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Samanta, T., Tian, H., Yurchyshyn, V. et al. (9 more authors) (2019) Generation of solar spicules and subsequent atmospheric heating. Science, 366 (6467). pp. 890-894. ISSN 0036-8075

https://doi.org/10.1126/science.aaw2796

Title: Generation of Solar Spicules and Subsequent Atmospheric Heating

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Abstract: Dynamical phenomena in the solar chromosphere include rapidly evolving fine-scale jets of magnetized plasma known as spicules. It remains unclear how these prevalent jets originate from the solar surface and what role they play in heating the solar atmosphere. Using the Goode Solar Telescope at the Big Bear Solar Observatory, we observe spicules emerging within minutes of the appearance of opposite-polarity magnetic flux around the dominant-polarity magnetic field concentrations. Data from the Solar Dynamics Observatory show subsequent heating of the adjacent corona. The dynamic interaction of magnetic fields (likely due to magnetic reconnection) in the partially ionized lower solar atmosphere appears to generate these spicules and heat the upper solar atmosphere.

Main text: Solar spicules are small-scale, jet-like plasma features observed ubiquitously in the solar chromosphere, the interface between the visible surface (photosphere) of the Sun and its hot outer atmosphere (corona) (*1–4*). Spicules may play a key role in the supply of energy and material to the corona and solar wind (*4, 5*). They often have lifetimes ranging from 1 to 12 minutes and are characterized by rising and falling motions with speeds of 15–40 km s^{-1} (*1, 6*). Some spicules may have apparent speeds of ~100 km s^{-1} and lifetimes less than 1 minute (*7*). In on-disk chromospheric observations, spicules often appear as elongated, short-lived dark structures (*8*). Some spicules are heated to $\gtrsim$ 100,000 Kelvin (*9, 10*).

Theoretical models of spicules have included driving by shock waves (*2, 3*), Alfvén waves (*11, 12*), amplified magnetic tension (*13*), or magnetic reconnection (*14*). However, observations of their formation process are limited, due to insufficient resolution and sensitivity. Two observations reveal a tendency for new magnetic fluxes to appear near pre-existing fields before the occurrence of some spicules (*15, 16*). However, further analysis did not yield an obvious association between spicules and magnetic field evolution (*16*).

We observed spicules using the 1.6-m Goode Solar Telescope (GST; *17, 18*) at the Big Bear Solar Observatory (BBSO; Fig. S1). We performed Hα wing observations and simultaneous magnetic flux measurements with GST's Near Infra-Red Imaging Spectropolarimeter (NIRIS; *19*). NIRIS enables us to obtain information on photospheric magnetic fields via spectropolarimetric observations of the Fe I 1.56 µm line (*18,* Figs. S2 & S3). Figure 1A shows an image of the solar surface at the blue wing (-0.8 Å from line core) of the Hα line. It is dominated by numerous elongated dark jets - spicules. These spicules mostly originate from the magnetic network, indicated by the locations of magnetic field concentrations with positive polarity (Figs. 1 & S2).

In addition to frequent individual spicules, occasionally several spicules originate simultaneously from a small region, appearing as enhanced spicular activity at a single location (Movie S1). These enhanced spicular activities are accompanied by weak magnetic elements with a polarity opposite to the dominant polarity of the magnetic network at their footpoints (Fig. 1B-J). When spicules occur, these weak elements are typically within several hundred km from the edge of the strong network fields. In contrast, the strong and evolving unipolar fields (present for a much longer time in the network) generally do not produce enhanced spicular activities.

These enhanced spicular activities appear to be driven by the dynamical interaction of magnetic fields, often preceded by new flux emergence/appearance, and sometimes accompanied by apparent flux cancellation near the network edge. Figure 2A-D shows a patch of small-scale weak field with negative polarity that emerges near the strong positive-polarity network fields in the photosphere. Its coincidence with a patch of large blue shift of Fe I also indicates the emergence of the field (Movie S2, Figs. S4 & S5). This flux emergence is followed (within minutes) by enhanced spicular activity, observed in the blue wing of Hα. Figure 2E-H shows a larger patch of weak negative-polarity field that approaches the strong network fields; the subsequent flux cancellation leads to enhanced spicular activity (Movie S3). The flux cancellation takes place at the boundary of a convection cell that is characterized by red shifts of Fe I.

