Generation of solar spicules and subsequent coronal heating

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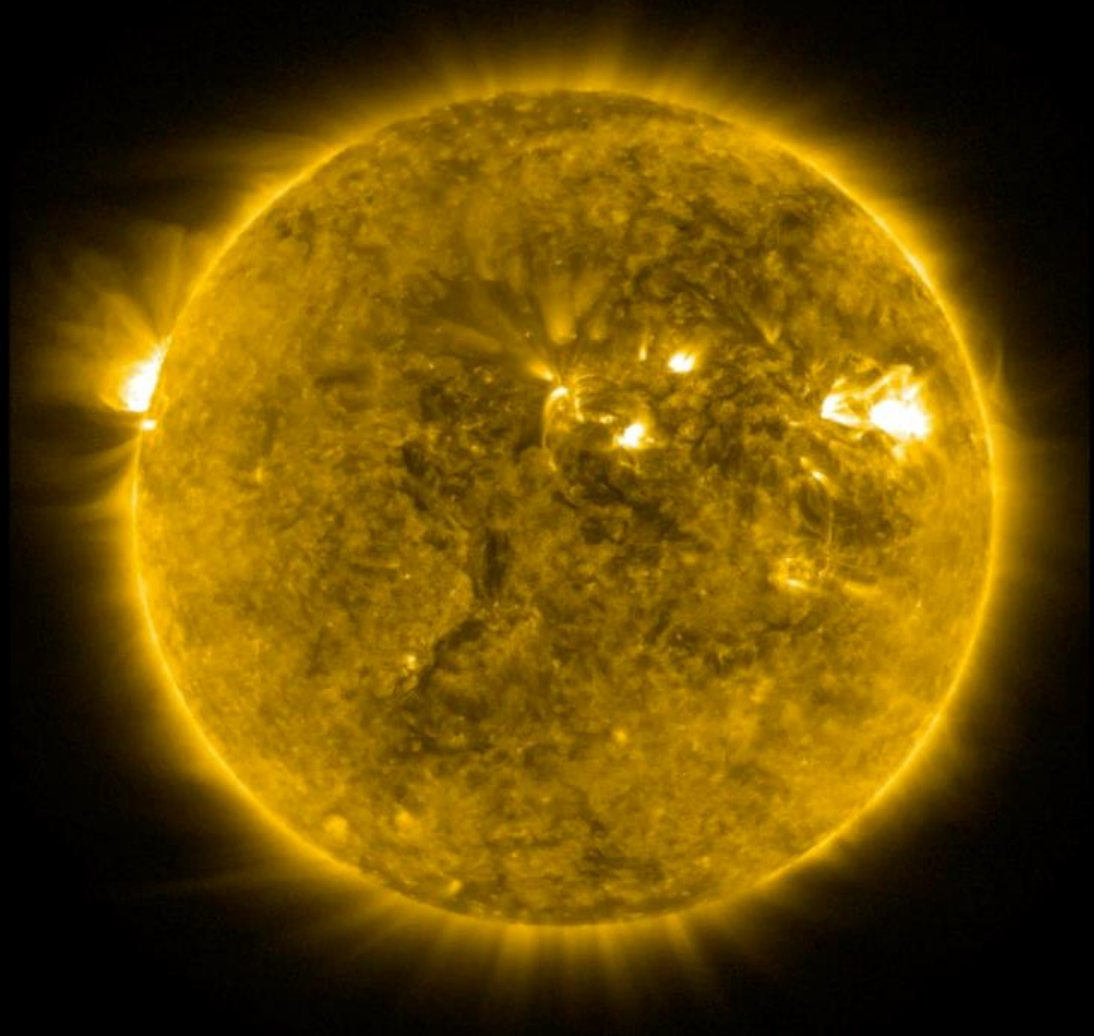
(田 晖)



School of Earth and Space Sciences, Peking University

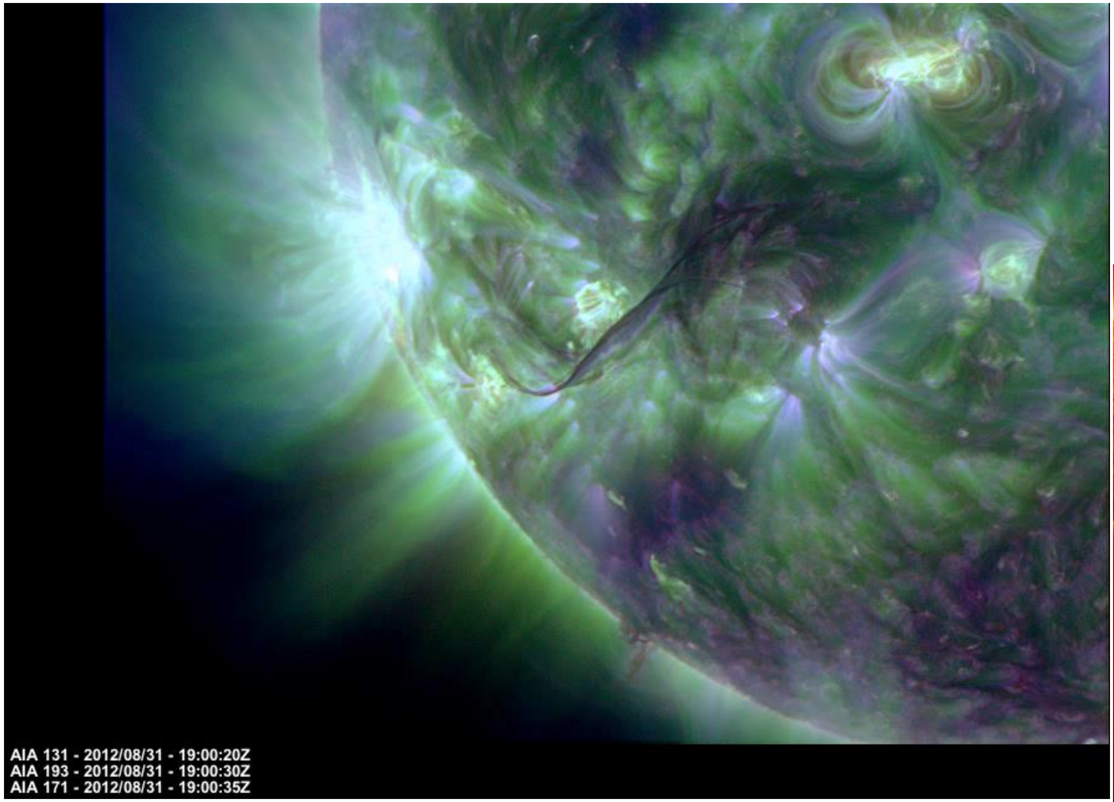
Outline

- Brief introduction to solar physics
- Generation mechanisms of solar spicules
- Spicules and coronal heating

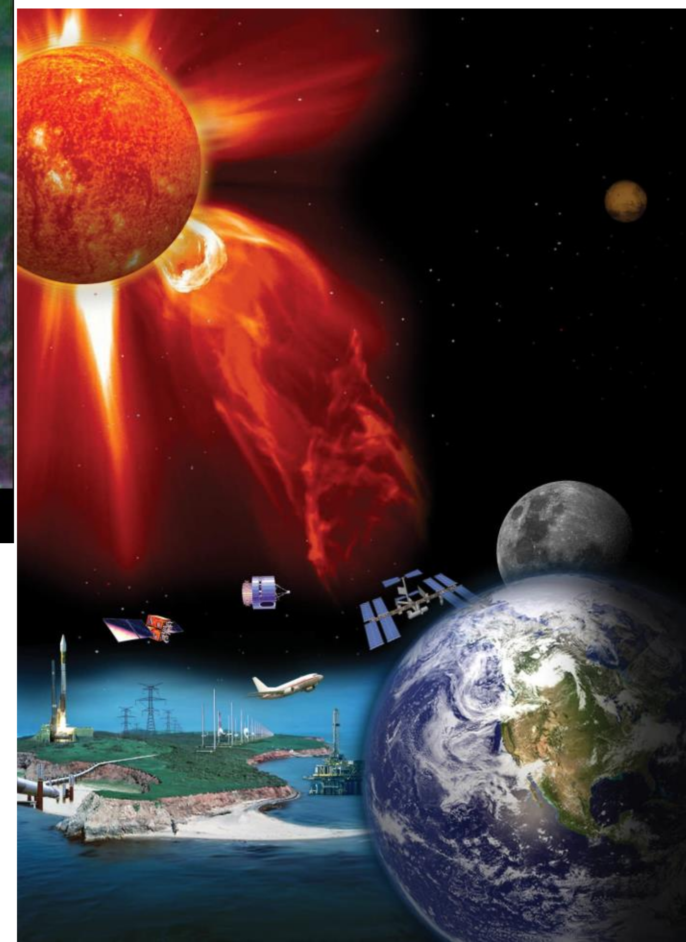
The Sun: ultimate source of space weather

- Space weather: disturbance of space environment by solar eruptions
- Consequences: aurora; damage or cause problems of electric grids, satellites, navigation and communication systems

The Sun: the only star that can be observed at a high spatial resolution

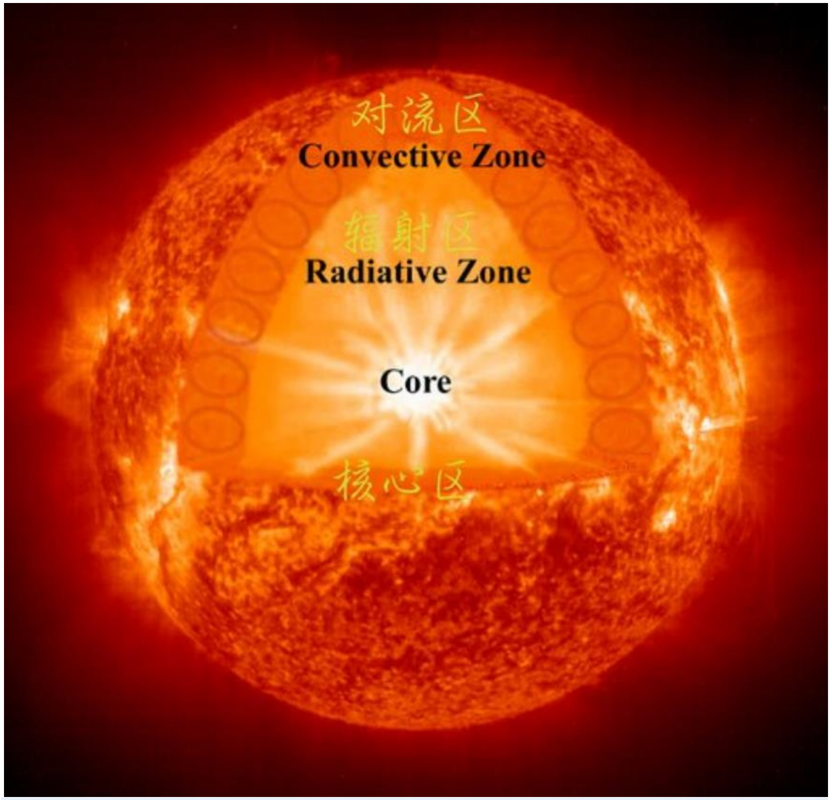


- A unique reference for other stars: stellar magnetic activity



- A unique reference for other star-planet systems: strong stellar EUV/X-ray fluxes and intense stellar eruptions could affect the habitability of exoplanets

