall back to the Sun. Velocities of the spicules we observe are frequently ~ 50—150 km s^{-1}. These velocities and fading properties are consistent with what De Pontieu et al. (2007b) identified as "Type II" spicules.

The disk is filled with dynamic, transient features that we call "Ca II brightenings." They are of size $\sim 1''$ with lifetimes of a few $\times 100$ sec, and many have horizontal velocities of a few $\times 10$ km s^{-1}. These may be what are variously known as "H_{2V} grains," "K_{2V} grains," or "K_{2V} bright points" (e.g., Sivaraman et al. 2000; Nindos & Zirin 1998; de Wijn et al. 2008; Rutten & Uitenbroek 1991); those features have been discussed in terms of acoustic shocks (e.g. Kalkofen 2007; Reardon et al. 2008), and also as a manifestation of the magnetic field (e.g., de Wijn et al. 2008).

Spicules on the Disk Just Inside the Limb

When we can identify spicules originating on the disk just inside the limb, they frequently appear to have Ca II brightenings at their bases. Moreover, in several cases the *appearance* is as though the spicule emanates from where Ca II brightenings come close together, and then disappear as the spicule takes off. Figure 1b—1f shows one example of the apparent coalescence of bright points and the concurrent or subsequent ejection of a spicule. Figure 2 shows a second example, where Ca II brightenings come together, and this time create a "curtain" of spicules, as the Ca II brightenings that came together disappear.

Table 1 presents a summary of the circumstances for six specific cases of Ca II brightenings (CBs) at the base of spicules from our study.

Splitting Spicules Above the Limb

A second aspect apparent in the Ca II movie is that many spicules expand or split into two or more spicules, after being ejected as what appears to be a single spicule. Figure 3 shows an example.

Table 2 lists several cases of splitting or breaking-up spicules. Some events are rather complex. For example events 6 and 7 seem to be coordinated, with both seemingly-separate spicules “fraying” into two or more components each at the same time; the close coordination and breakup of these spicules suggests that both spicules could be part of a single collimated structure some $2''$ wide, that breaks apart by expanding outward horizontally. Before breaking up, the eastern spicule travels upward at $\sim$ 115 km s^{-1}. Several of the Table 2 events (events 1, 3, 4, 6, and 7) are initially very thin ($\lesssim$150 km) and perhaps even unresolved by SOT, as they jet upward. They then expand laterally into two or more strands while fading, and at the same time or shortly afterwards their upward motion seems to slow or stop. Event 2 is a fainter and broader object that moves more slowly and goes to higher altitudes than most others. Event 5 seems to be a compact structure moving upward, with two legs spreading out beneath it. Suematsu et al. (2008) described multi-threaded structure in spicules from *Hinode* observations, and much earlier Tanaka (1974) observed twinning in mottles; what we see here may be the same or a similar phenomena.

Discussion

Close examination of high-cadence Ca II images from *Hinode*/SOT, enhanced using the PSF deconvolution technique, shows hitherto undiscussed aspects of polar limb spicules. When viewed just inside the limb, many spicules emanate from Ca II brightenings, and sometimes from apparently coalescing Ca II brightenings. When viewed above the limb, some spicules split into two or more components as they fade. We have not however so far been able to follow an individual spicule that emanates from Ca II brightenings, and then subsequently spits into two or more spicules as it fades. Therefore we cannot rule out the possibility that we are observing two or more different types of ejective phenomena.

If the Ca II brightenings are acoustic shocks, it is hard to understand how the energy from acoustic shocks could be directly converted to spicules of such high velocities, based on model calculations (e.g. Hollweg 1982; Sterling & Mariska 1990; De Pontieu et al. 2004) (although some of the assumptions going into the earlier models should be reconsidered in light of newer data). If these brightenings represent different magnetic elements, the merging of the brightenings could correspond to magnetic cancelation and reconnection, and this could result in a corresponding deposition of thermal energy in the low atmosphere, perhaps somehow creating the spicules (e.g., Sterling et al. 1991; Shibata et al. 2007).