Almost all the enhanced spicular activities we observe are associated with emergence or appearance of negative-polarity fluxes and/or subsequent flux cancellation around the boundary of the positive-polarity magnetic network (Figs. 2 & S6, Movie S4). Moreover, many individual spicules appear to originate, sometimes repeatedly, from small-scale negative-polarity magnetic features located near the strong network fields (Figs. 3 & S7). Although small-scale flux emerges/appears ubiquitously in the quiet Sun, our observations indicate that only when it is close to the strong network fields (often < 3 Mm, Fig. 3, Movie S4) does it generate spicules. For some small spicules no opposite polarity is detected at their footpoints. Because the magnetograms have a spatial resolution (~150 km) about 3 times lower and a cadence (71 s) around 20 times slower than the Hα images, there may be smaller-scale or highly dynamic fields at the footpoints of these small spicules that we are not able to detect.

Our results support the hypothesis that fast spicules originate from magnetic reconnection (*14, 20, 21*). It is possible that a sub-photospheric local dynamo mechanism (*22*) or magnetoconvection process (*13, 23*) generates weak magnetic fields close to the large-scale network fields. These small-scale weak fields may occasionally emerge into the photosphere and rise to the chromosphere, where they reconnect with adjacent or overlying network fields to produce high-speed spicules. Alternatively, an opposite-polarity magnetic element could appear due to the coalescence and concentration of previously-existing dispersed and unresolved fluxes (*24*), then reconnect with the network fields to generate spicules.

Spicules might supply hot plasma to the solar corona (*4, 5, 9*). We analyzed coronal observations of the same region with the Atmospheric Imaging Assembly (AIA; *25*) on the Solar Dynamics Observatory (SDO) spacecraft (*18*). Most of the enhanced spicular activities are seen to channel hot plasma into the corona (Figs. 4, S8, S9, Movies S5-S8). Coronal emission (visible in AIA images at 171 Å) generally appears at the top of the spicules. Our results complement previous observations (*4, 26*), where similar coronal signatures were identified for some chromospheric upflow events observed above the solar limb or in on-disk active regions (regions around sunspots). Our observations reveal that magnetic reconnection events at network boundaries can drive spicules and produce hot plasma flows into the corona, providing a link between magnetic activities in the lower atmosphere and coronal heating. It is unclear whether this process provides sufficient heating to explain the high temperature of the corona (*27, 28*).

Heated material sometimes falls back from the corona (Fig. S10, Movie S9), which could be responsible for the prevalent redshifts of emission lines formed in the chromosphere-corona transition region (*29–30*). Our observations of the formation of spicules, the subsequent heating, and the return flows reveal a complete mass cycling process between the chromosphere and corona.

