Solar jets and their associated instabilities

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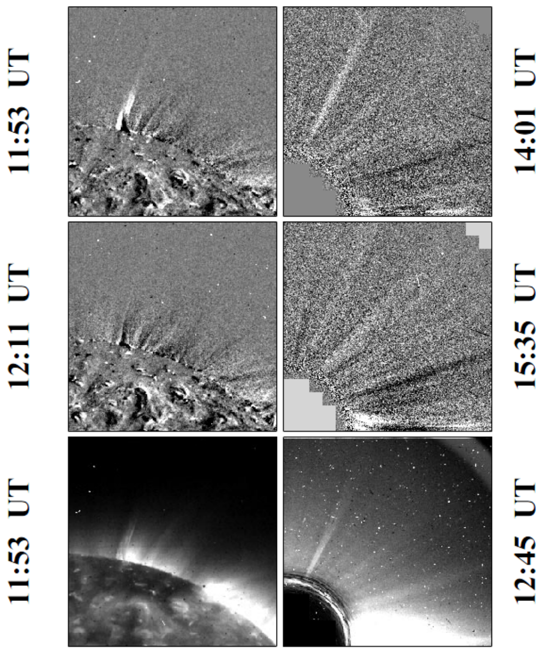
Outline

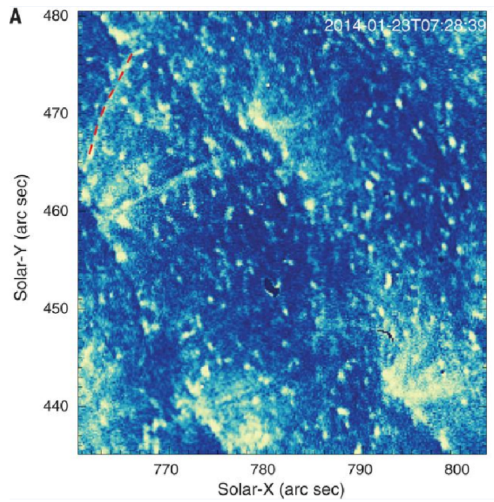
1. Brief introduction of solar jets
2. Instabilities in the solar jets
3. Summary and outlook

Brief introduction of solar jets

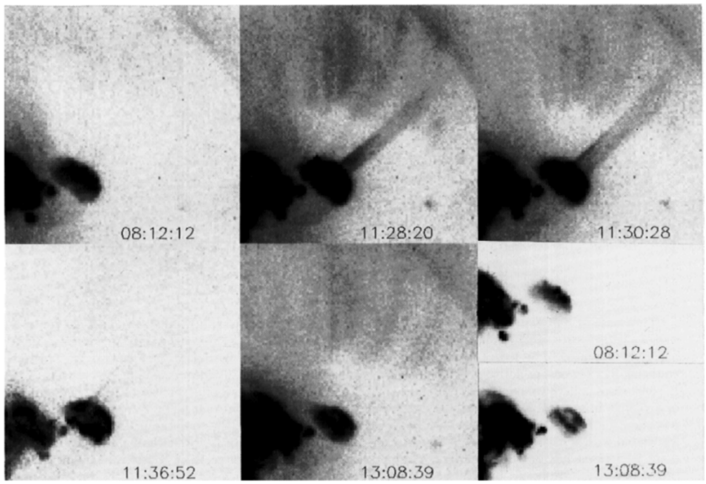
➢ Solar jets are plasma eruptions that are magnetically rooted in the photosphere and ejected into the corona along open field lines or the legs of large-scale coronal loops. They occur in different solar environments over a broad range of temporal and spatial scales.



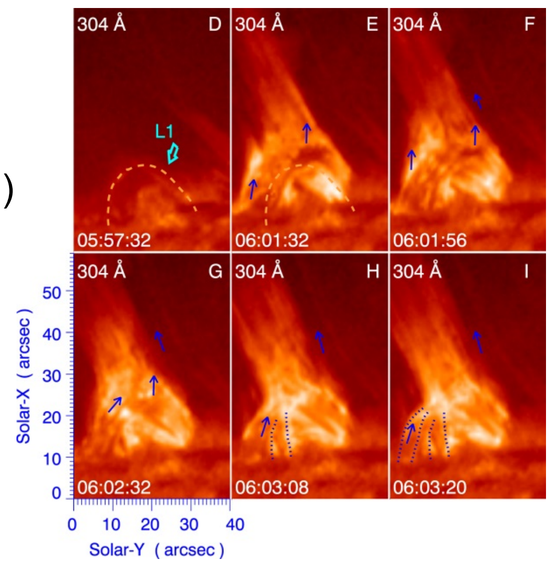
white-light jets (Wang et al. 1998)



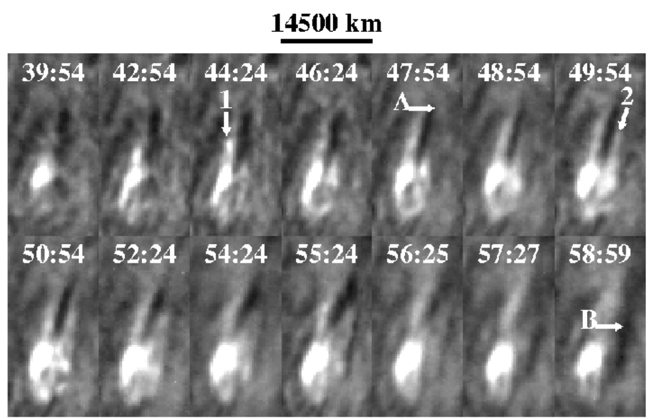
network jets (Tian et al. 2014)



X-ray jets (Shibata et al. 1992)



extreme-ultraviolet (EUV) jets (Zhang et al. 2017)



Hα surges (Chae et al. 1999)

Solar jets: properties

- Location:
  active regions (ARs; Shimojo et al. 1996; Brooks et al. 2007; Nitta et al. 2008);
  coronal holes (CHs; Cirtain et al. 2007; Savcheva et al. 2007; Culhane et al. 2007);
  quiet regions (Subramanian et al. 2010; Sako et al. 2013).
- Lengths:
  several Mm in X-ray/EUV observations, up to several solar radius in WL images
- Widths: 5 − 100 Mm
- Lifetimes:
  a few minutes to several hours (Shimojo et al. 1996, 1998; Savcheva et al. 2007; Kim et al. 2007; Nisticò et al. 2009)
- Energy:
  $\sim 10^{27} - \sim 10^{29}$ erg (Shimojo & Shibata 2000)
  $\sim 10^{26} - 10^{28}$ erg (Pucci et al. 2013)
- Density:
  10^{10} cm^{-3} (Roy 1973)
  10^{11} cm^{-3} (Gu et al. 1994; Schmieder et al. 1988)
  3×10^{8} cm^{-3} – 3×10^{9} cm^{-3} (Shibata et al. 1996)
  6.6×10^{9} cm^{-3} – 3.4×10^{10} cm^{-3} (Yang et al. 2011)
  DEM （Differential Emission Measure) methods may be able to give a reliable estimation.

Solar jets: temperature

- The temperature of different jets can vary greatly (Hα surges ~10^4 K, EUV jets ~10^5–10^6 K, X-ray jets ~10^6 K). Within the same jet, temperature of the material at different locations may also be very different.