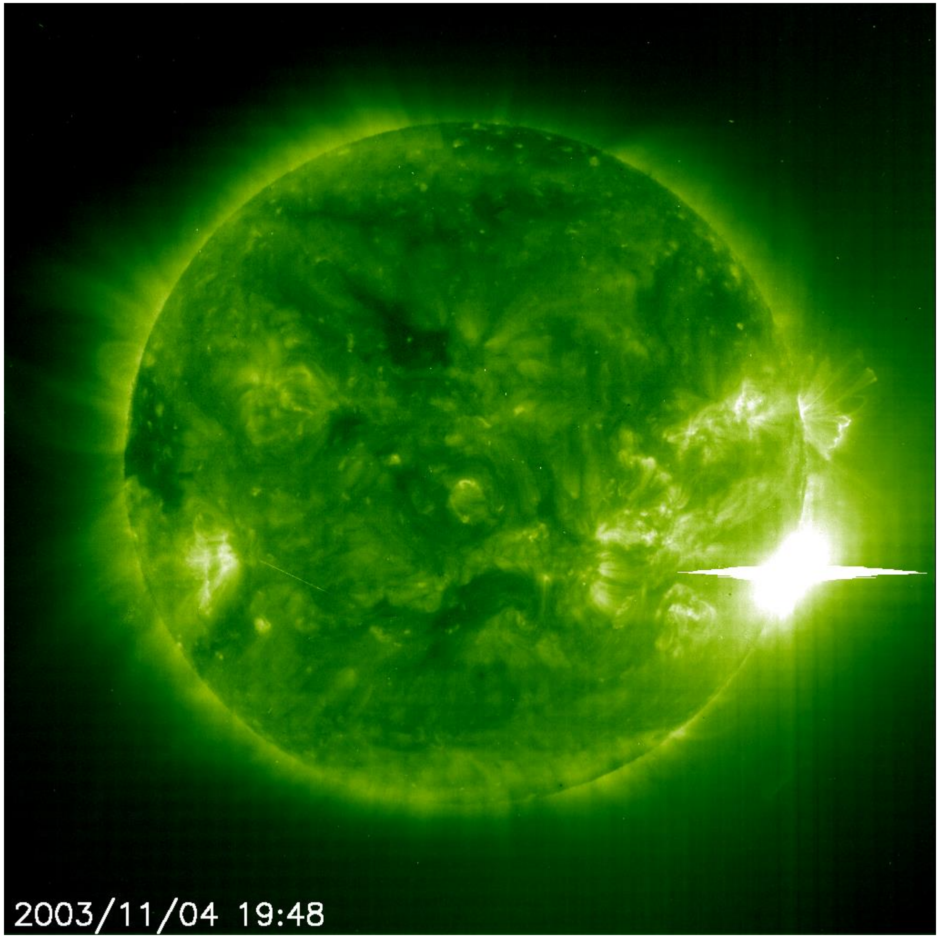
Science topic I: coronal heating

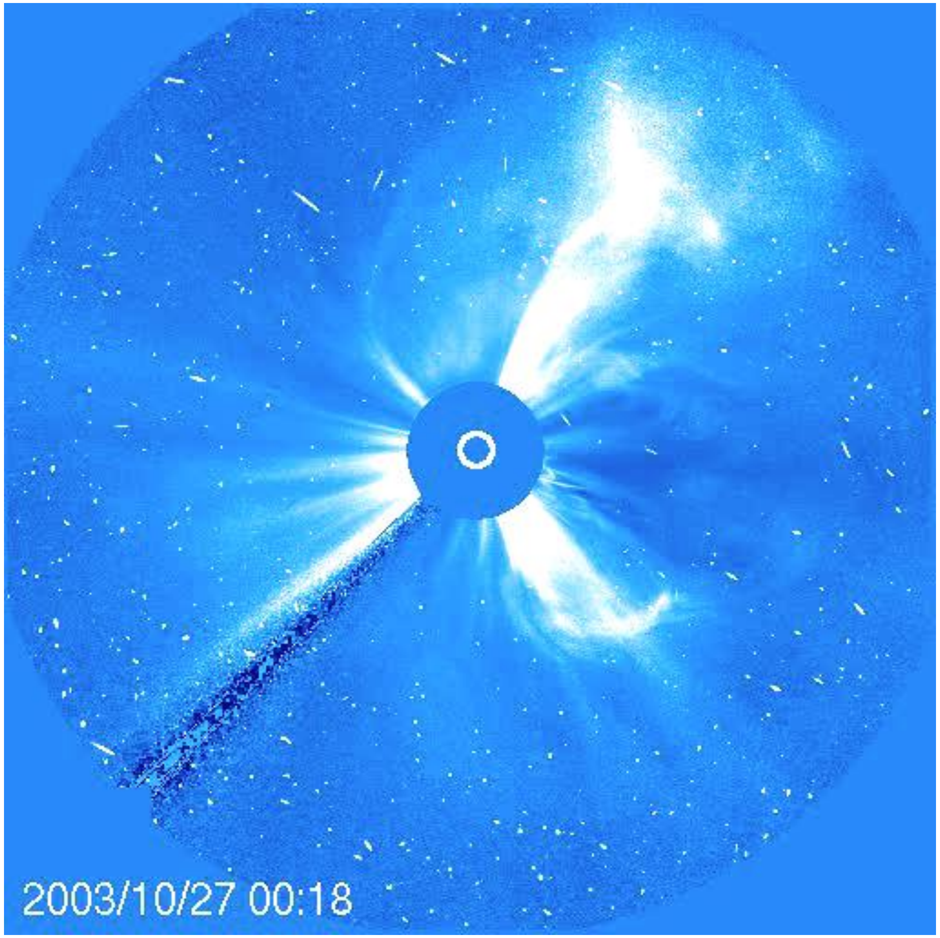


- *T* drops from core to surface (photosphere)
- *T* increases from chromosphere to corona

What processes cause the high temperature of the corona?

Science topic II: solar eruptions



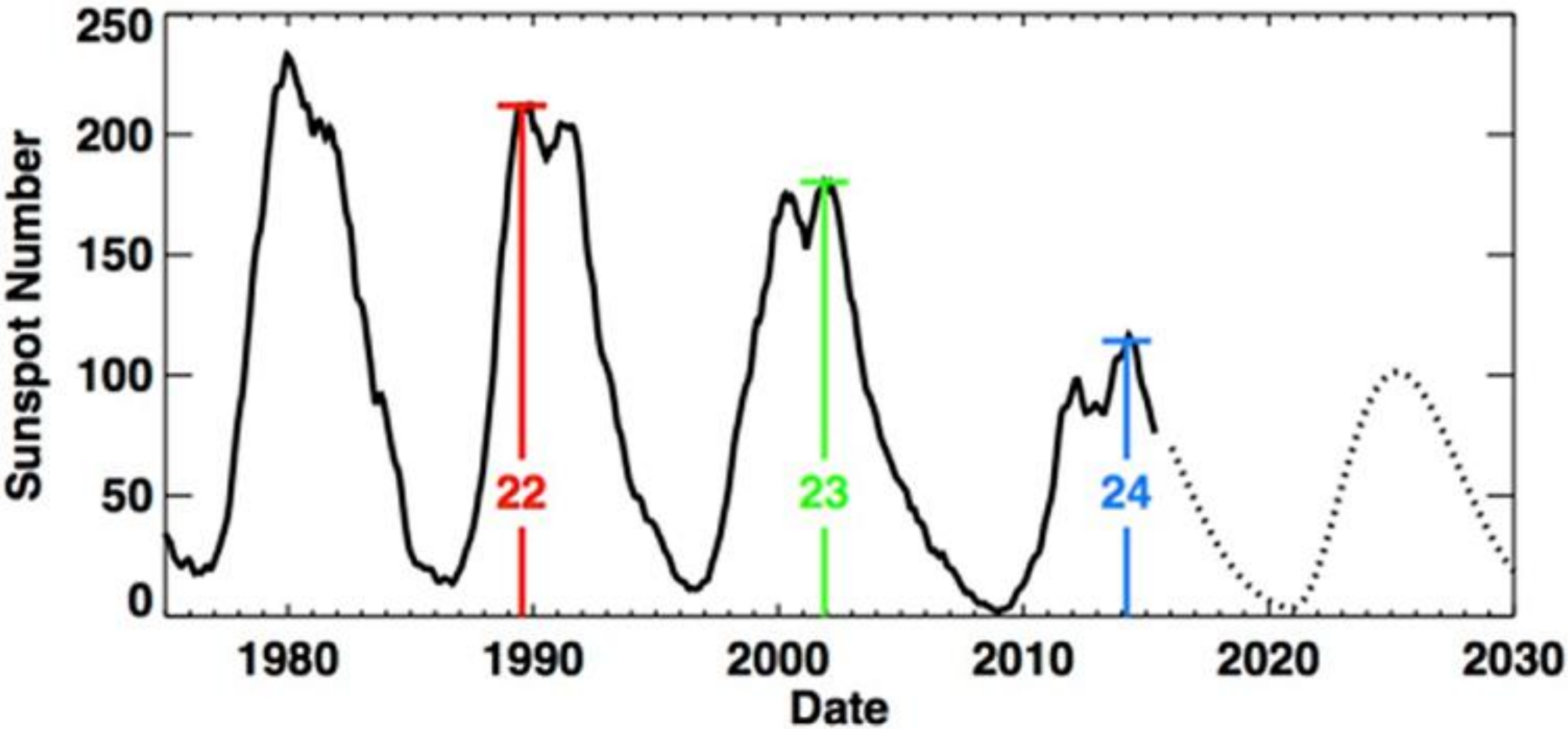


A solar flare observed by SOHO/EIT Coronal mass ejections observed by SOHO/LASCO

What drives solar eruptions?

How to forecast these eruptions and their impact on the Earth?

Science topic III: solar cycle



http://solarcyclescience.com/forecasts.html

What drives the sunspot cycle and how to predict it?

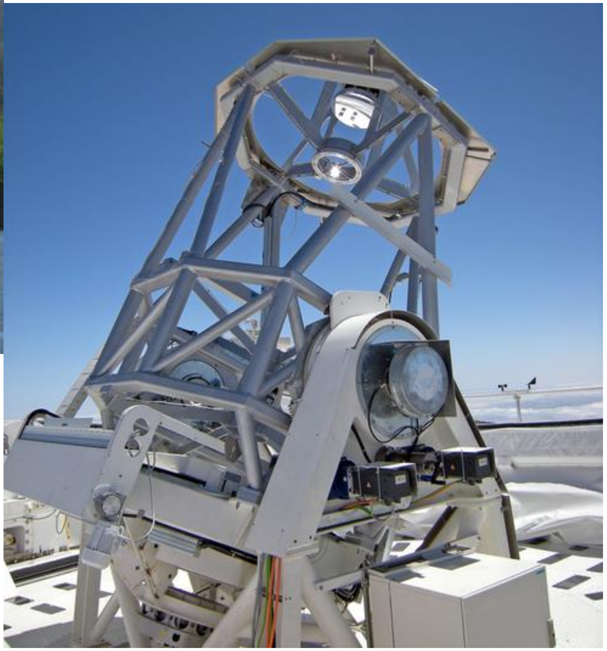
One of the 125 big questions selected by *Science* in 2005