Observations of splitting spicules suggest another possibility: a spicule eruption could be a miniature filament eruption with the Ca ii brightenings being produced early in the eruption. Consistent with this idea, the motion of the splitting spicules is reminiscent of the spreading of the legs of filament eruptions, and the expansion of the erupting filament in the onsets of coronal mass ejections (CME) (e.g., Hirayama 1974; Moore et al. 2001). That is, spicules themselves may frequently be magnetic eruptions, similar to CMEs, occurring on a much smaller size scale and occurring much more frequently (Moore et al. 1977; Moore 2001). Such a scenario could perhaps explain why the Ca ii brightenings often appear to move rapidly toward and collide with each other. This apparent movement could reflect the onset of eruption (e.g., Sterling et al. 2007), with the apparent "collision" location corresponding to flare loops, which would only be bright for a very short time due to the small scale-size of the putative erupting region. Innes et al. (2009) present another example of mini-CME-like events. Their features are longer-lived and of lower velocity than our features. But they observed an on-disk coronal hole in EUV, while we observed the Ca ii limb, and so we cannot draw simple conclusions about the possible relationship with our observations. Much more detailed examination of spicule data is needed to sort out the actual eruption mechanism, and their connection with other solar features.

A.C.S. and R.L.M. were supported by funding from NASA's Office of Space Science through the Solar Physics Supporting Research and Technology Program and the Sun-Earth Connection Guest Investigator Program. We thank Drs. T. E. Berger, T. D. Tarbell, and D. M. Zarro for useful discussions and assistance. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway).

Table 1: Ca II Brightenings (CBs) at Spicule Bases

Event	Location	CB Start Time	CB Interaction Time	CB Lifetime (s) [a]	CB Velocity [b]	Spicule Notes
1	19.5,938.0	07:04:56	07:06:32	144	15	At least one set of CBs. Spicule velocity: $\sim$ 40 km s^{-1}—100 km s^{-1}.
2	5.0,938.0	$\sim$ 07:06:22	07:08:48	$\sim$ 288	25	Curtain of short spicules, hard to trace above the limb.
3	17.0,939.0	07:07:58	07:10:12	268	50	Ejection appears to "sweep up" a $\sim$ $5''$circular radius of CBs by 07:12:36 UT. Spicule material flows up at $\sim$ 60 km s^{-1}.
4	1.5,938.0	$\lesssim$ 07:13:05	07:13:34(?)	$\sim$124	40	Clear spicule ejected at e.g. 07:13:24, but CB collision not so obvious.
5	1.5,938.0	$\lesssim$07:15:19	07:16:36(?)	$\sim$182	30	Clear spicule visible at e.g. 07:16:36, repetition of previous. Initial spicule velocity $\sim$ 40 until about 07:17:14 UT, then at least 85 km s^{-1}. Again CB collision not so obvious.
6	22.5,940.0	07:26:11	07:27:27	$\sim$115	15	Clear spicule ejected.

---

[a] Time from appearance to disappearance of Ca II brightenings (CBs).

[b] Velocities estimates from horizontal displacements, and uncertainties are $\sim$ a factor of two.

Table 2: Splitting Spicules List.

Event	Location	Start Time	Time to breakup (s) [a]	Spicule Vel (km s^{-1})	Split Vel (km s^{-1})	Notes
1	20.0,942.0	07:01:44	$\lesssim$48	170 ± 50	45 ± 10	Comes out as single strand, blows apart into two or more strands. Diffuse top makes upward velocity uncertain.
2	8.5,950.5	<07:26:20	> 106	40 ± 10	45 ± 10	Different from most others: Initially faint, slow, tall, never narrow; starts broad and gets broader ($\sim 4''$).
3	18.5,943.0	07:27:46	104	220 ± 70	37 ± 12	Fig. 3 event. Faint extensions appear early, making velocities hard to measure precisely.
4	9.5,950.5	07:33:32	$\gtrsim$38	70 ± 15	27 ± 10	Single strand, expands while fading into diffused structure.
5	20.0,947.0	07:41:21	48	120 ± 30	50 ± 15	Faint. Plug at top, with two legs below.
6	18.5,944.0	07:49:30	67	130 ± 20	55 ± 30	Perhaps part of Event 7.
7	21.0,944.5	07:49:49	48	67 ± 10	60 ± 15	Perhaps part of Event 6.