- An important characteristic of solar jets is that some coronal jets consist of both cool and hot plasma flows and the cool component is often delayed with respect to the hot component (e.g., Schmieder et al. 1994; Yokoyama & Shibata 1995; Alexander & Fletcher 1999; Jiang et al. 2007; Lee et al. 2013; Mulay et al. 2017; Shen et al. 2017)
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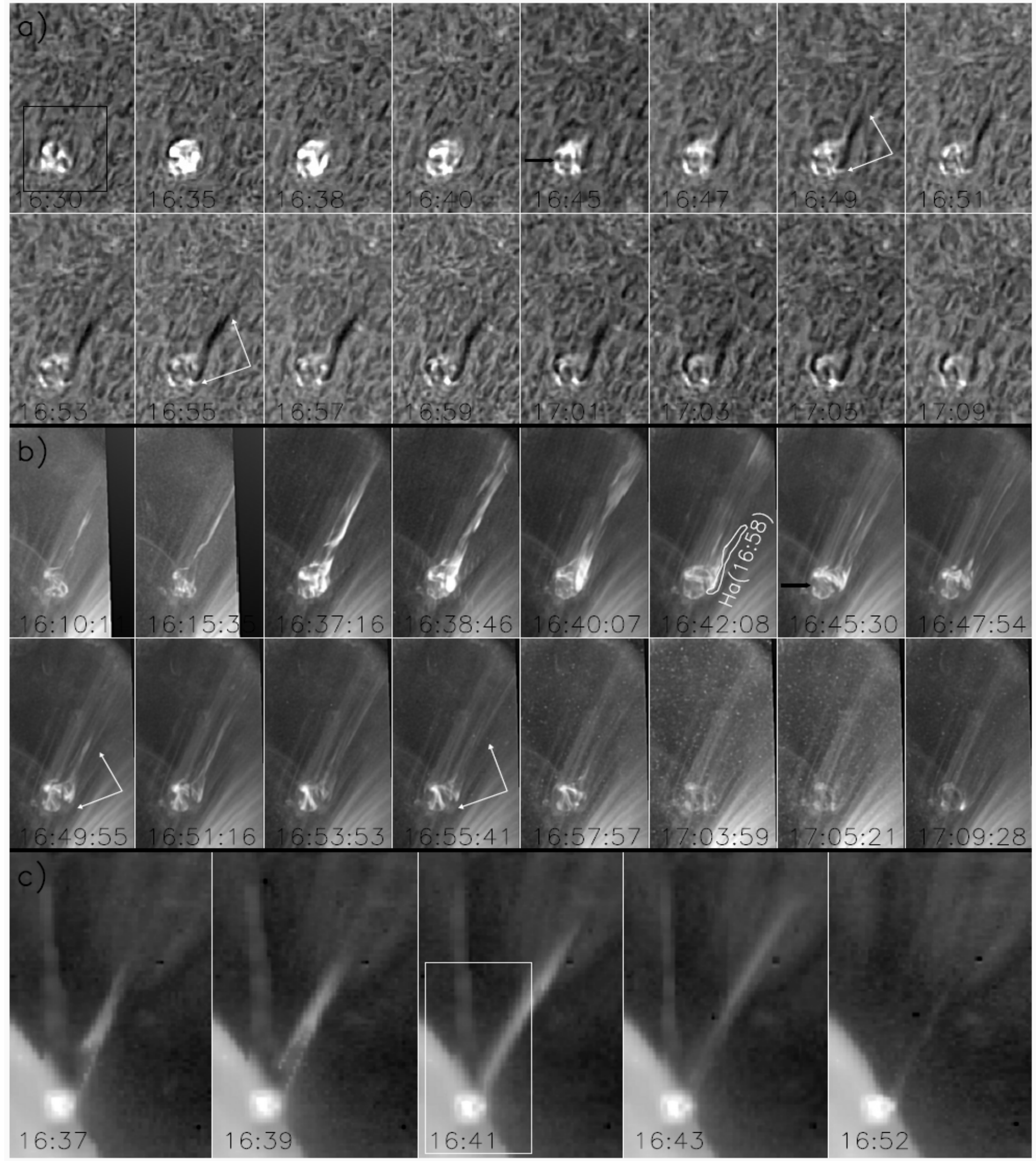
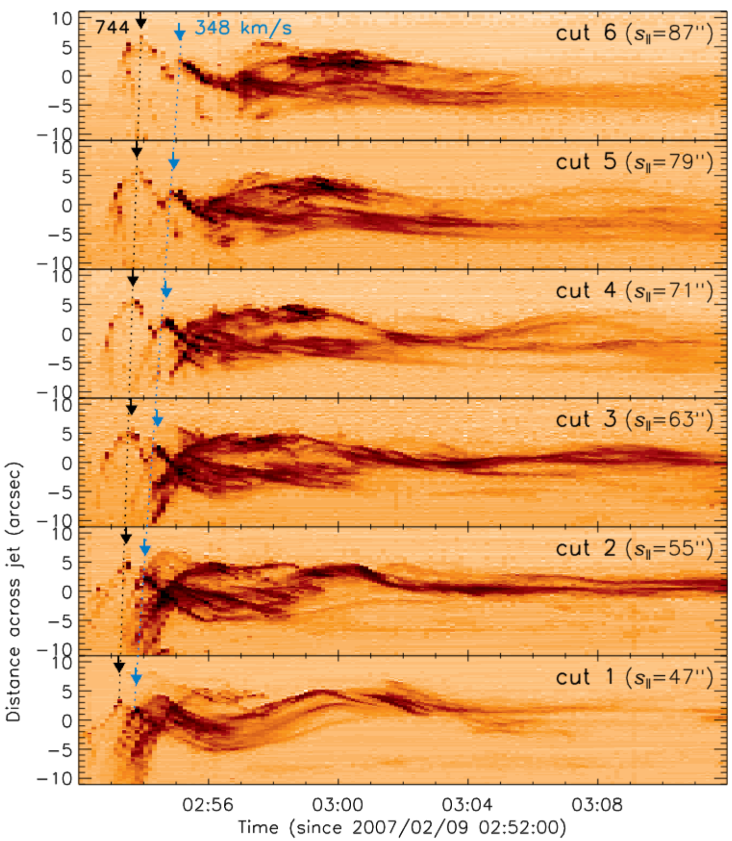


(Jiang et al. 2007)

Solar jets: dynamics

- ➢ Apparent speed: range from 10 to 1000 km s⁻¹, with a mean value of 200 km s⁻¹
- ➢ Transverse motion: whip-like motions (Shibata and Uchida 1986)
  - expanding motions (~ 20 – 100 km s⁻¹; Shibata et al. 1992; Savcheva et al. 2007; Shimojo et al. 2007)
  - oscillations (~ 360 s, Morton et al. 2012; ~ 250 – 536 s, Liu et al. 2009)
- ➢ Untwisting motion: a few km s⁻¹ to > 100 km s⁻¹



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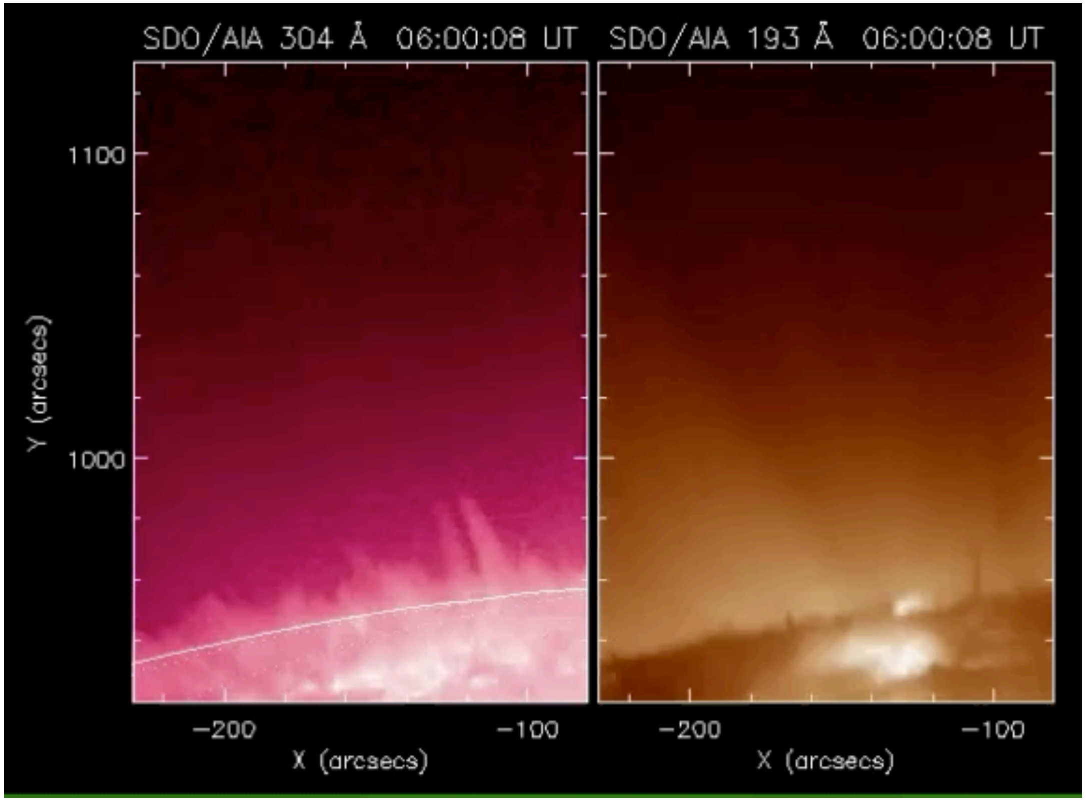