Large solar optical telescopes on the ground

SST, 1m, 2002, Sweden

GST, 1.6m, 2010, USA

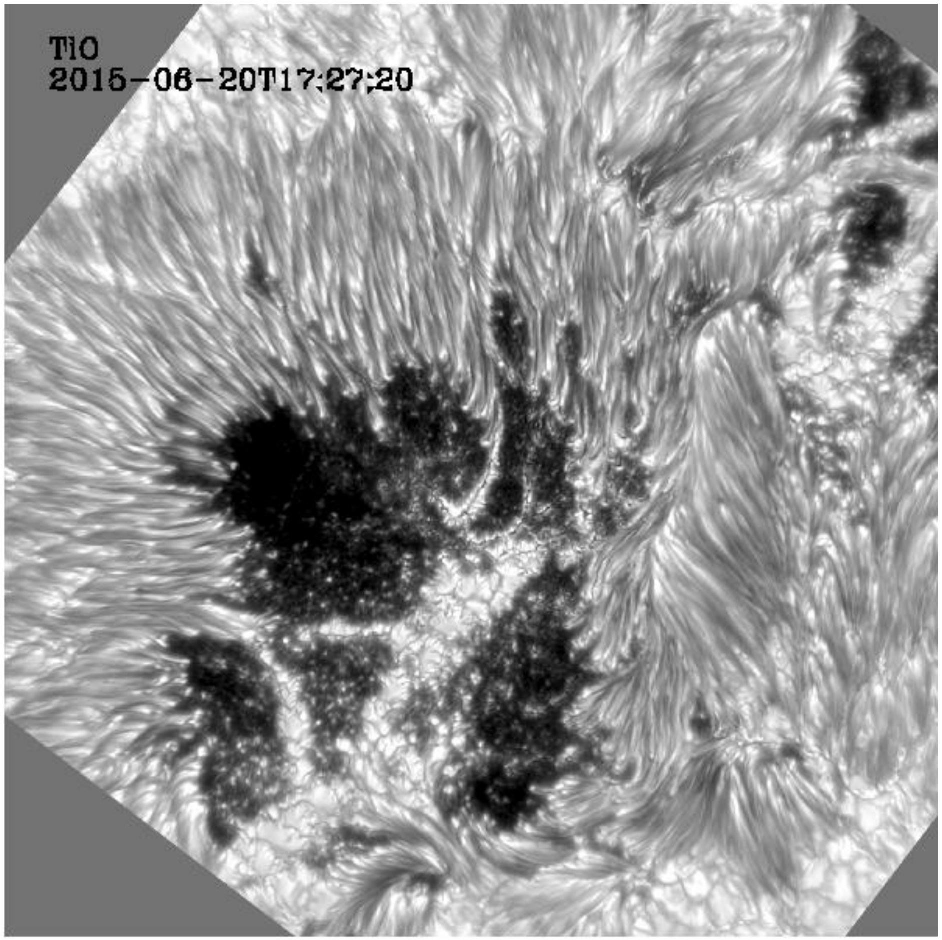
NVST, 1m, 2012, China



GREGOR, 1.5m, 2014, Germany

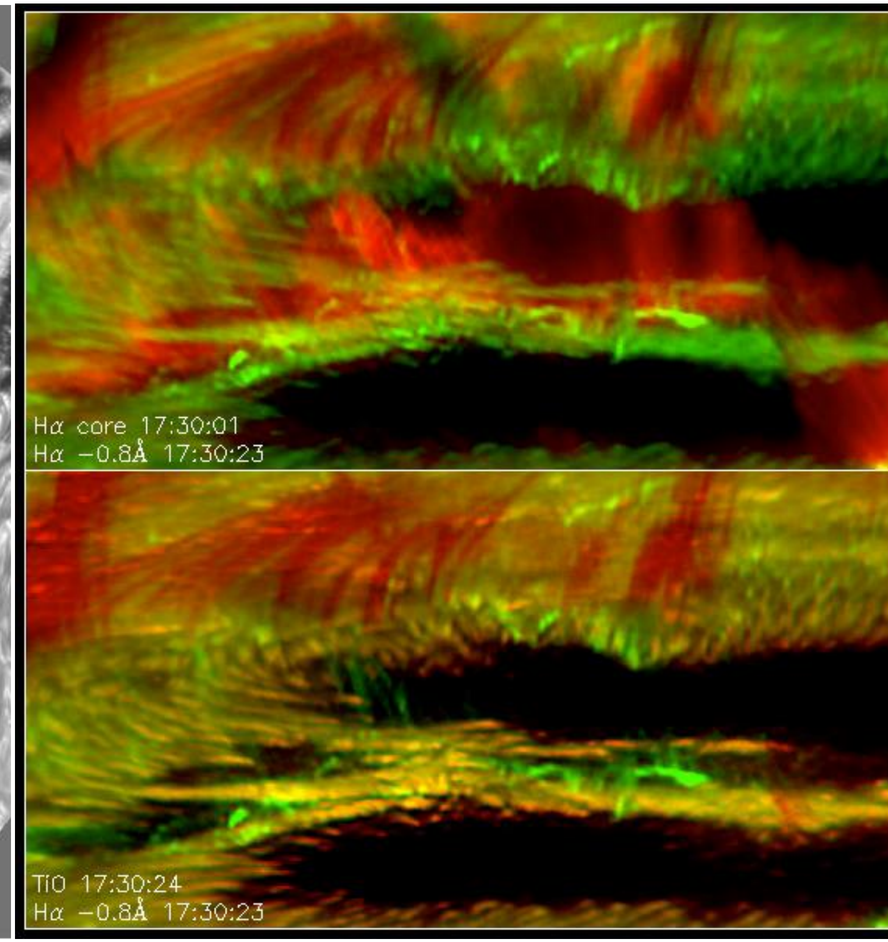
High-resolution observations of the photosphere/chromosphere

Fine structures in sunspots



Zhang, Tian, Solanki, et al. 2018, ApJ

Jets in sunspots



Tian, Yurchyshyn, Peter, et al. 2018, ApJ

Radio telescopes on the ground

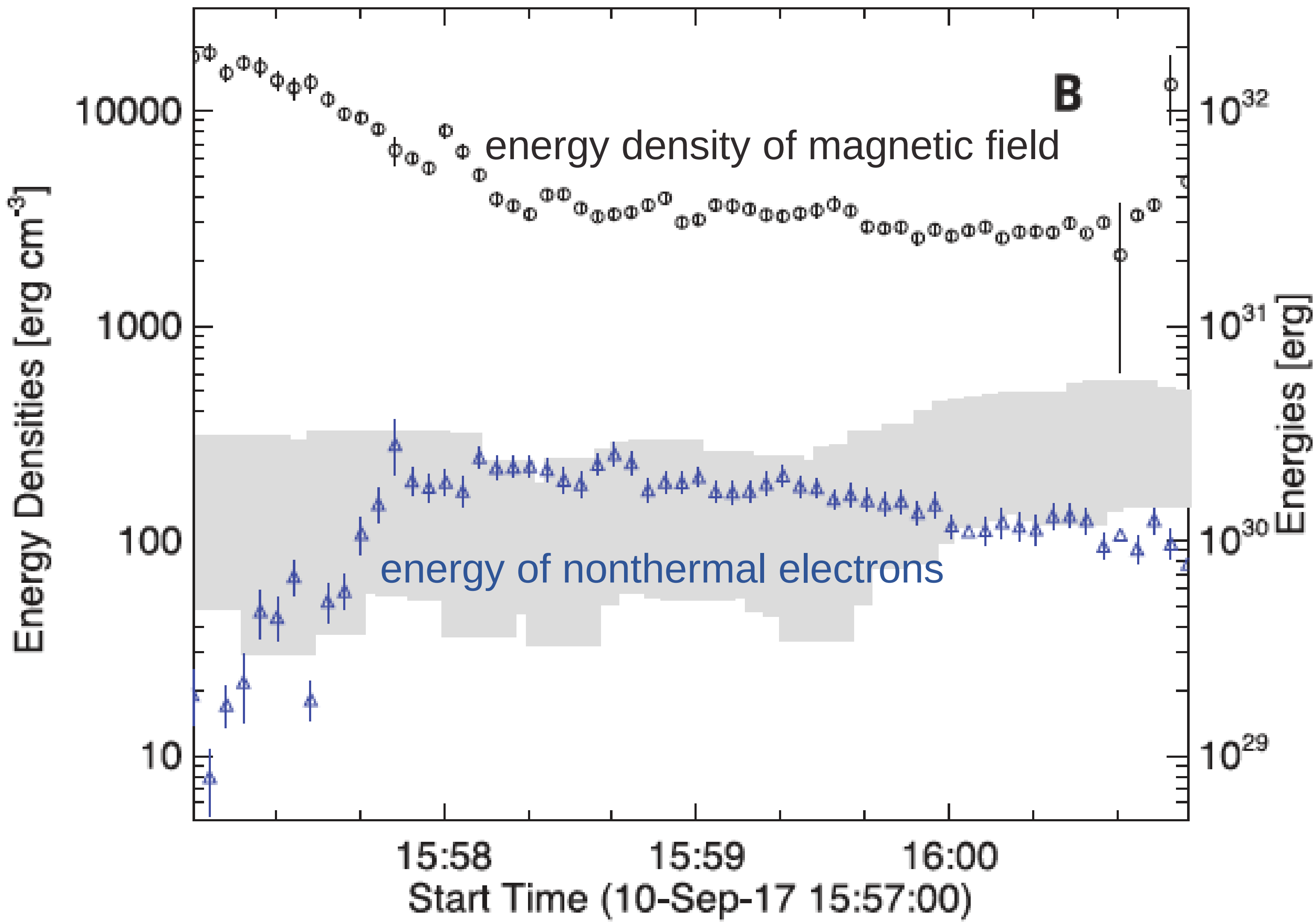
Expanded Owens Valley Solar Array (EOVSA), USA

Nobeyama Radioheliograph (NoRH), Japan

Nancay Radio Heliograph (NRH), France

Mingantu Spectral Radioheliograph (MUSER), China

Particle acceleration



Fleishman et al. 2020, Science

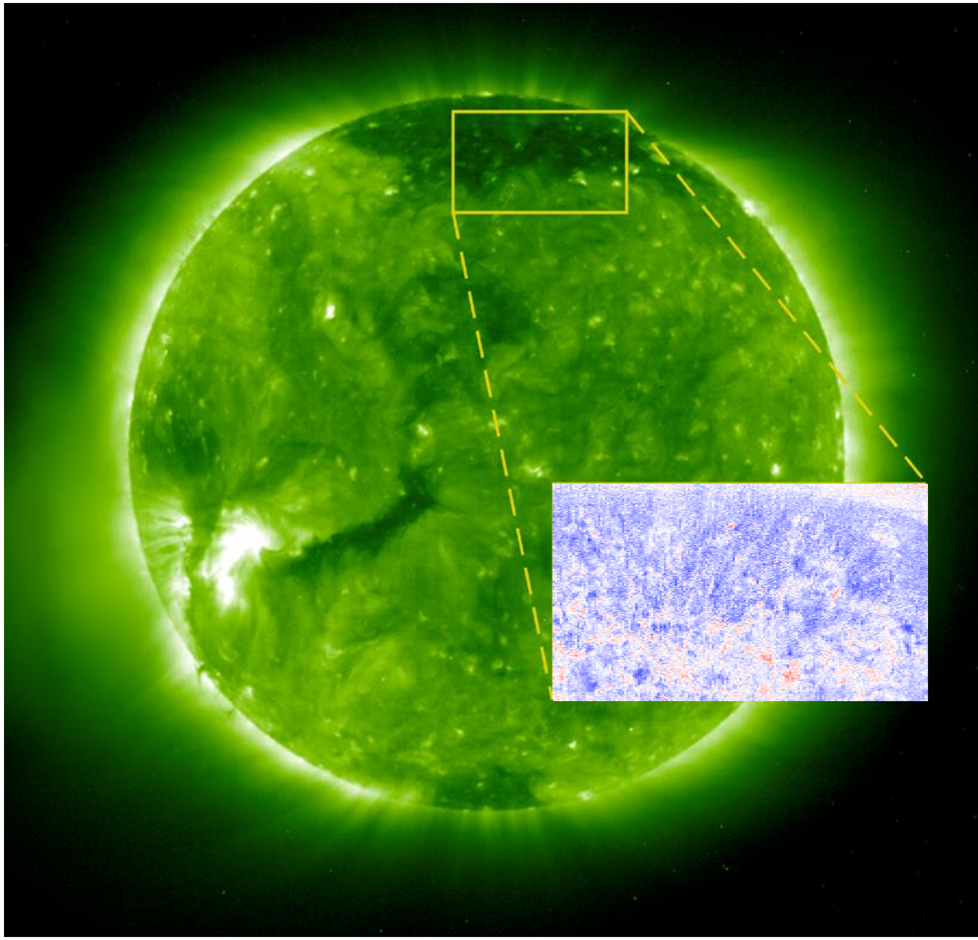
Solar space missions since 1995

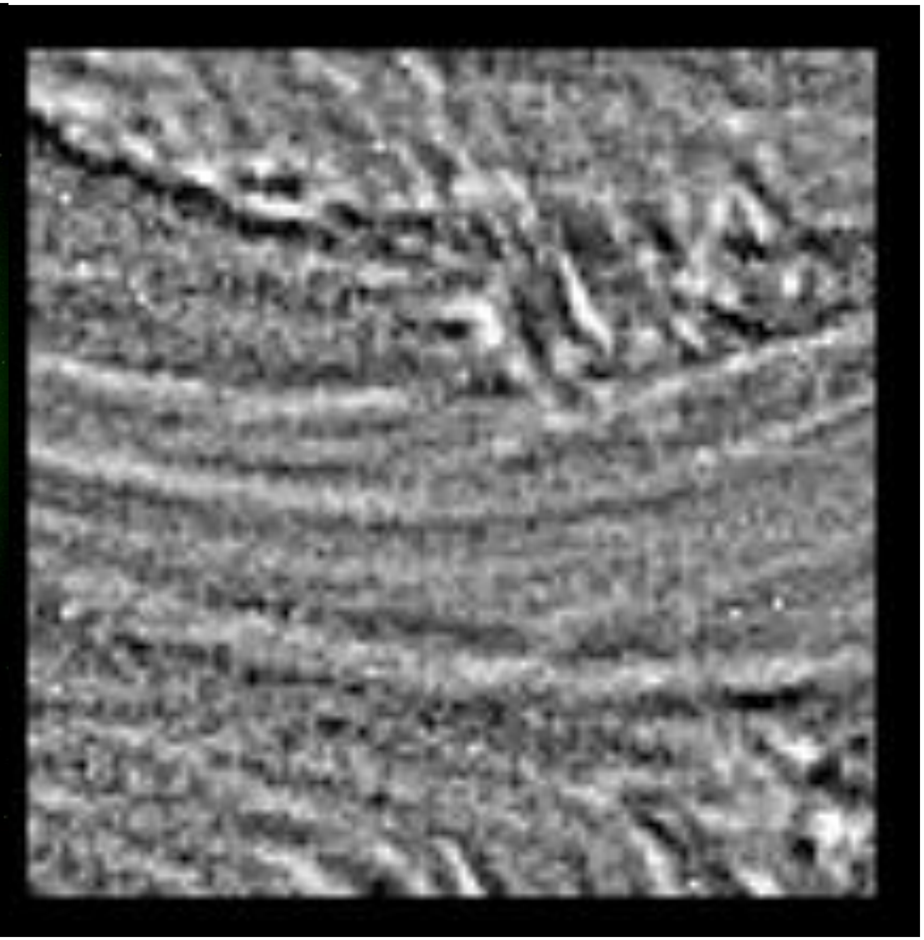
- Extend to (E)UV and X-ray
- Continuous observations, not affected by seeing and weather

EUV observations of the corona

Prevalent blueshifts of Ne VIII 770 Å in coronal holes: nascent solar wind

Alfvénic wave energy large enough to power the corona?