---

[a] Time from when spicule is first visible until it starts to expand or split.

REFERENCES

DeForest, C. E., Martens, P. C. H., & Wills-Davey, M. J. 2009, ApJ, 690, 1264

De Pontieu, B., Erd'elyi, R., & James, S. P. 2004, Nature, 430, 536

De Pontieu, B., Erd'elyi, R., & De Moortel, I. 2005, ApJ, 624, L61

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, Sol. Phys., 34, 323

Hollweg, J. V. 1982, ApJ, 257, 345

Kalkofen, W. 2007, ApJ, 671, 2154

Innes, D. E., Genetelli, A., Attie, R., & Potts, H. E. 2009, A&A, 495, 319

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

Moore, R. L., Sterling, A. C., Hudson, H. S., & Lemen, J. R. 2001, ApJ, 552, 833

Nindos, A., & Zirin, H. 1998, Sol. Phys., 179, 253

Reardon, K. P., Lepreti, F., Carbone, V., & Vecchio, A. 2008, ApJ, 683, 207

Rutten, R. J., & Uitenbroek, H. 1991, Sol. Phys., 134, 15

Shibata, K., et al. 2007, Science, 318, 1591S

Sivaraman, K. R., et al. 2000, A&A, 363, 279

Sterling, A. C., & Mariska, J. T. 1990, ApJ, 349, 647

Sterling, A. C., et al., 1991, ApJ, 381, 313

Sterling, A. C., Harra, L. K., & Moore, R. L. 2007, ApJ, 669, 1359

Sterling, A. C., Moore, R. L., & DeFores t, C. E. 2010, ApJ, 714, L1

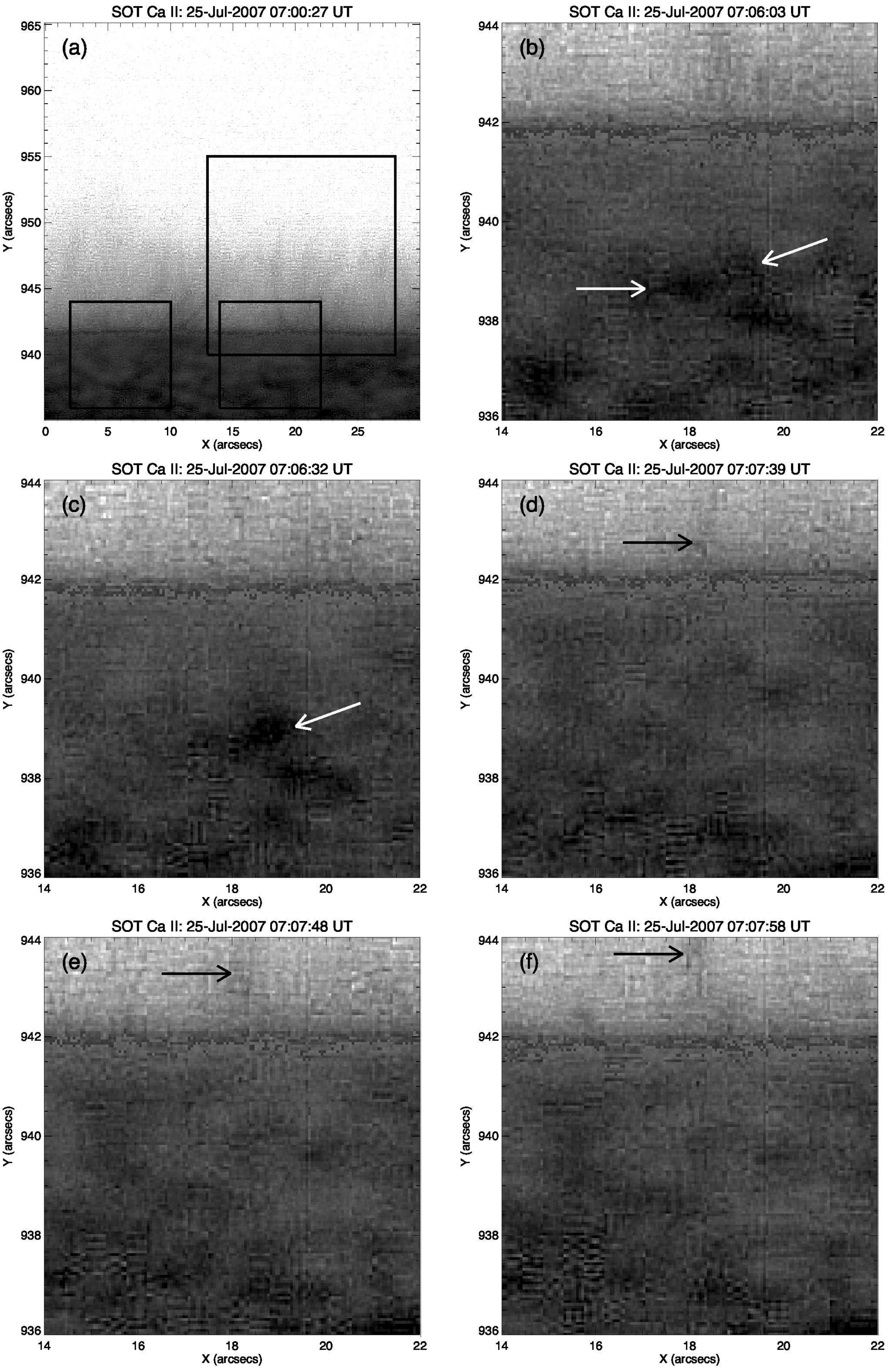
Suematsu, Y., et al. 2008, ASP Conference Series, 397, 27S