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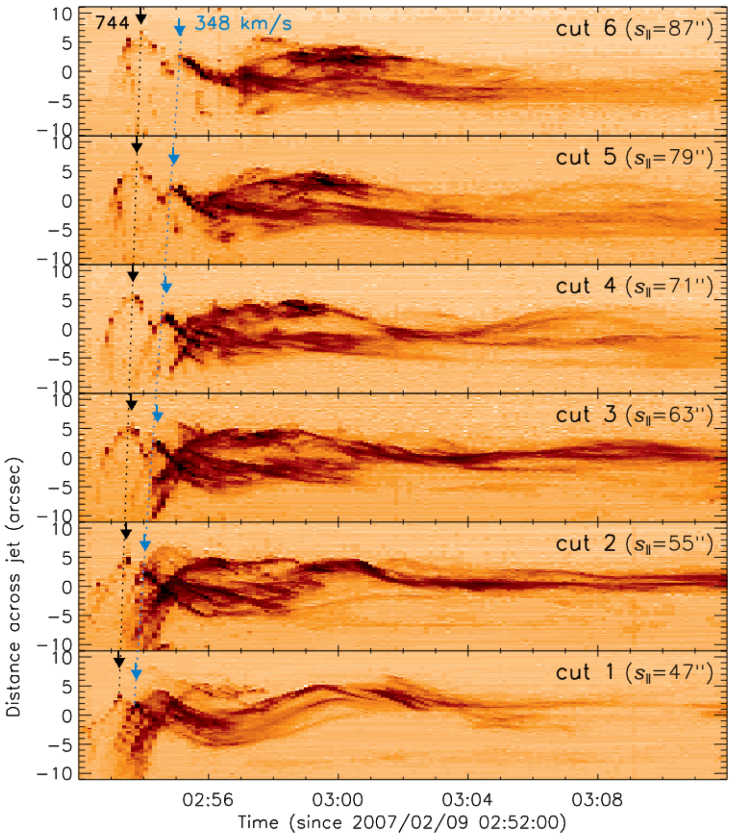

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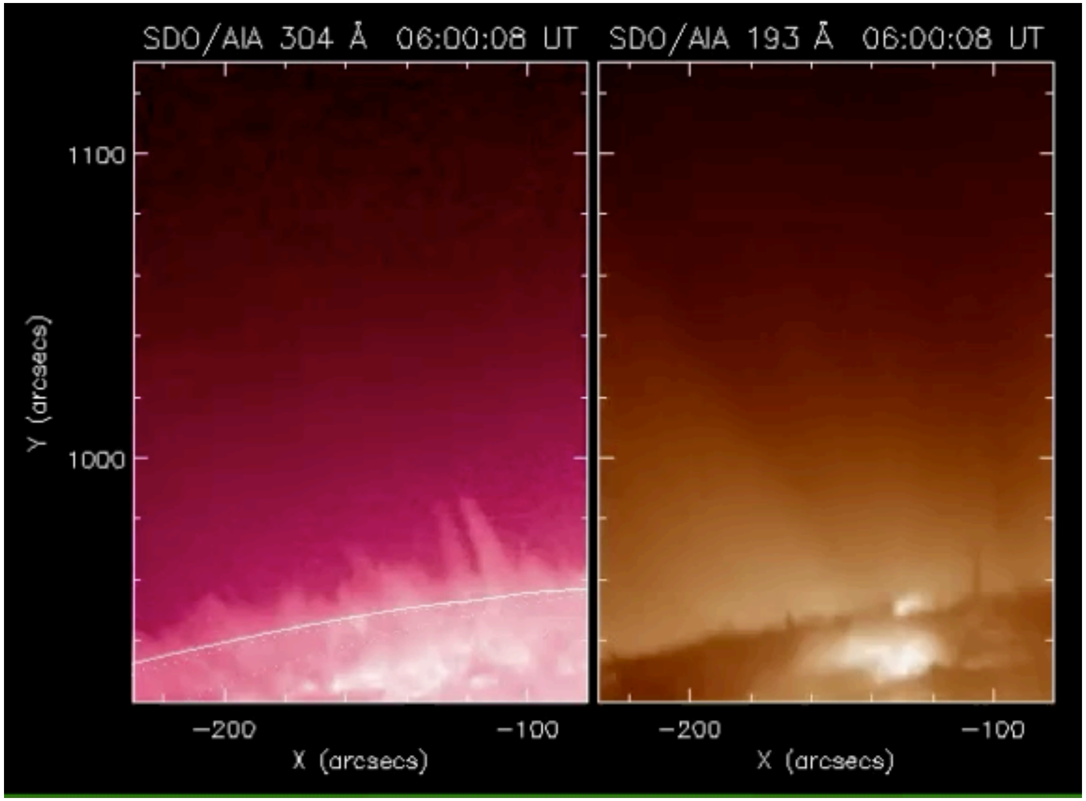

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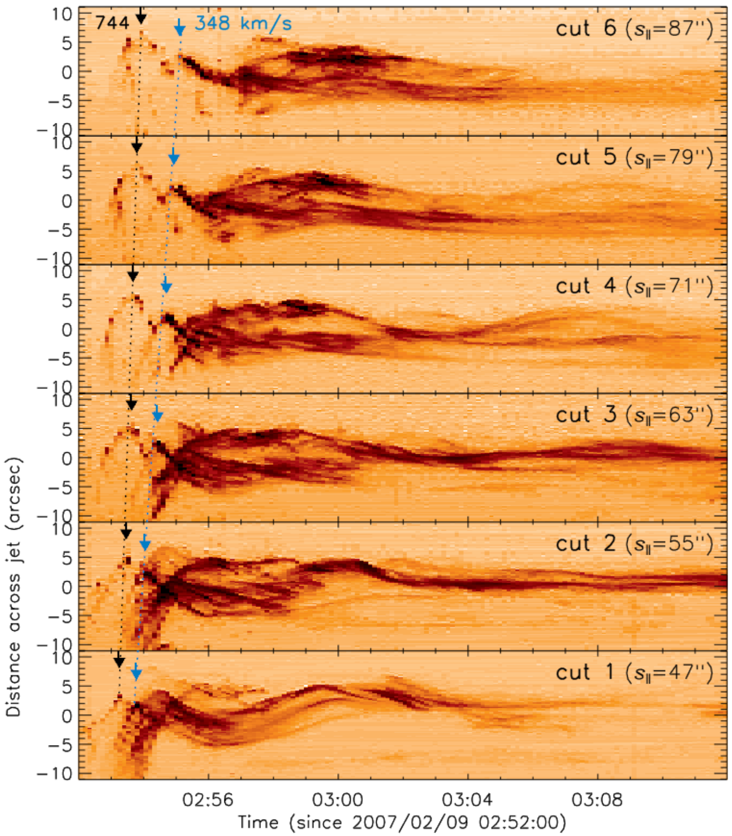

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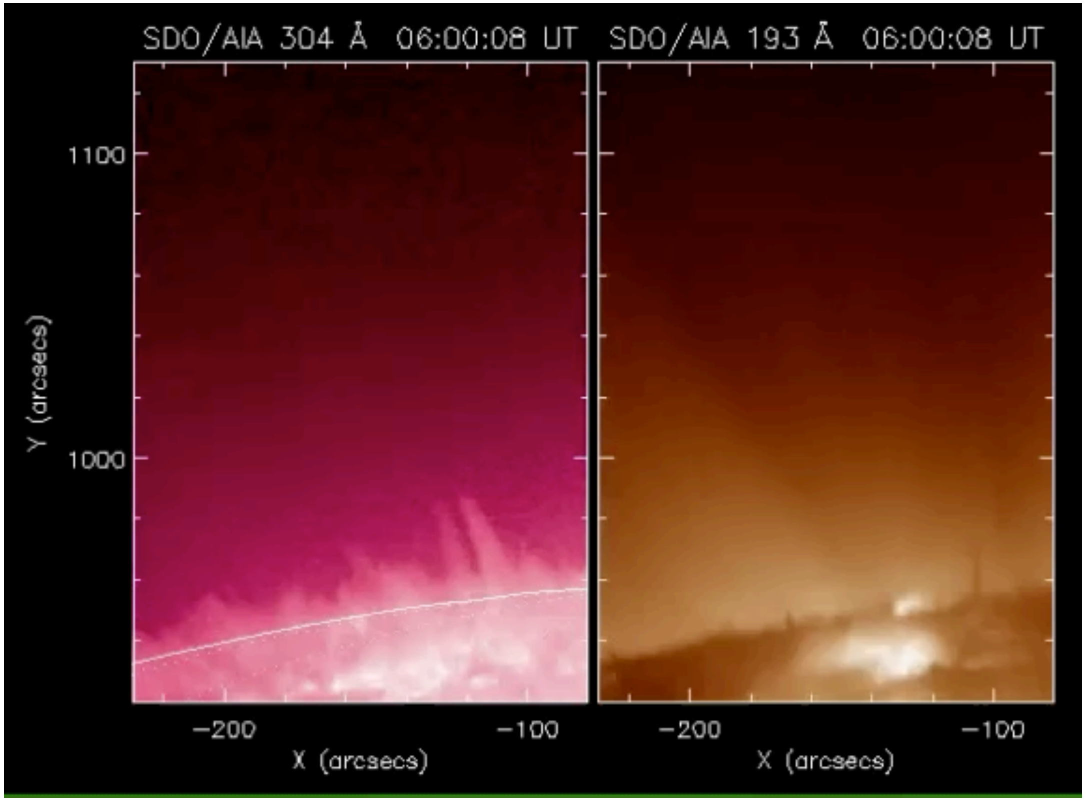