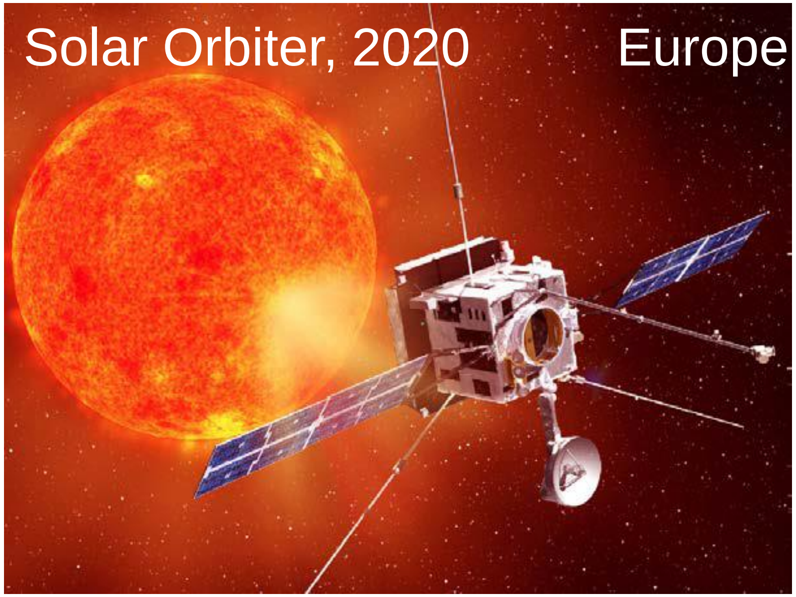


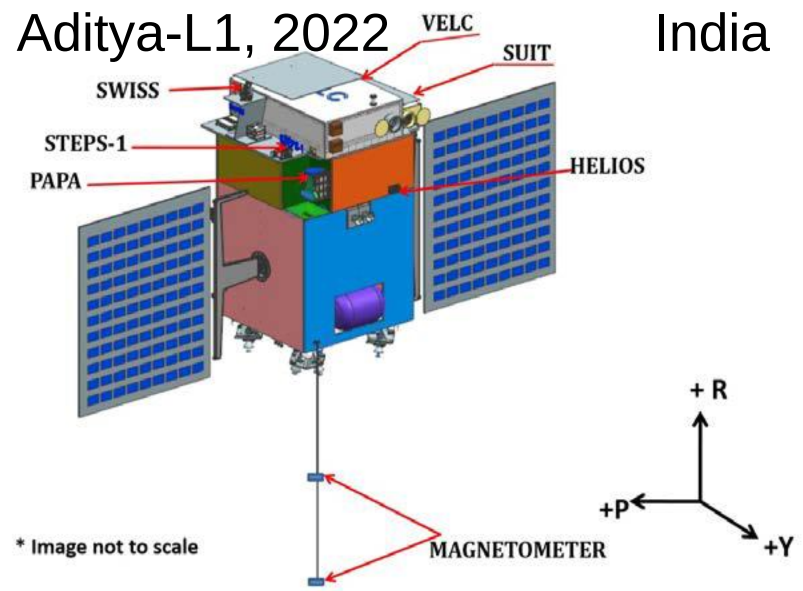


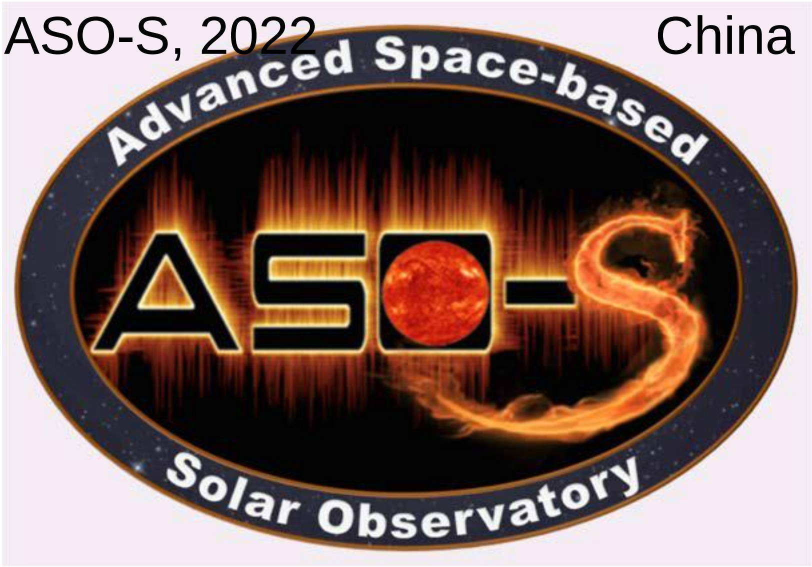
Hassler et al. 1999, Science
Tu et al. 2005, Science

McIntosh et al. 2011, Nature

Solar observatories in the next 5 years

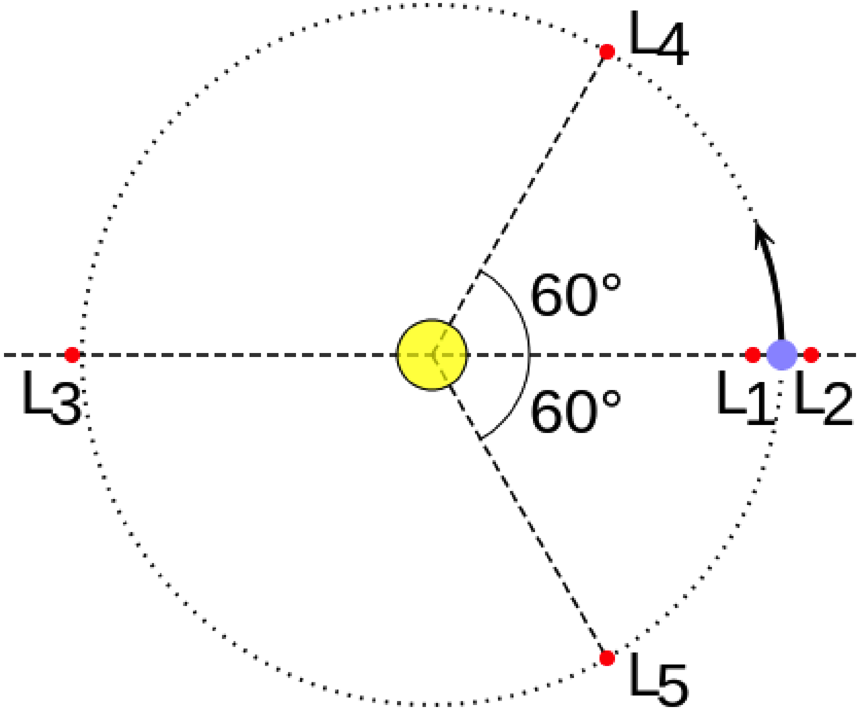


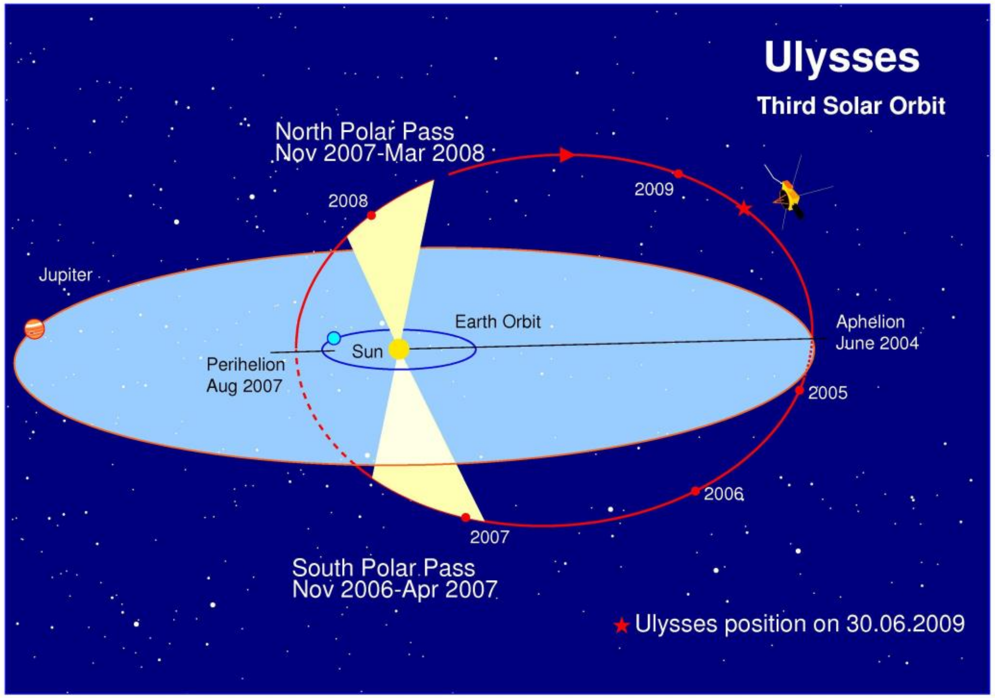




Golden age of solar physics!

Future flagship solar space missions





Multi-position solar space observatory

Solar polar observatory

Proposed by solar physicists in USA, Europe, China, Japan, India, et al.

Golden age of solar physics will continue!

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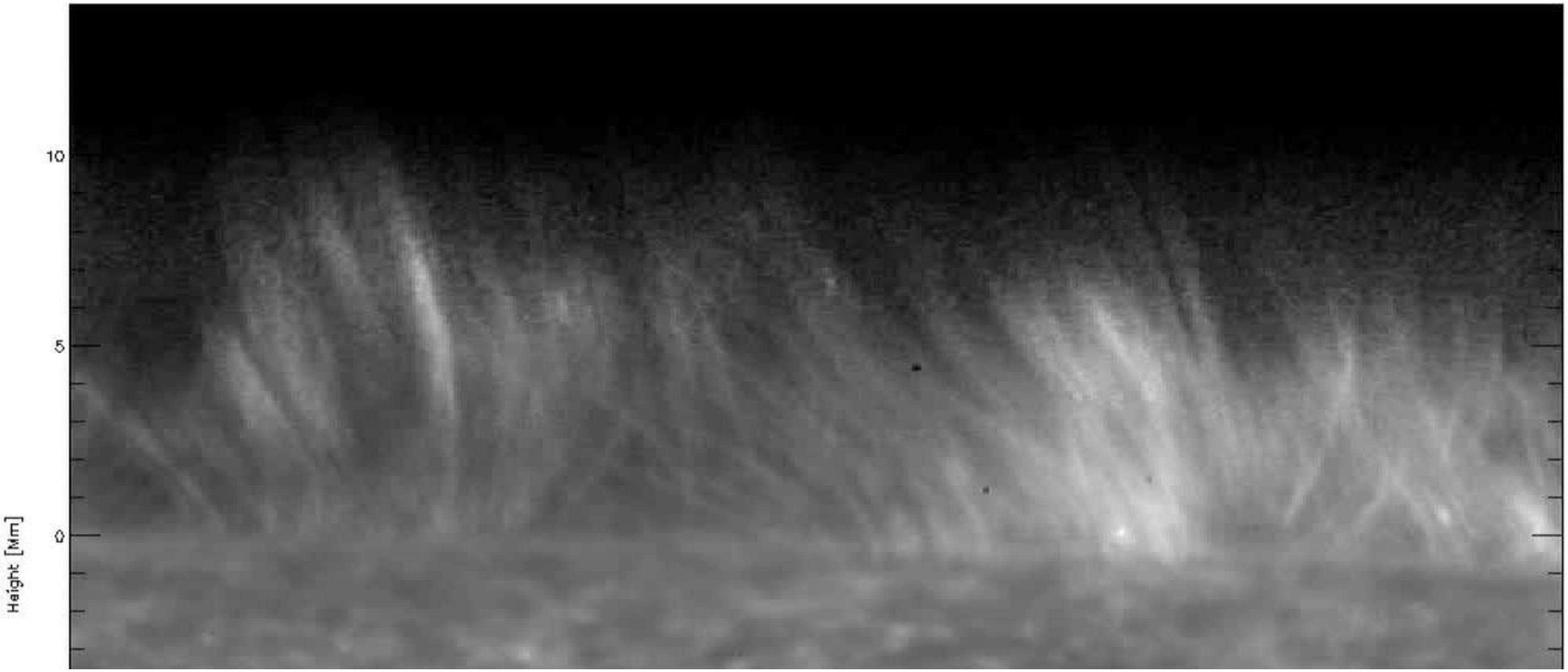
- Generation mechanisms of solar spicules
- Spicules and coronal heating