Tanaka, K. 1974, IAUS, 56, 239

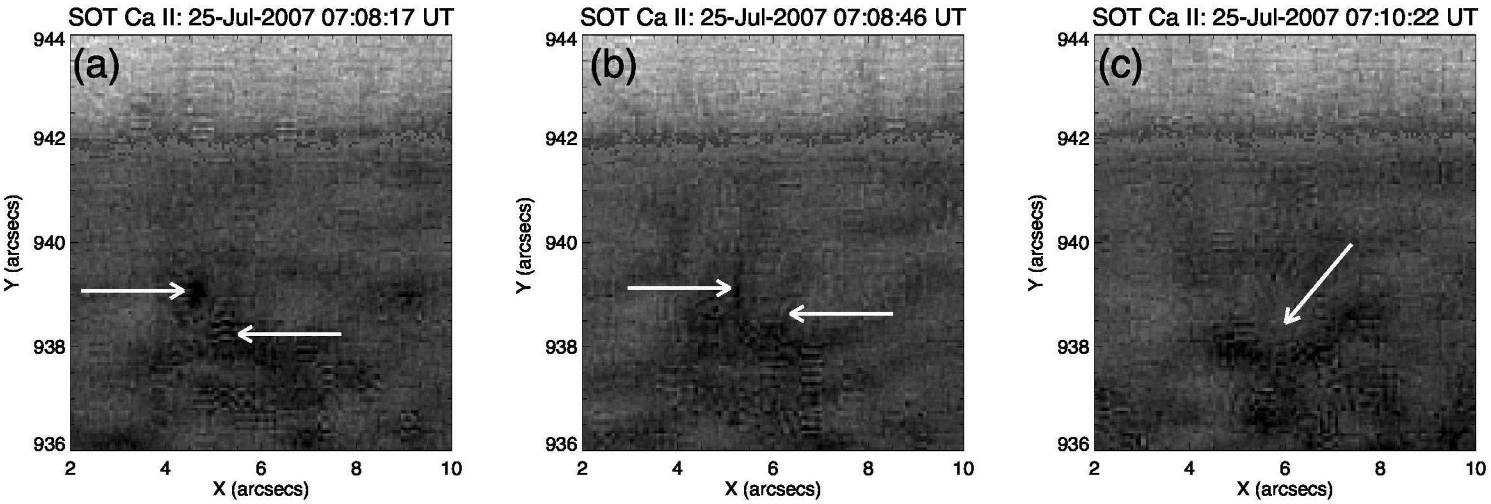
Fig. 1.— Frame a is from video 1a of Sterling, Moore, & DeForest (2010), showing Ca II spicules at the north polar limb. Boxes represent the fields of view (FOV) of closeups shown in other figures: the small box on the right is the FOV for Figs. 1b—1f; the small box of the left is the FOV for Fig. 2; and the large box is the FOV for Fig. 3. Figs. 1b—1f are from video 1b_f of Sterling, Moore, & DeForest (2010), and show merging of two Ca II brightenings in (b) and (c), and a spicule ejected after the merging and fading of the brightenings in (d)—(f); this is event 1 of Table 1. In (d)—(f) other spicules are abundant, forming a haze identifiable in the broader solar context in (a), and also there is at least one other relatively prominent spicule visible in (b). But the arrows in (d)—(f) point out the specific spicule apparently resulting from the interaction of the Ca II brightenings of (b) and (c), and this is better seen in video 1b_f of Sterling, Moore, & DeForest (2010). For this and all figures the color table is reversed, so that Ca II brightenings on the solar disk appear dark. North is up and West is to the right in this and all other figures of this *Poster.* A weak radial filter was applied to this figure and to figure 2 to enhance the detail in the stills; this results in an artifact of an intensity jump at the limb.