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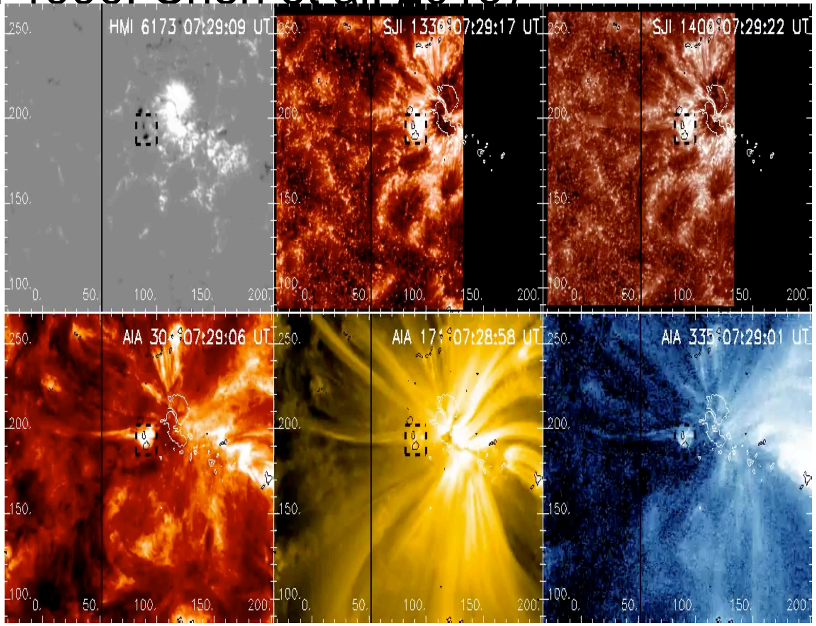
Solar jets: characteristics

➢ Many jets are observed to be closely associated with photospheric magnetic activities (Innes et al. 2016):

- magnetic flux emergences (e.g., Yokoyama & Shibata 1995; Liu & Kurokawa 2004; Shibata et al. 2007; Huang et al. 2012; Li et al. 2015; Liu et al. 2016)
- magnetic flux cancellations (e.g., Jiang et al. 2007; Chifor et al. 2008; Young & Muglach 2014; Shen et al. 2012, 2017; Panesar et al. 2016, 2017)
- moving magnetic features (Canfield et al. 1996; Chen et al. 2015)

➢ Coronal jet is typically accompanied by microflare or bright point at an edge of their base (called the jet-base bright point, JBP) and a bright spire.

➢ periodic recur at the same position: ~ 50 s to ~ 40 min (Morton et al. 2012; Liu et al. 2014, 2018; Zhang and Ji 2014)



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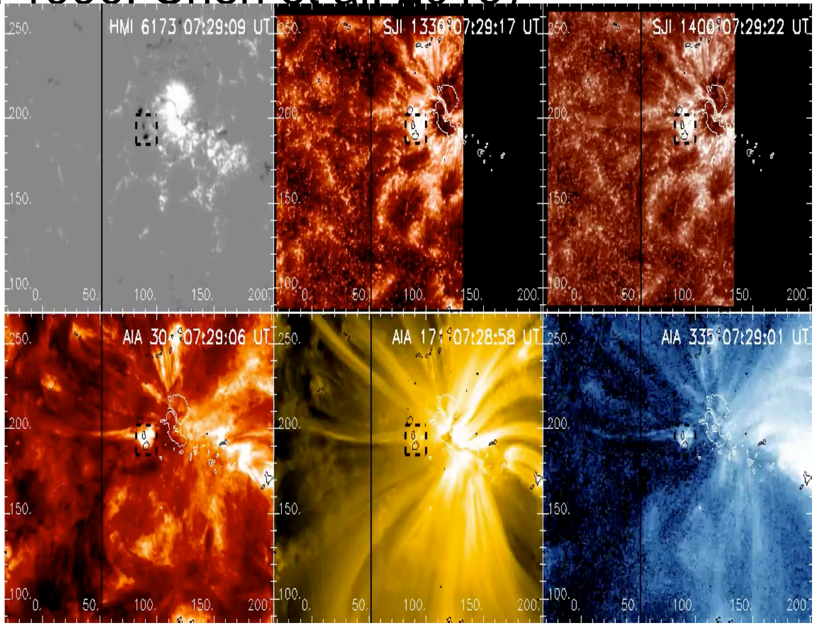

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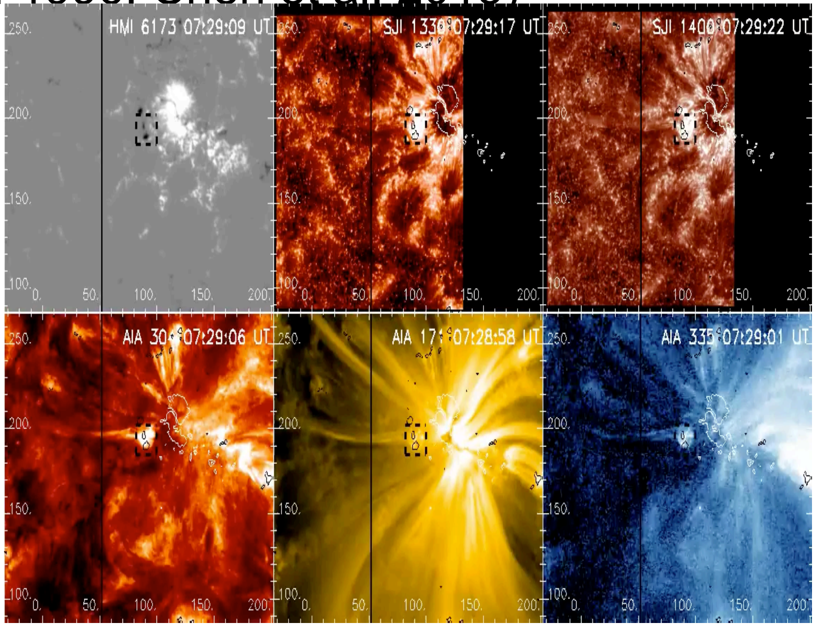

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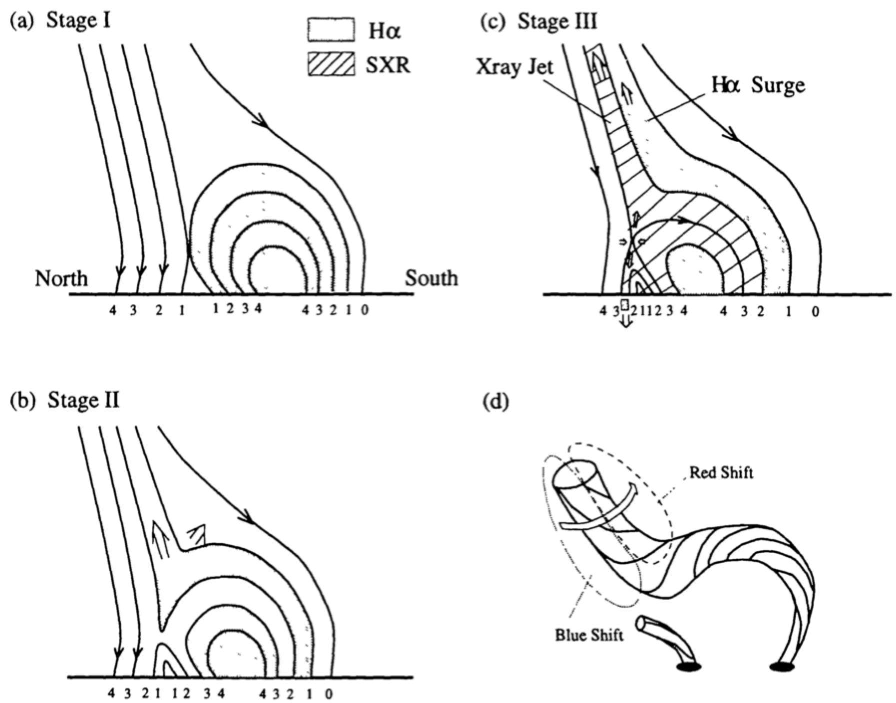
Solar jets: standard model