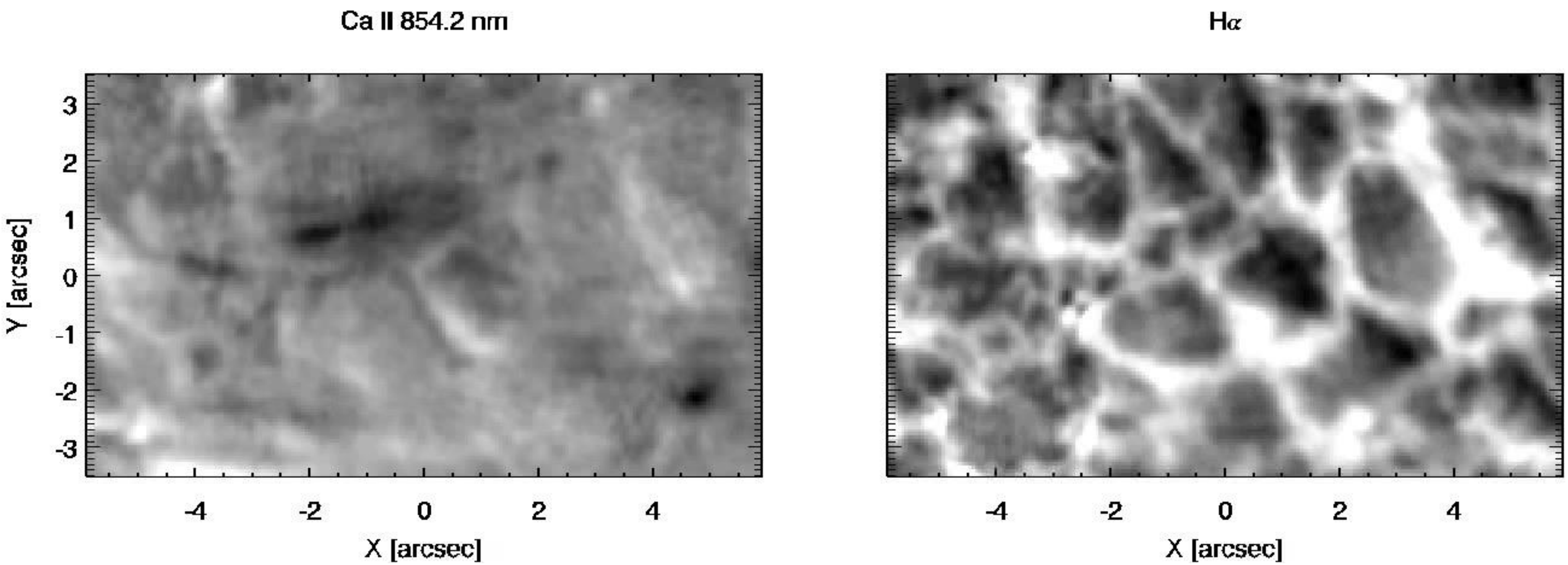
Chromospheric spicules



De Pontieu et al. 2007, PASJ
Also see Zhang et al. 2012, ApJ

- Ubiquitous jet-like features above solar limb in chromospheric passbands
- Width: often <500 km; Temperature: ~10^4 K

On-disk counterparts of spicules



Sekse et al. 2013, ApJ

May be identified as dark propagating features from on-disk observations of Hα/Ca II blue wing (Wang et al. 1998, Lee et al. 2000, Rouppe van der Voort et al. 2009)

Hypotheses/models on spicule generation mechanisms

- Driven by shock waves (De Pontieu et al. 2004; Hansteen et al. 2006; Shibata et al. 1982; Takasao et al. 2013).
- Driven by upward forces associated with Alfvén waves (Cranmer & Woolsey 2015; Iijima & Yokoyama 2017)
- Manifestation of warps in sheet-like structures (Judge et al. 2011)
- Driven by amplified magnetic tension (Martínez-Sykora et al. 2017)
- Driven by magnetic reconnection (Ding et al. 2011; Sterling & Moore, 2016; Yang et al. 2018)
- ...

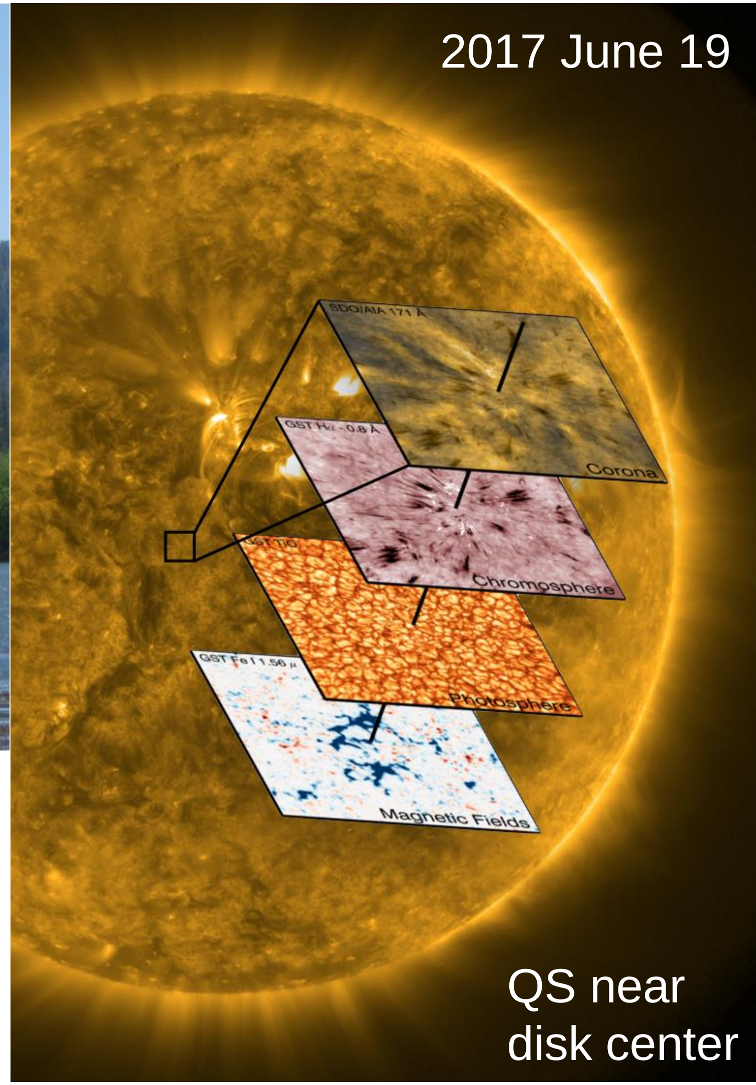
Observational evidence?

- Observations of their formation process are very limited, due to insufficient resolution and sensitivity of magnetic field measurements in the quiet Sun.

- Due to the lack of sufficient observational evidence for almost all these mechanisms, there is no consensus on the spicule-production mechanism in the solar physics community.

Our GST and SDO observations

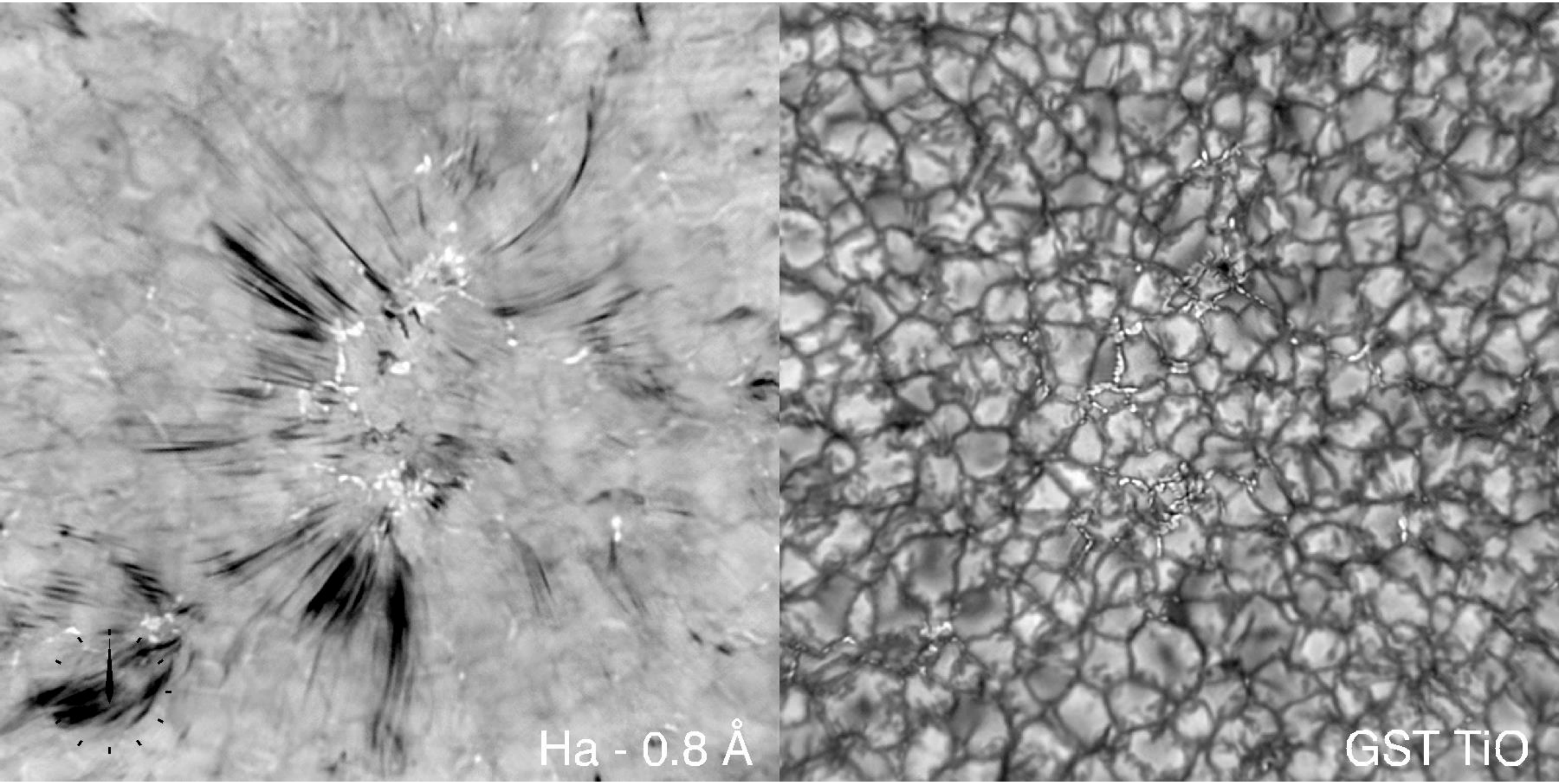
- VIS: Hα - 0.8 Å, 45 km resolution
- BFI: TiO 7057 Å, 45 km resolution
- NIRIS: Fe I 1.56 μm, 150 km resolution



- AIA: 171 Å (Fe IX/Fe X), 900 km resolution

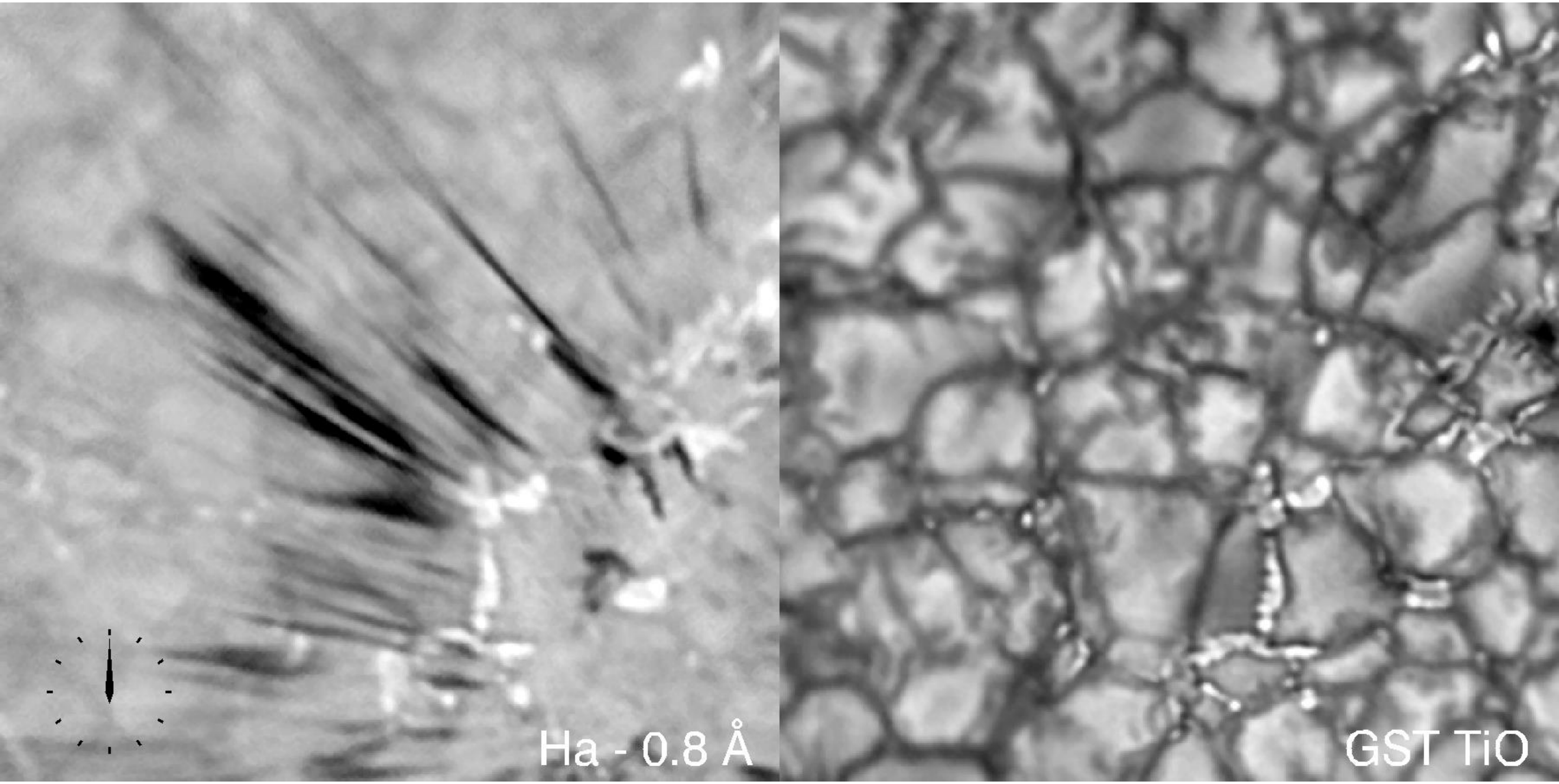
T. Samanta, H. Tian*, V. Yurchyshyn, H. Peter, W. Cao, A. Sterling, R. Erdélyi, K. Ahn, S. Feng, D. Utz, D. Banerjee, Y. Chen, *Science,* 366, 890 (2019)