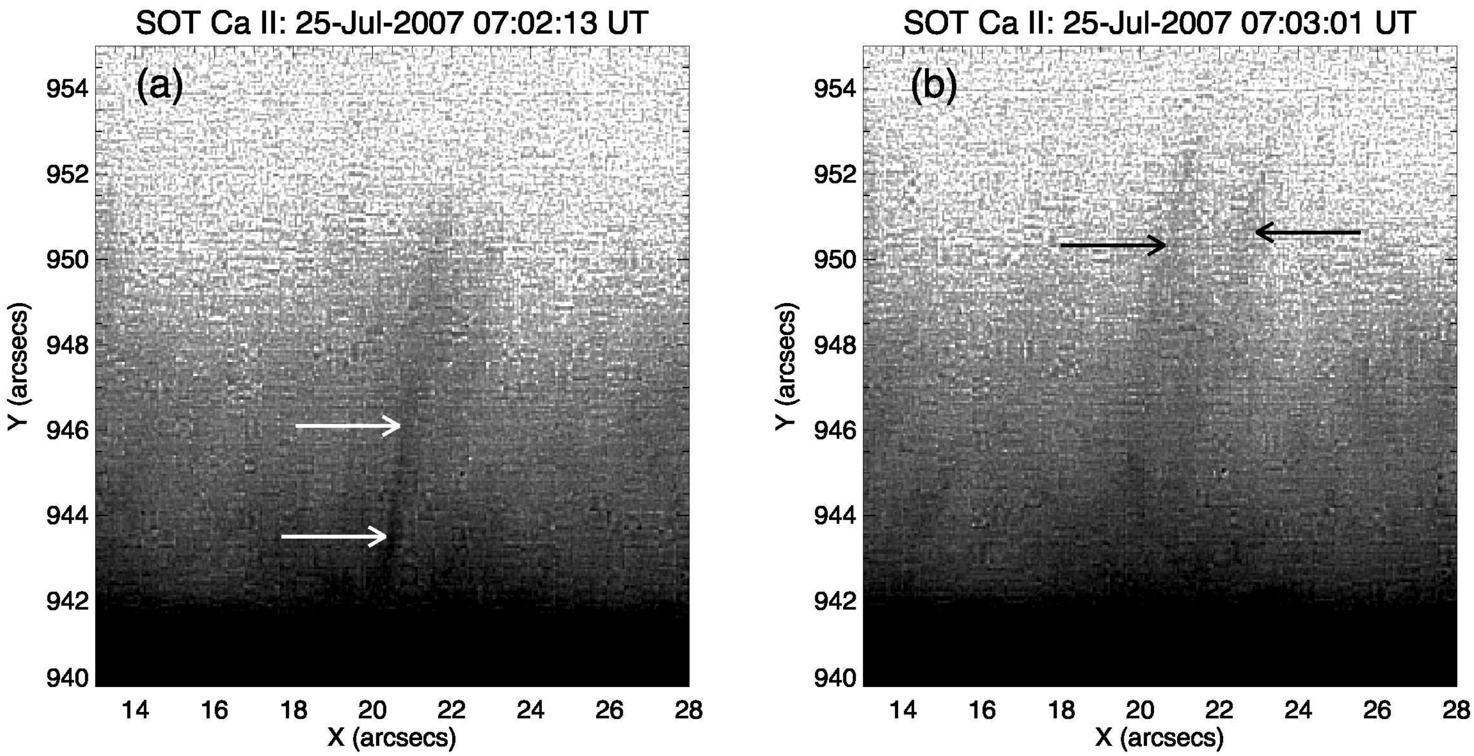
Fig. 2.— Frame from video 2 of Sterling, Moore, & DeForest (2010), showing Ca II brightenings coming together (a), resulting in spicular ejections (b), and leaving a void after the brightenings and spicules have faded (c). This is event 2 in Table 1.

Fig. 3.— Frame from video 3 of Sterling, Moore, & DeForest (2010), showing a spicule ejected as a single strand (a), and splitting into two strands later (b). A spicule appears as a single-jet structure when it is ejected at 07:01:44 UT. From about 07:02:22 UT however, this single spicule “breaks up” into two structures, with one moving westward at ~ 45 km s^{-1}. This is event 1 of Table 2. The color table was changed from earlier figures to better show above-the-limb features.