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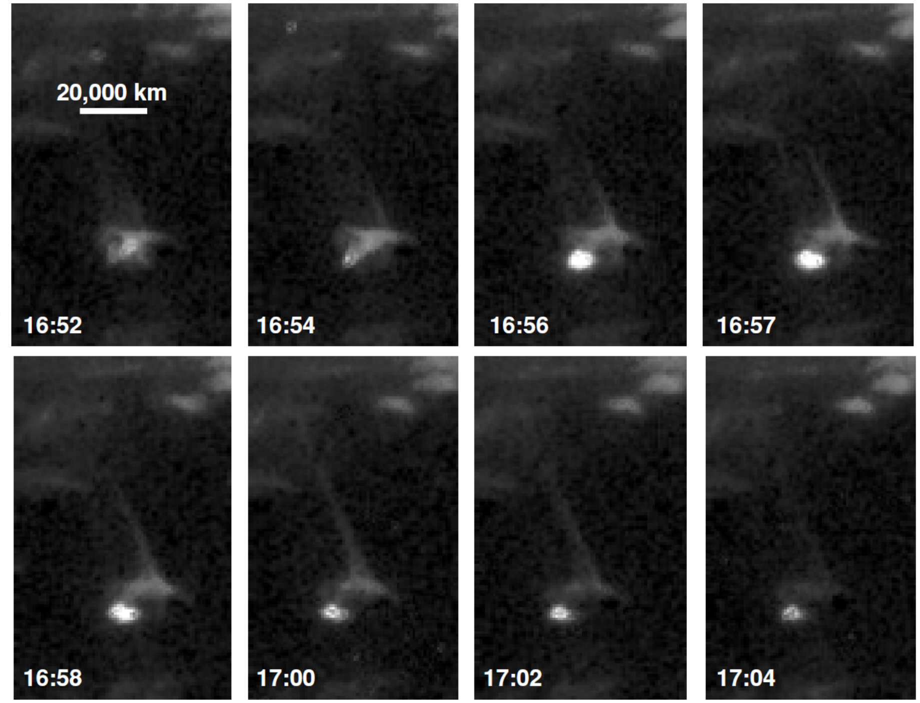
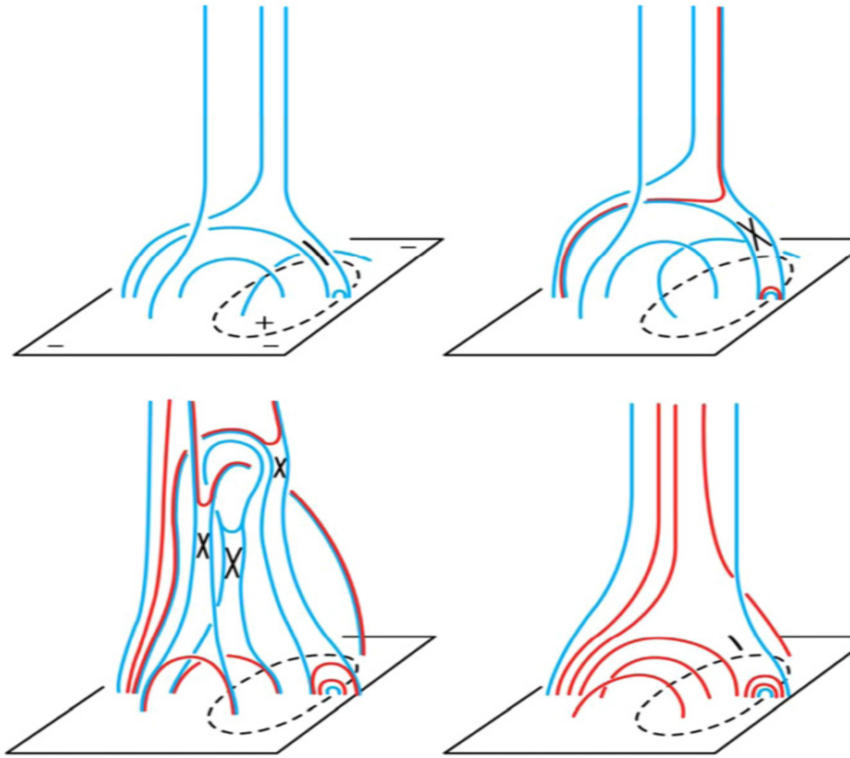


(Moore et al. 2010)

- ➢ Shibata et al. (1992) presented a two-dimensional jet model: an emerging magnetic bipole continuously presses against the ambient opposite polarity open fields, and the magnetic reconnection between open and closed fields produces the jet.
- ➢ JBP: reconnected small loops connecting the footpoints of the ambient fields to the opposite polarity of the small arch

  Jet spire: reconnection-heated material flows out along the reconnected ambient fields
- ➢ two-dimensional (2D) and three-dimensional (3D) simulations (Yokoyama & Shibata 1995; Pariat et al. 2009, 2010; Moreno-Insertis & Galsgaard 2013; Fang et al. 2014)

Solar jets: blowout model



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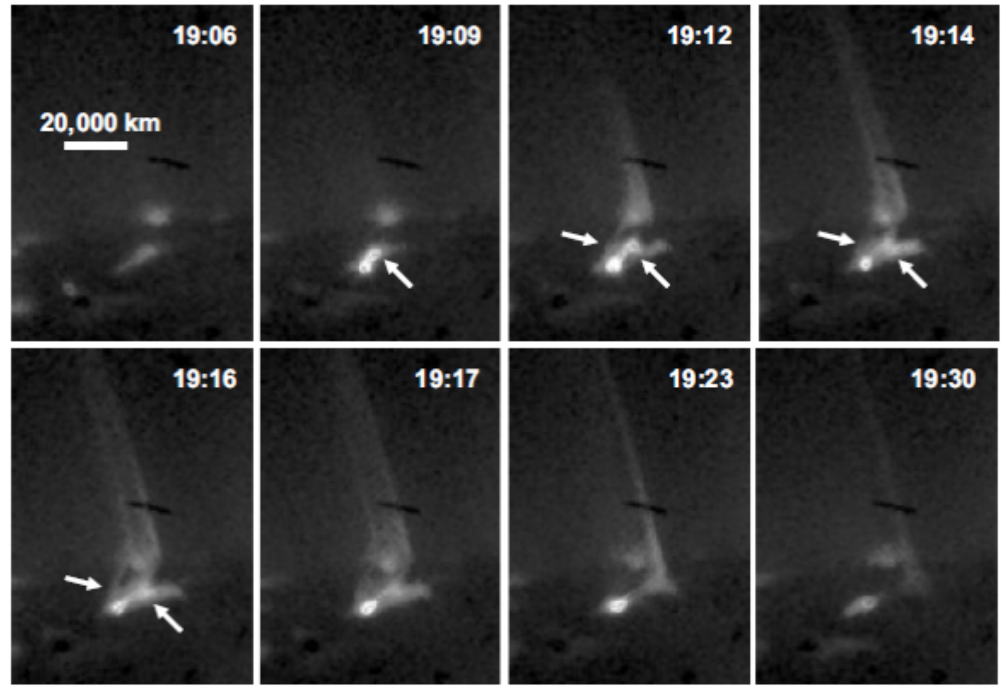
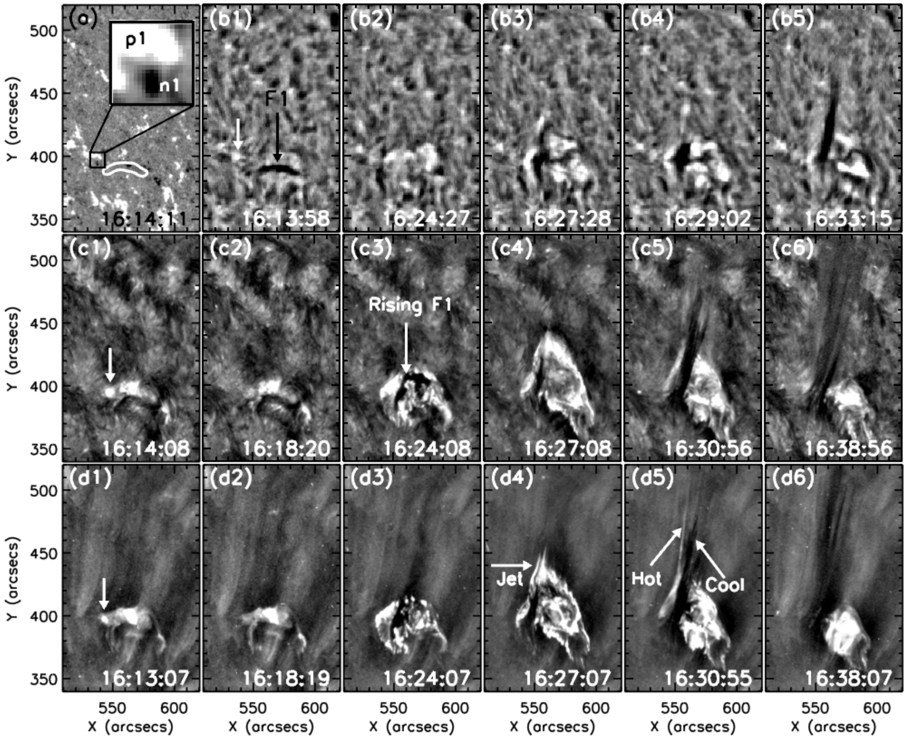