Magnetic origin of spicules



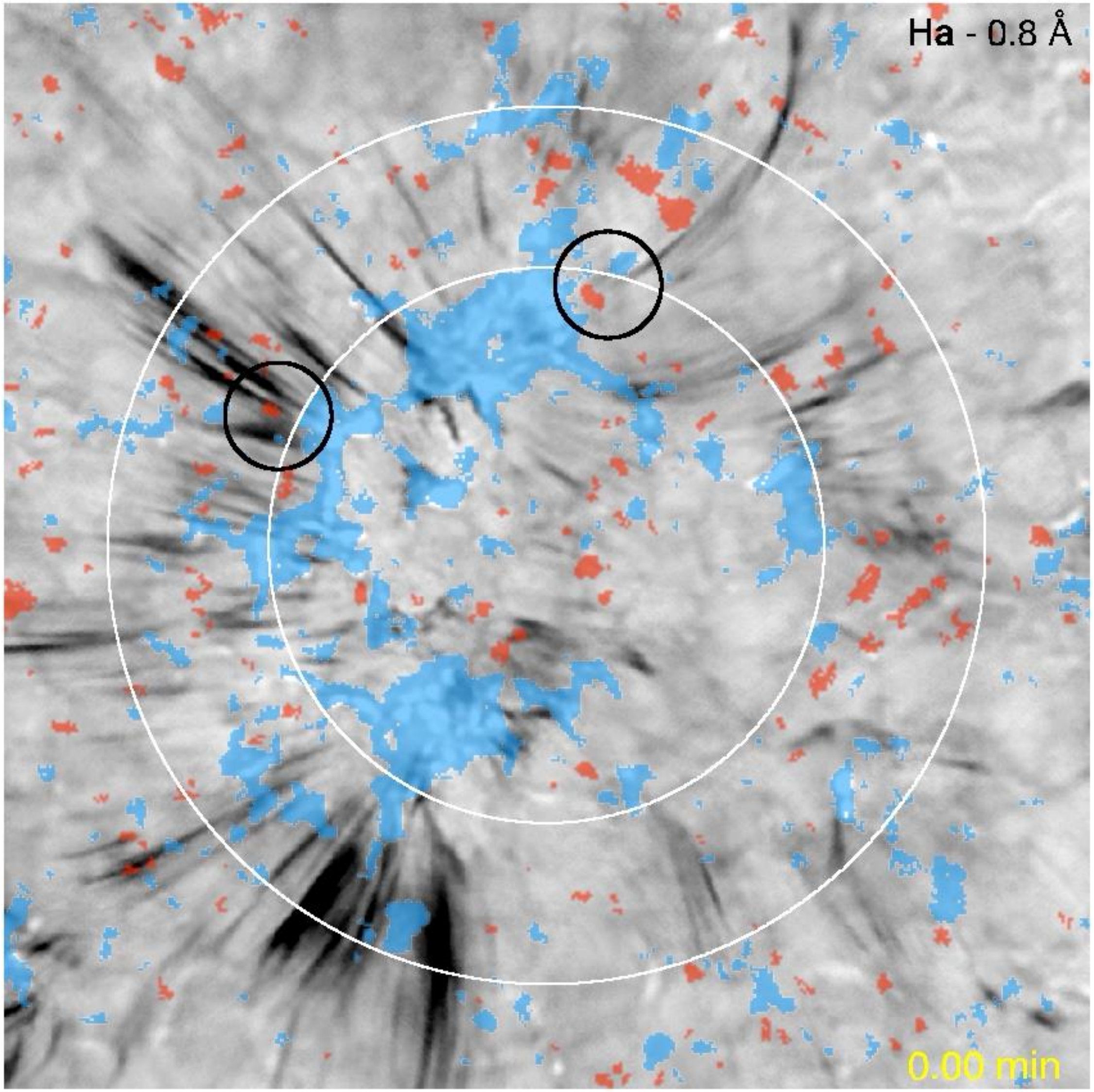
Spicules mostly originate around patches of kilogauss magnetic fields (indicated by the bright points) in the network

Magnetic origin of spicules



Spicules mostly originate around patches of kilogauss magnetic fields (indicated by the bright points) in the network

Spicule generation by interaction of magnetic fields

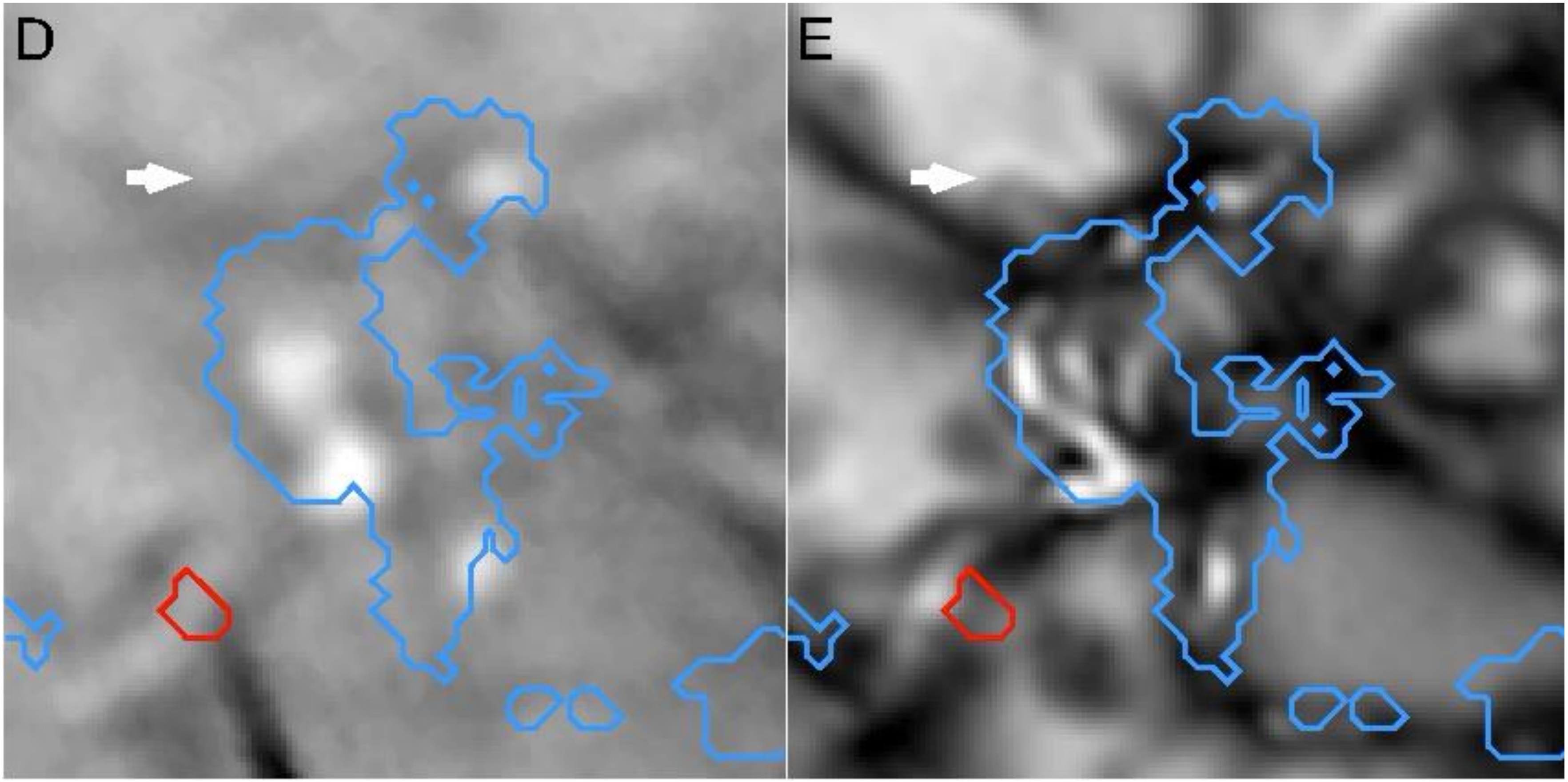


Blue/Red : positive/negative magnetic polarity

- Blue: strong positive-polarity network fields
- Red: weak negative-polarity fields

- Appearance of weak magnetic elements with a polarity opposite to the polarity of network fields at spicule footpoints

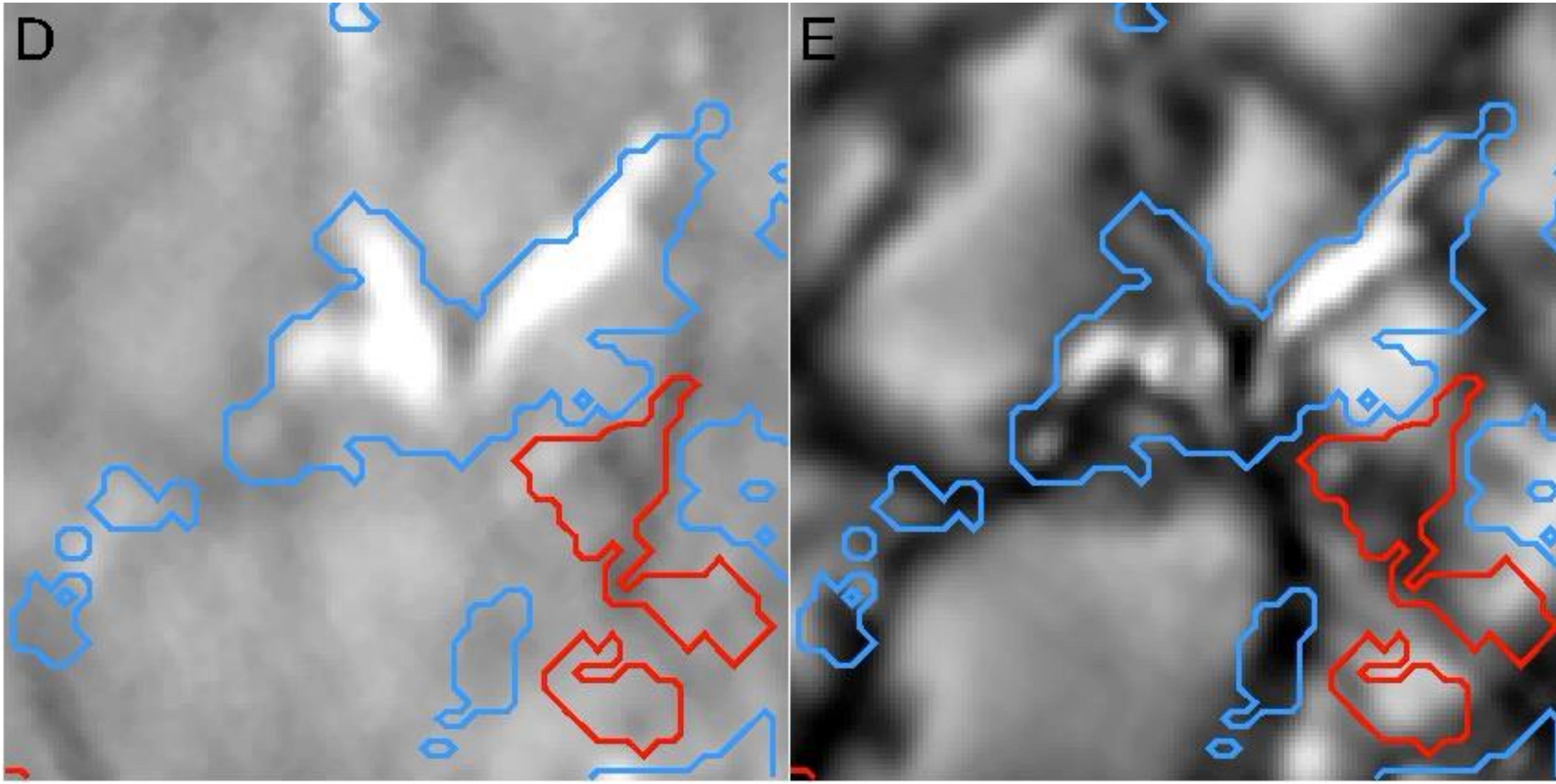
Spicule generation during flux emergence



Blue: positive magnetic polarity Red: negative magnetic polarity

- Spicules often emerge within minutes of the appearance of opposite-polarity magnetic flux around the dominant-polarity magnetic field concentrations
- Appear to be driven by the dynamical interaction of magnetic fields with different polarities