SOT Ca II: 25-Jul-2007 07:00:27 UT
(a)
SOT Ca II: 25-Jul-2007 07:06:03 UT
(b)
SOT Ca II: 25-Jul-2007 07:06:32 UT
(c)
SOT Ca II: 25-Jul-2007 07:07:39 UT
(d)
SOT Ca II: 25-Jul-2007 07:07:48 UT
(e)
SOT Ca II: 25-Jul-2007 07:07:58 UT
(f)
Y (arcsecs)
X (arcsecs)
965
960
955
950
945
940
0
5
10
15
20
25
944
942
940
938
936
14
16
18
20
22


SOT Ca II: 25-Jul-2007 07:08:17 UT
(a)
SOT Ca II: 25-Jul-2007 07:08:46 UT
(b)
SOT Ca II: 25-Jul-2007 07:10:22 UT
(c)
Y (arcsecs)
944
942
940
938
936
X (arcsecs)
2
4
6
8
10


SOT Ca II: 25-Jul-2007 07:02:13 UT
(a)
Y (arcsecs)
X (arcsecs)
954
952
950
948
946
944
942
940
14
16
18
20
22
24
26
28
SOT Ca II: 25-Jul-2007 07:03:01 UT
(b)
Y (arcsecs)
X (arcsecs)
954
952
950
948
946
944
942
940
14
16
18
20
22
24
26
28