(Moore et al. 2010)

- Moore et al. (2010) further propose an extension of the emerging-flux model to explain blowout jets.
- Wider spire and a more eruptive jet base than standard jets
- Sometimes, the magnetic arch of the blowout jet could be observed to carry a mini-filament to erupt along with the blowout jet spire (Hong et al. 2011, 2013; Shen et al. 2012, 2017; Moore et al. 2013; Adams et al. 2014; Li et al. 2015).

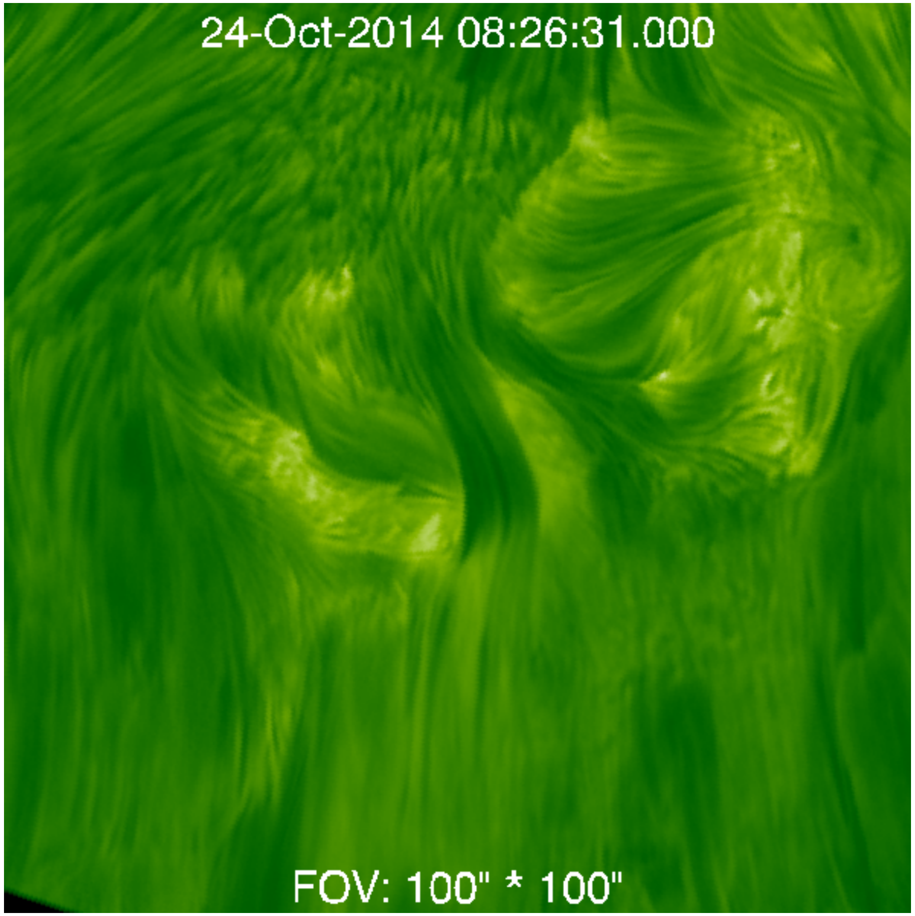
Solar jets: blowout model

- The formation of the cool component in the jet was due to the eruption of the mini-filament, while the hot component resulted from the heated plasma during the reconnection .



(Shen et al. 2012)

- Rotation of the jet:
  Open magnetic field reconnect with the filament, jet rotates due to the untwisting of the filament



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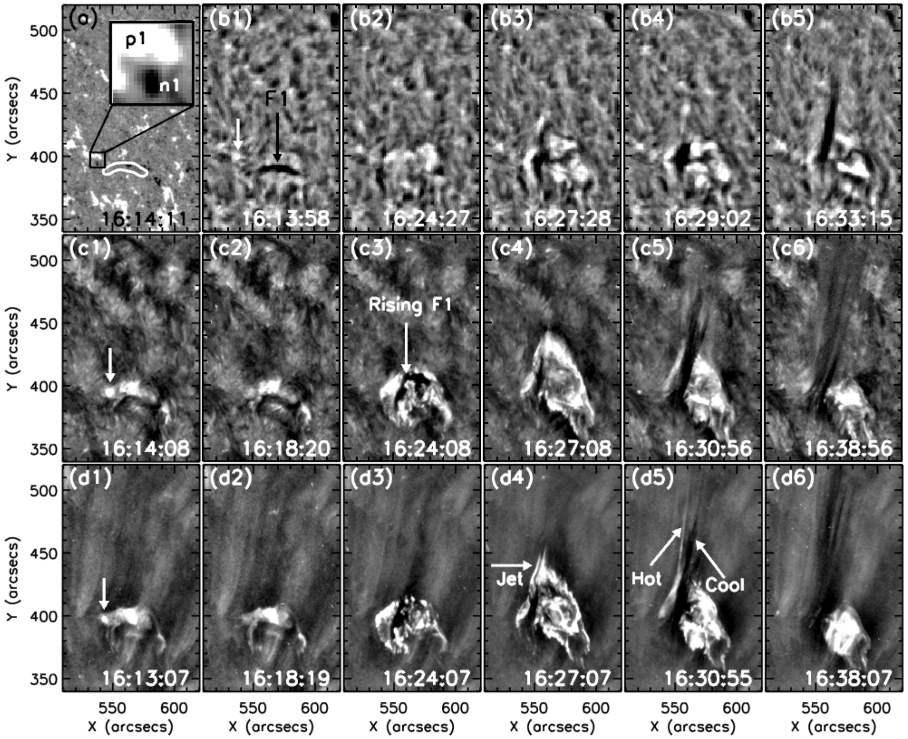

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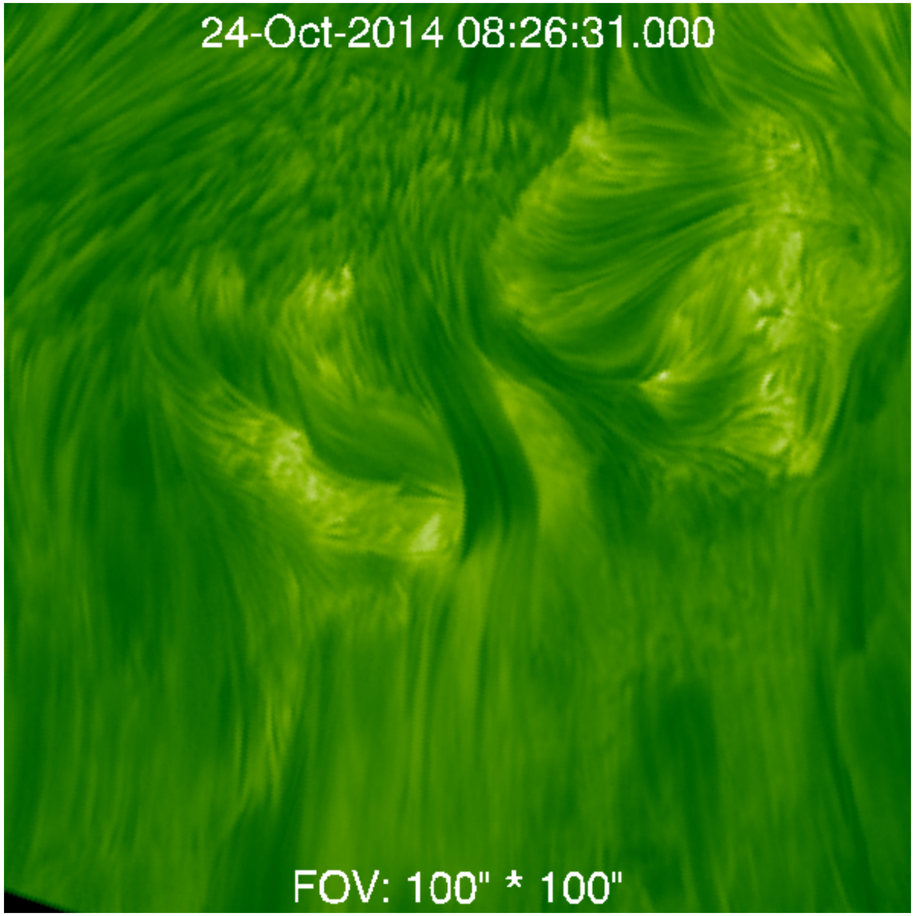