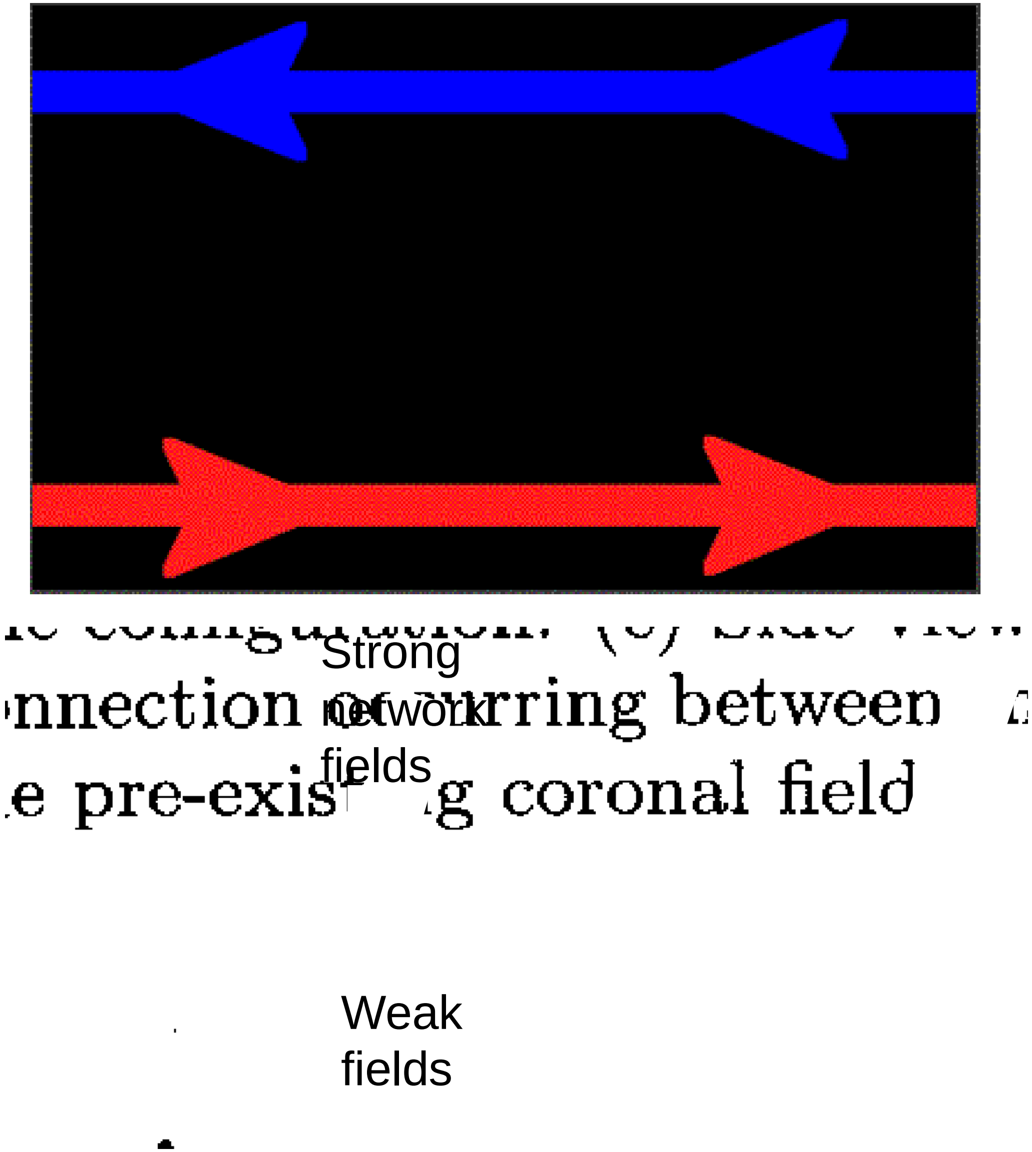
Spicule generation during flux cancellation



Blue: positive magnetic polarity Red: negative magnetic polarity

- Magnetic flux cancellation, a signature of magnetic reconnection (Wang & Shi 1993), is identified at the footpoints of some spicules
- The cancelled flux is ~10^{16} Mx for a typical spicule
- Typical cancellation period is ~3 min

Spicules driven by reconnection



- Our scenario: small-scale weak fields reconnect with adjacent or overlying network fields to produce spicules

- Do not support the two most popular mechanisms of spicule generation (shock waves and amplified magnetic tension)

Modified from the jet generation scenario of Shibata et al. (1992)

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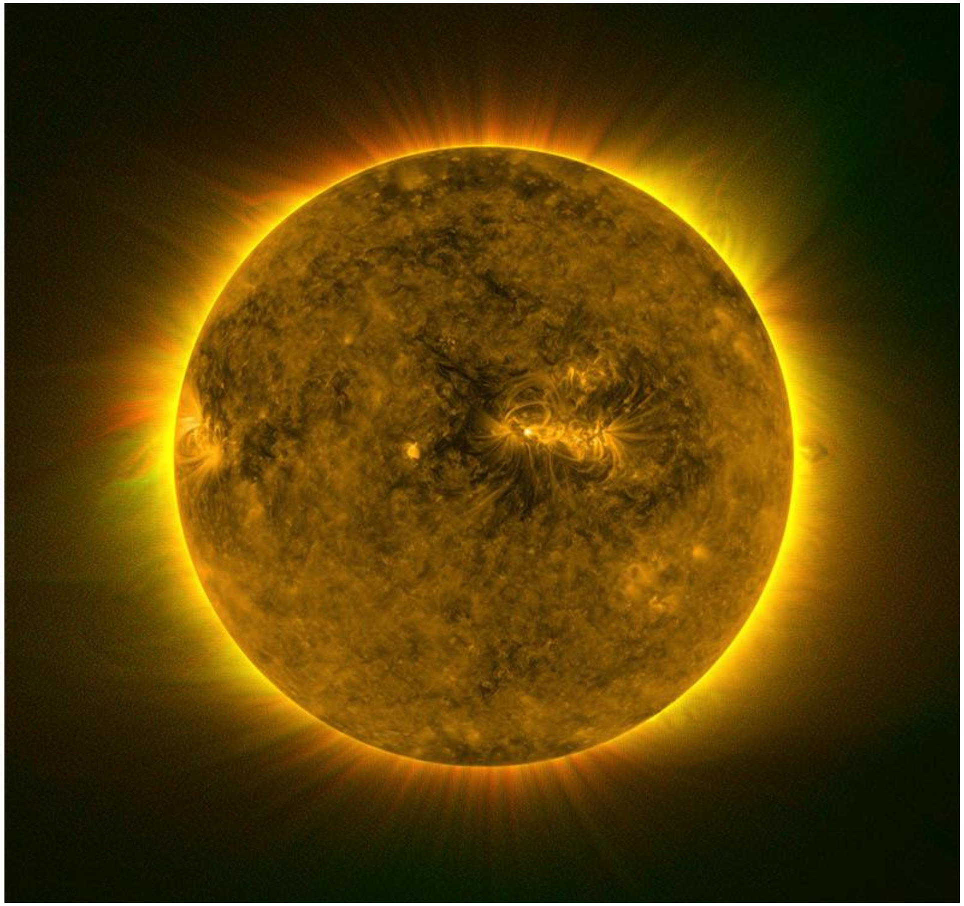
Hot corona

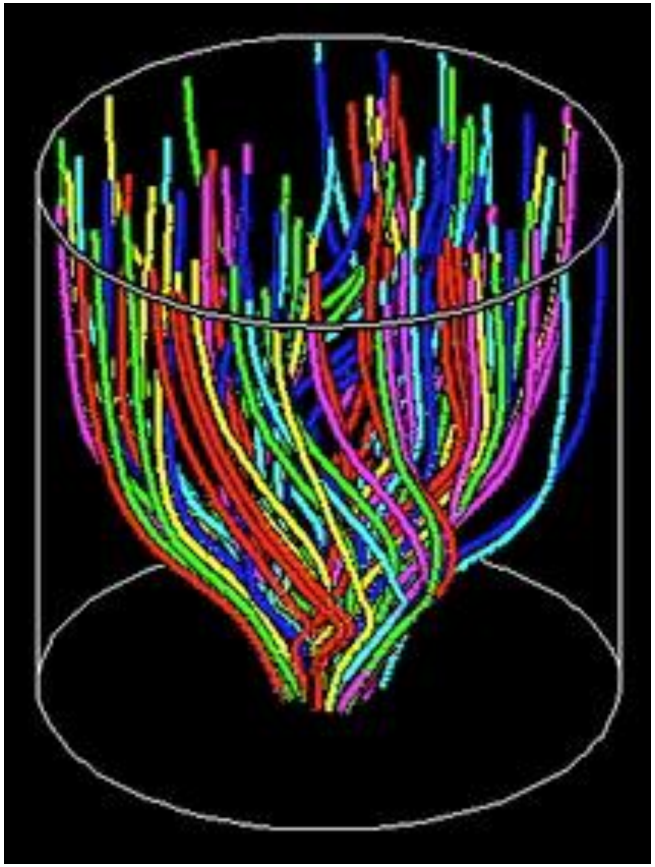
White-light image taken during the 2016 eclipse (Credit: M. Druckmuller)



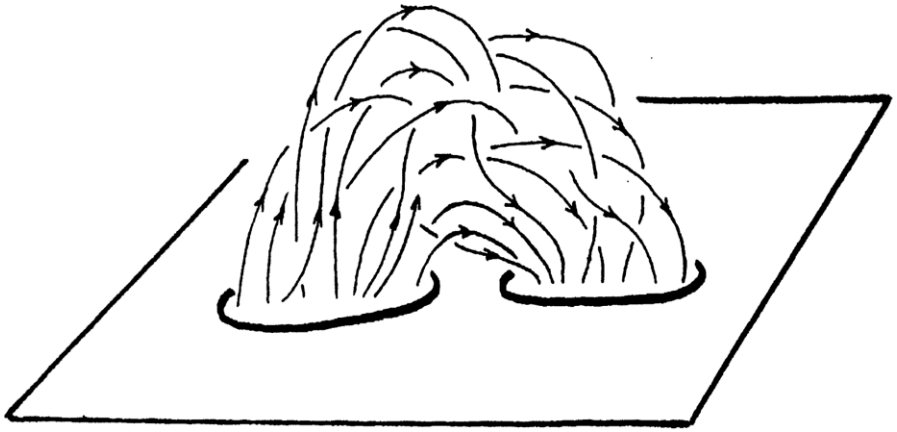
Composite coronal image taken during the 2017 eclipse (Chen, Tian, Su, et al. 2018, ApJ)

- Emission lines from Fe^{13+} in corona: million degree
- Coronal expansion leads to formation of solar wind

Popular models of coronal heating

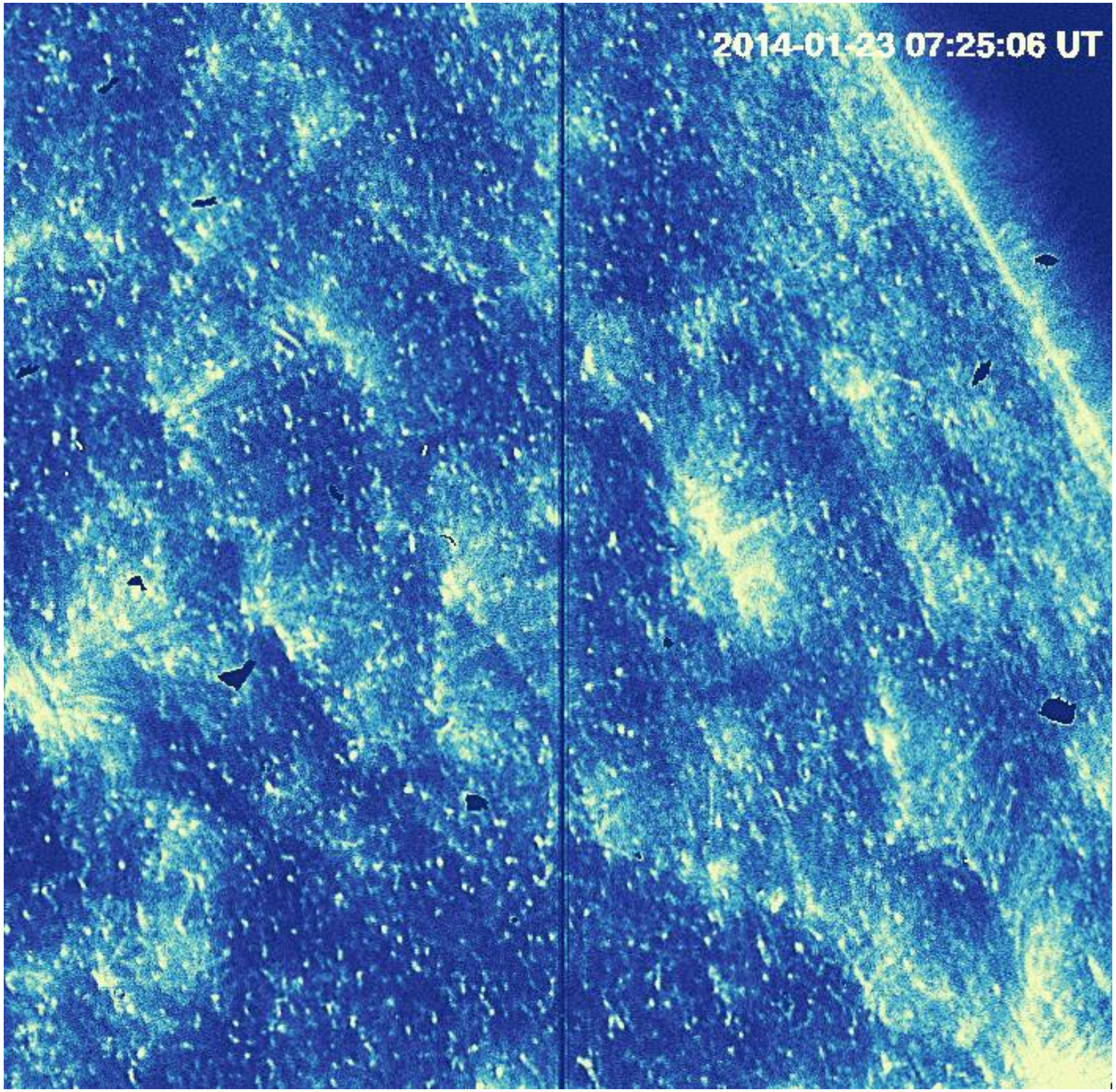


Alfvén waves (van Ballegooijen et al. 2011, ApJ)