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Acknowledgments: BBSO operation is supported by NJIT and NSF. GST operation is partly supported by the Korea Astronomy and Space Science Institute (KASI), Seoul National University, the Strategic Priority Research Program of CAS with grant No. XDB09000000, and the Operation, Maintenance and Upgrading Fund for Astronomical Telescopes and Facility Instruments administrated by CAS. The AIA is an instrument on SDO, a mission of NASA's Living With a Star Program. We thank the GST and SDO teams for providing the data, and Sami K. Solanki and Luis R. Bellot Rubio for helpful discussion. **Funding:** This work is supported by NSFC grants 11825301, 11790304(11790300), 41574166, 11729301, U1931107 and 11850410435, NSF grants AGS 1821294, 1620875 and AST-1614457, AFOSR FA9550-15-1-0322, NASA HGC 80NSSC17K0016 and HGI 17-HGISUN17_2-0047 grants, Max Planck Partner Group program, Strategic Priority Research Program of CAS with grant XDA17040507, Key Applied Basic Research Program of Yunnan Province (FS: 2018FA035), FWF project N27800, CAS Presidents International Fellowship Initiative Grant No. 2019VMA052, UK STFC grant ST/M000826/1 and the Royal Society. **Author contributions:** H.T. and T.S. defined the novel science case and wrote the manuscript. T.S. analyzed the data, generated the figures and movies under H.T.'s guidance. V.Y. generated the GST observations, processed the GST data, and gave advice to the data analysis. W.C. developed instruments of GST. K.A. processed the GST NIRIS data for scientific usage. S.F. helped with co-alignment of the data. Y.C. performed the energy calculation and helped with verification of the results. H.P., A.S., R.E., D.U., D.B. have contributed to the interpretation of the observations. All authors have discussed the results and commented on the manuscript. **Competing interests:** There are no competing interests. **Data and materials availability:** The GST data can be retrieved from the GST Data Catalog http://www.bbso.njit.edu/~vayur/NST_catalog/2017/06/19/. The AIA data are available at the Joint Science Operations Center http://jsoc.stanford.edu/.

Supplementary Materials:
Materials and Methods
Supplementary Text
Figs. S1 to S10
Table S1
References (*31*-*88*)
Movies S1 to S9

Fig. 1. Association of enhanced spicular activities with opposite-polarity magnetic fields. (A) Hα blue wing image (greyscale) overlain with a binary magnetic field map shown in blue and red, representing longitudinal flux densities of at least +10 Mx cm^{-2} and -10 Mx cm^{-2}, respectively (1 Mx=10^{-8} Wb; the unit of Mx cm^{-2} is equivalent to Gauss). Movie S1 shows an animated version of this panel. (B-J) Examples of enhanced spicular activities. Blue and red contours outline regions of +/- 10 Mx cm^{-2} for the longitudinal flux density. Axes are the same in different panels. The black circle (radius 1 Mm) in each panel highlights a region around the footpoint of a region of enhanced spicular activity, where a small negative-polarity magnetic element is observed.

Fig. 2. Enhanced spicular activity triggered by flux emergence (A-D, Movie S2) and flux cancellation (E-H, Movie S3). (A) Enhanced spicular activity in a Hα blue wing image. (C) Photospheric Doppler shift pattern of the same region. (B) and (D) Temporal evolution around the spicule footpoint region (dotted boxes in A and C). Contour colors and levels are the same as in Fig. 1B. An arrow in (B) indicates the presence of an opposite-polarity flux. Panels (E-H) are the same as (A-D) but for a different region.

Fig. 3. Connection of individual spicules to opposite-polarity magnetic fluxes. (A) The same image as Fig. 1A, overlain with an inner white circle (a radius of 5.25 Mm) representing the approximate boundary of the network, and an outer white circle 3 Mm outside it. Black circles mark the footpoint regions of the same regions with enhanced spicular activity as shown in Fig. 1B-J. Yellow circles have a radius of 0.75 Mm and indicate regions shown in panels (B-Q) and in Fig. S7, which mostly lie within the outer white circle. Movie S4 shows an animated version of this panel. (B-Q) Sixteen examples showing the presence of an opposite-polarity flux near the spicule footpoint (indicated by the yellow circles). Contour colors and levels are the same as in Figure 1B. The white arrow in each panel indicates the direction radially outward from the center of the white circles.

Fig. 4. Coronal connection of enhanced spicular activities (Movie S5). (A) Hα blue wing image (grayscale) overlain with the simultaneously taken AIA 171 Å image (yellow). Boxes indicate regions shown in the other panels. (B-E) Four examples showing the enhancement of coronal emission above regions of enhanced spicular activity (more examples in Fig. S8). The Hα blue wing and the same image overlain with the simultaneous AIA 171 Å image are shown in each pair of panels. The white dotted boxes in (B-E) correspond to the black boxes (R1-R4) in panel (A), respectively.