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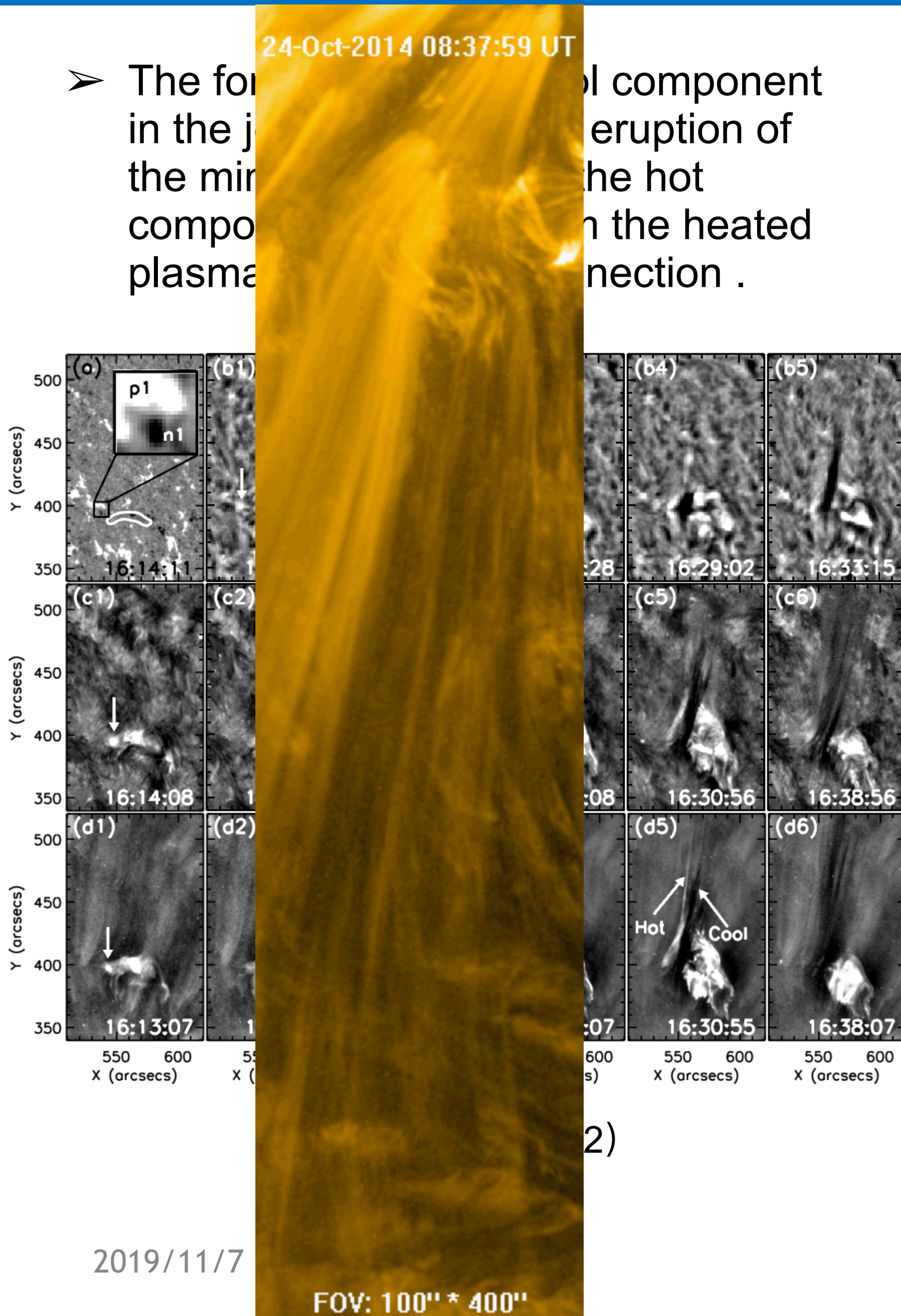

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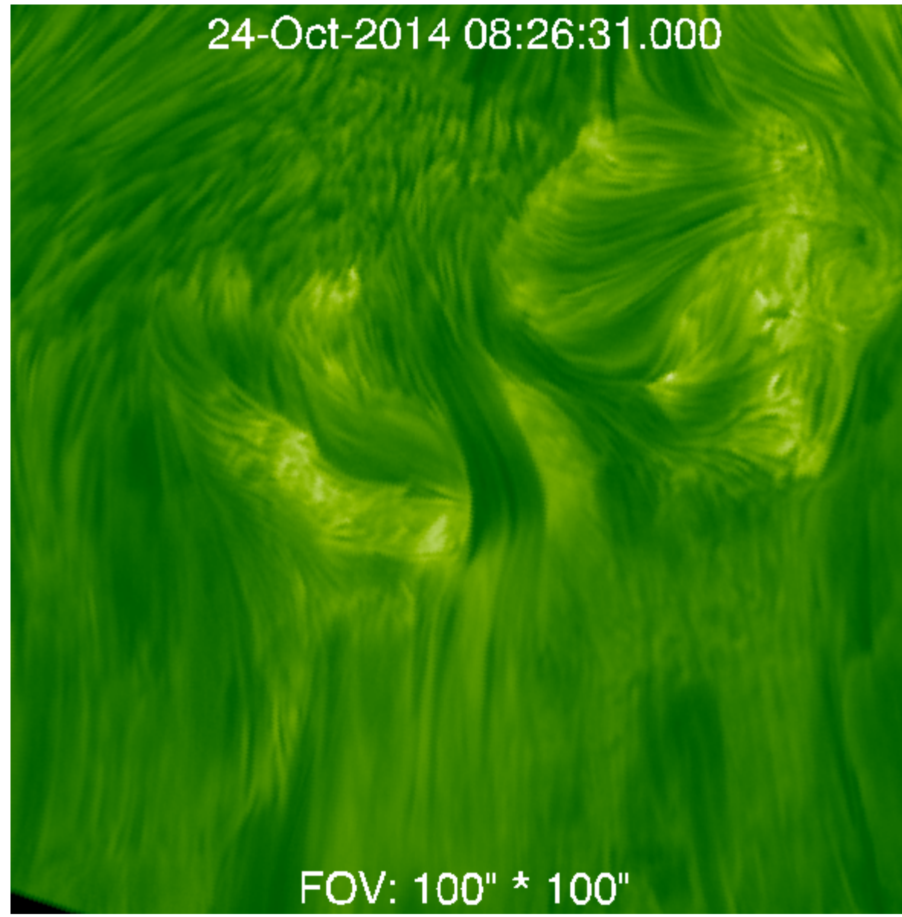
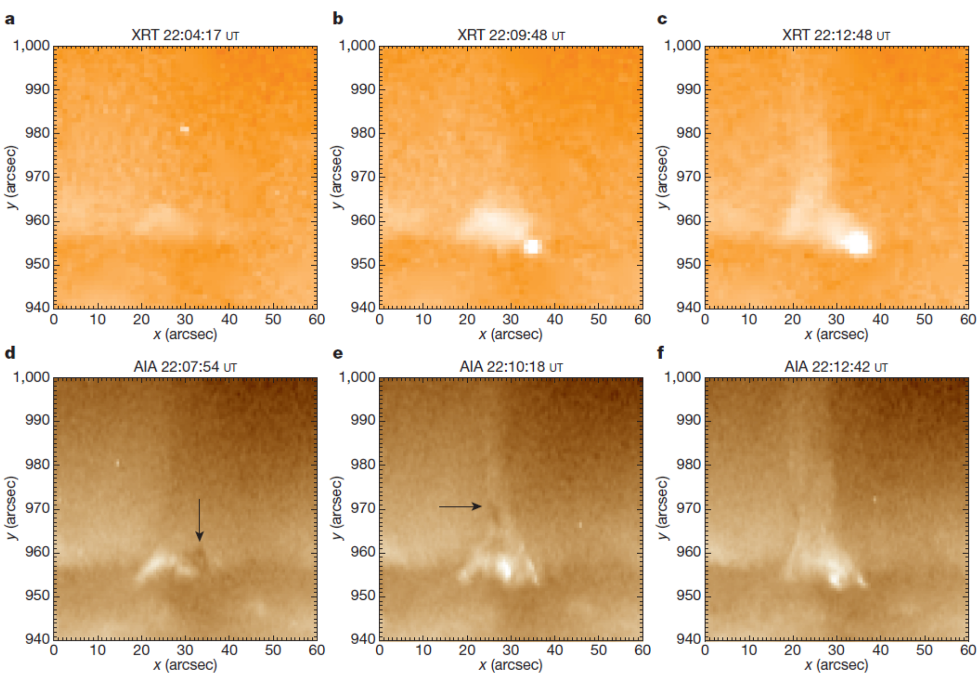