Nanoflares (Parker 1988, ApJ)

Spicules are conduits of mass and energy to the corona

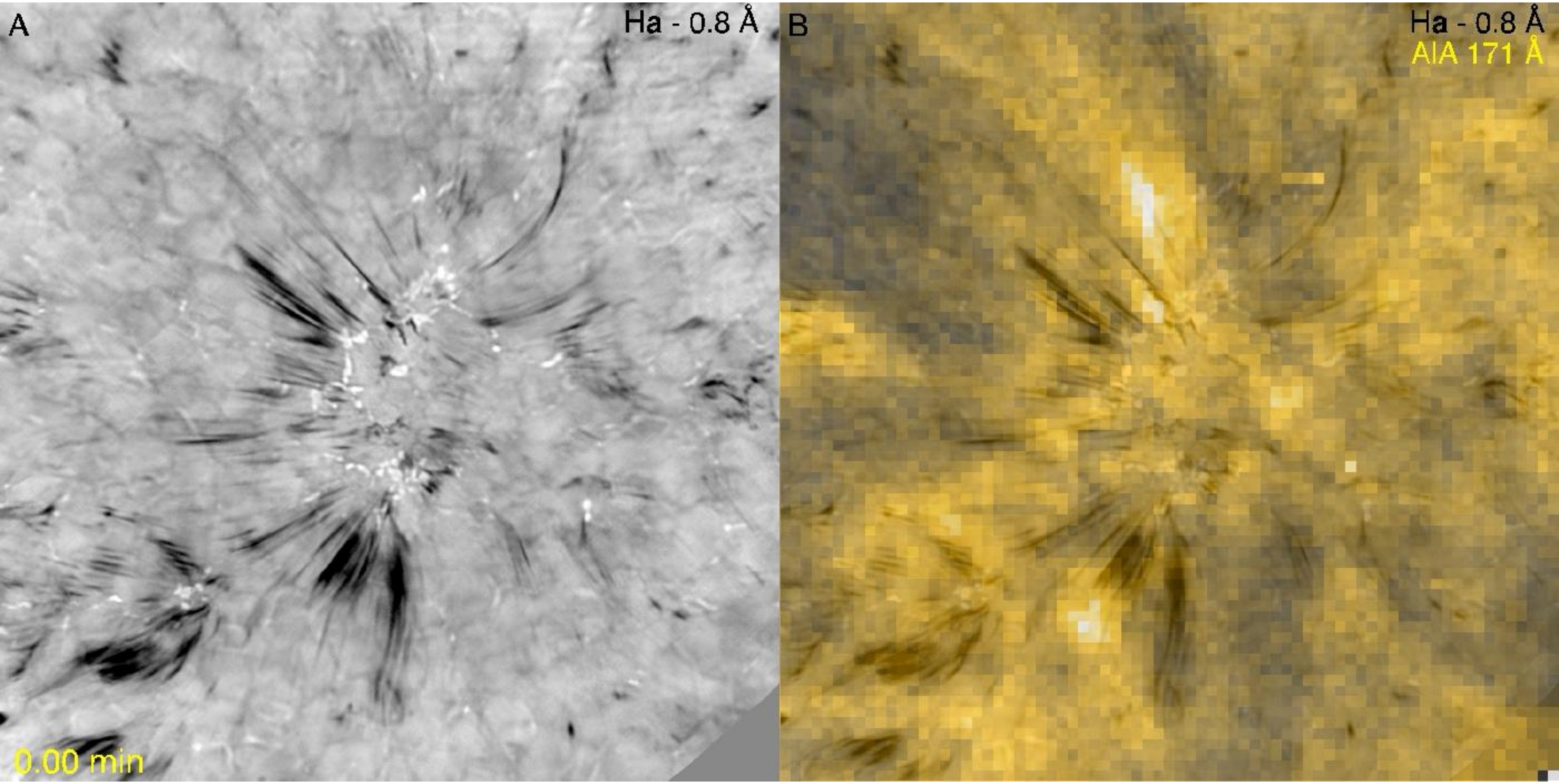


- Prevalent small-scale intermittent jets in lower atmosphere might be the key to understanding coronal heating

- Dynamically shoot upward to coronal heights (~5 Mm or higher)
- Many spicules heated to ~0.1 MK (Tian et al. 2014)

Tian, DeLuca, Cranmer, et al. 2014, Science

Coronal heating during propagation of spicules

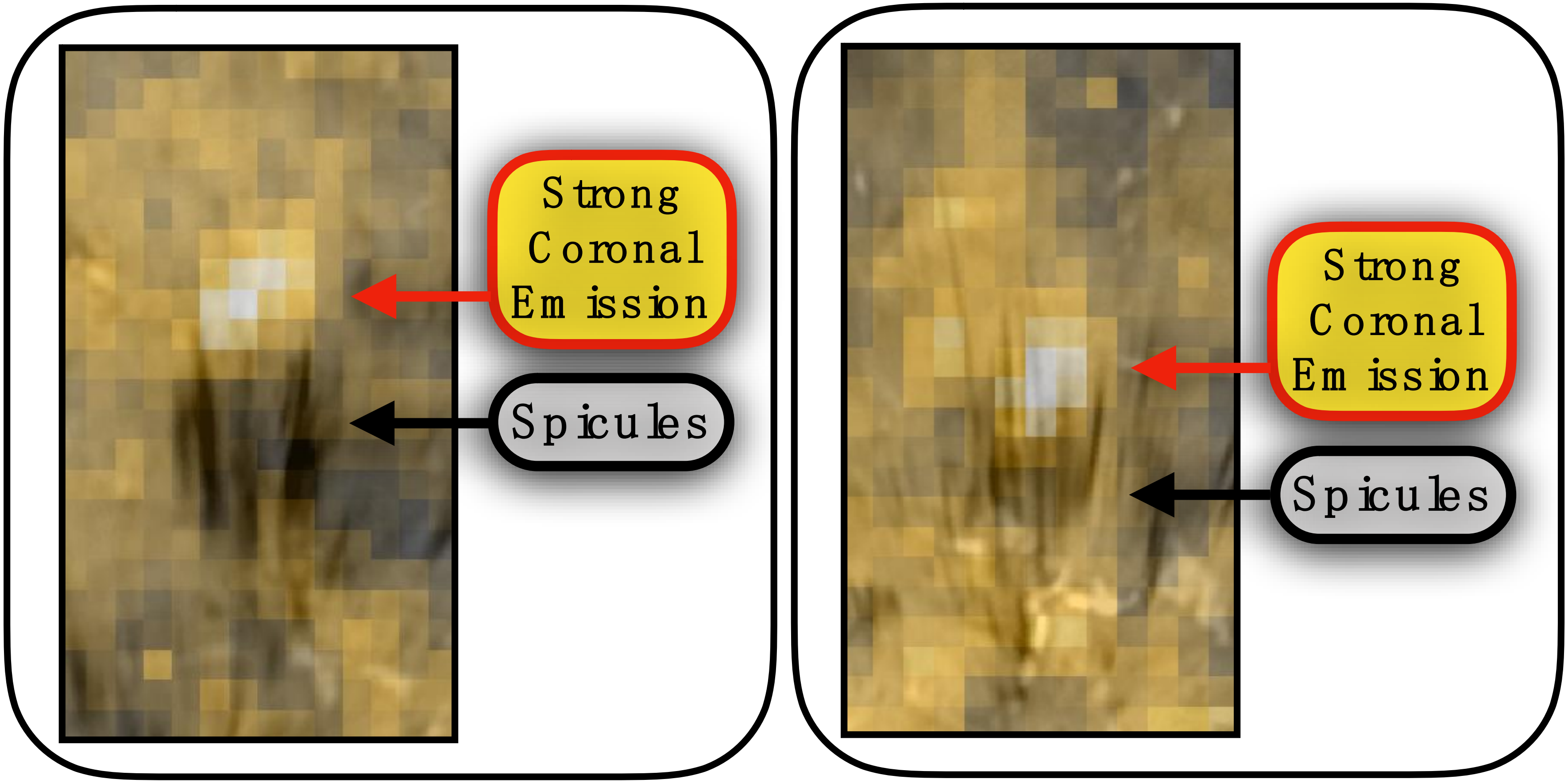


T. Samanta, H. Tian*, V. Yurchyshyn, et al., *Science,* 366, 890 (2019)

Spicules are commonly heated to coronal temperatures (~10^6 K)

Also see De Pontieu et al. 2011 & Ji et al. 2012

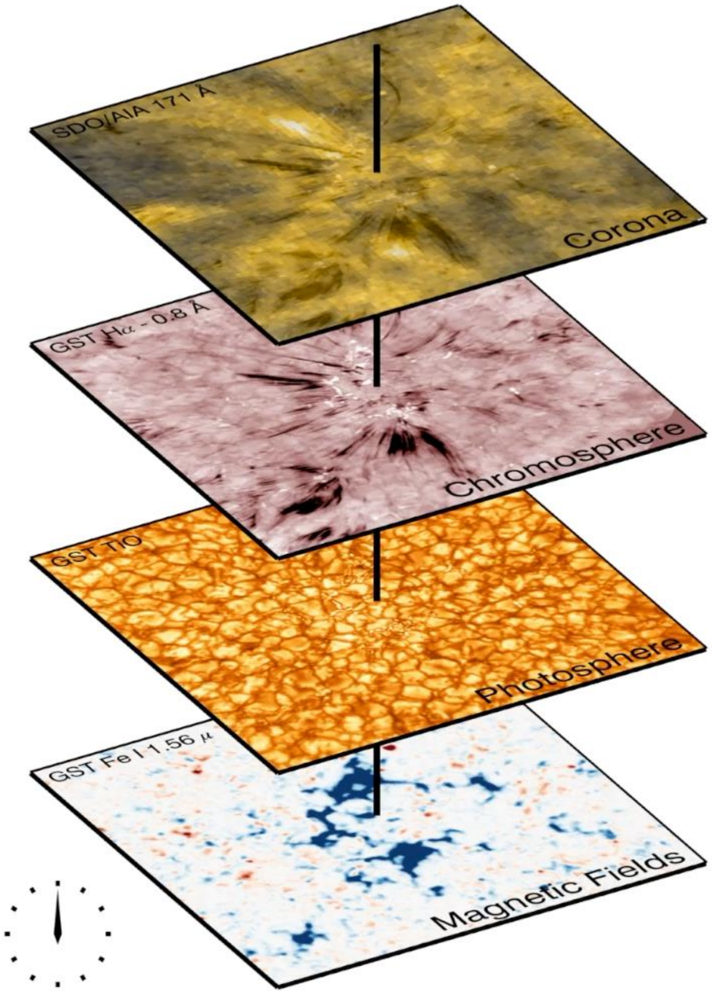
Coronal heating during propagation of spicules



Enhanced coronal emission (SDO/AIA Fe IX 171 Å, $\sim 10^6$ K) appears at the top of spicules

Link coronal heating to magnetic activities in lower atmosphere

- Our observations reveal that magnetic reconnection events at network boundaries can drive spicules and produce hot plasma flows into the corona, thus providing a link between magnetic activities in the lower atmosphere and coronal heating



- Simultaneous high-resolution observations of different layers in the atmosphere are required to understand coronal heating
- Need to track the mass and energy from lower atmosphere to the corona
- Don't just search for waves or nanoflares in the corona!

Summary

- The Sun is the ultimate source of space weather and the only star that can be studied at high spatial resolution. With more than 10 advanced solar observatories on the ground and in space, solar physics is now at its golden age.

- Solar spicules are the most prominent dynamic features between the solar surface and corona. However, it is unclear how these spicules are generated. For the first time, we observed spicules emerging within minutes of the appearance of weak opposite-polarity magnetic flux around dominant-polarity magnetic field concentrations, suggesting generation of many spicules by magnetic reconnection.

- Many spicules are heated to coronal temperatures during their propagation. Our simultaneous observations of different layers in the solar atmosphere reveal a link between magnetic activities in the lower atmosphere and coronal heating.