(Li et al. 2015)

Solar jets: minifilament eruption model

- ➢ Sterling et al. (2015) investigate 20 X-ray jets in polar coronal holes. They conclude that, regardless of standard type or blowout type, each jet is driven by erupting minifilaments.
- • Before the appearance of the jet spire, the minifilaments erupt from the site of JBP (internal reconnection).
- • The jets form as the minifilaments erupt to interact with open fields (external reconnection).
- ➢ Same result in active regions (Sterling et al. 2016) and quiet regions (Panesar et al. 2016).



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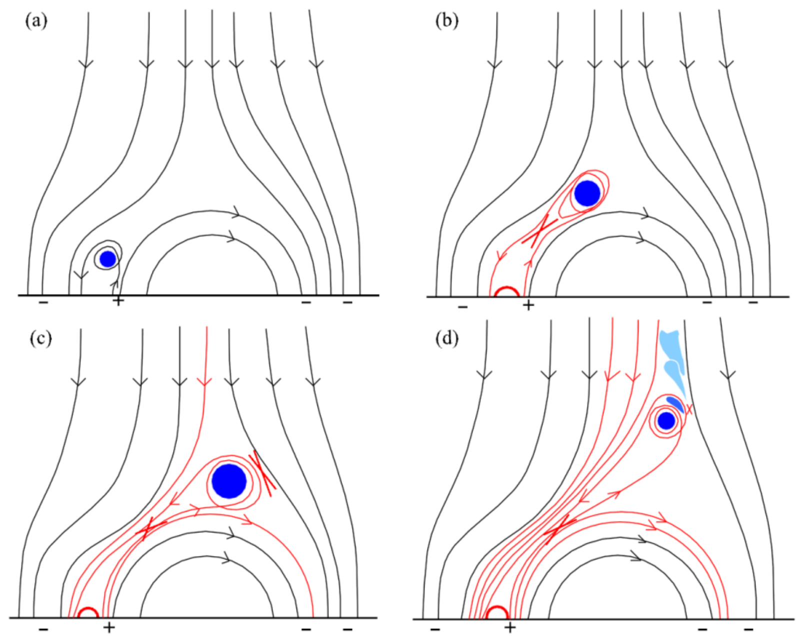

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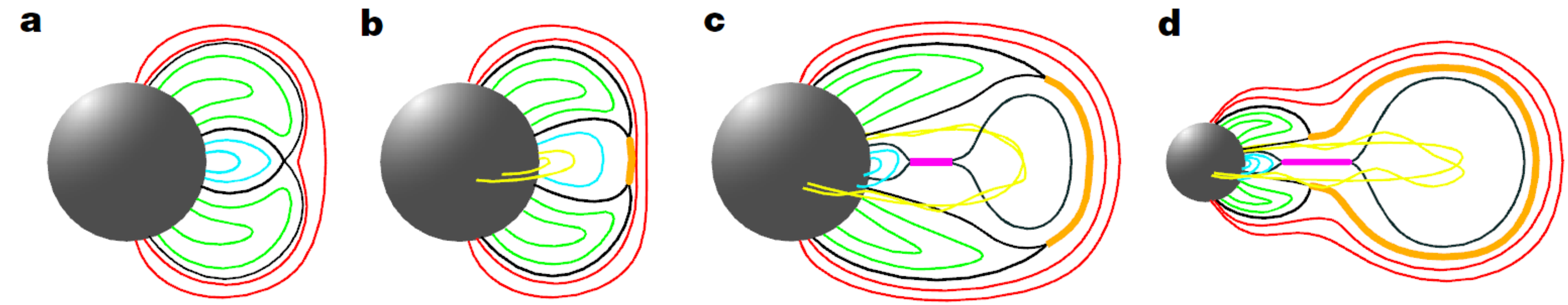
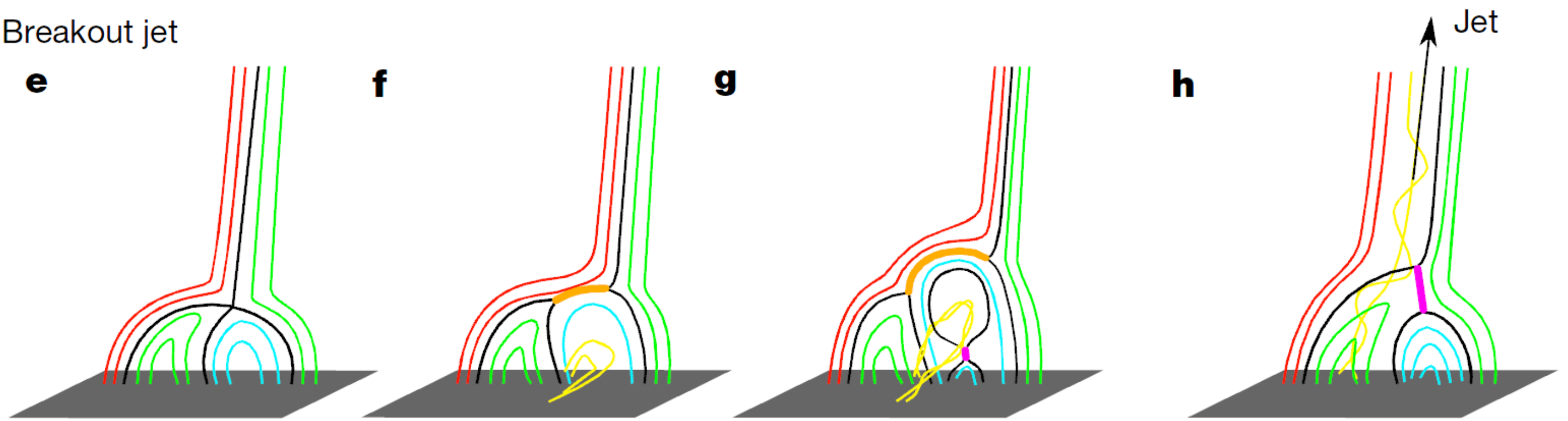
Solar jets: a universal model – breakout model

Breakout CME

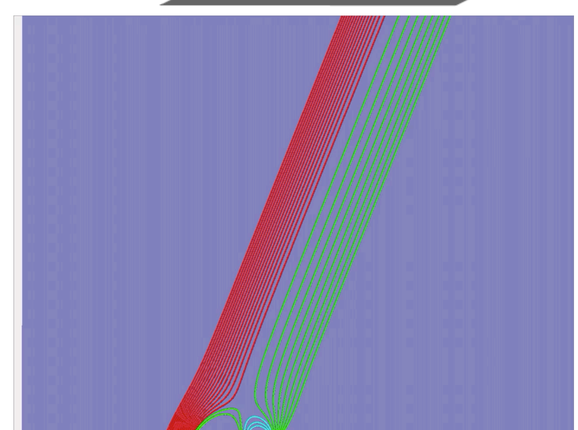


Breakout jet



(Wyper et al. 2017)

Using 3D magnetohydrodynamic (MHD) simulations, Wyper et al. (2017, 2018) demonstrated that the breakout model for large-scale solar eruptions equally explains small-scale jets and produces mini-filament eruptions, thus the breakout model can be a universal model.



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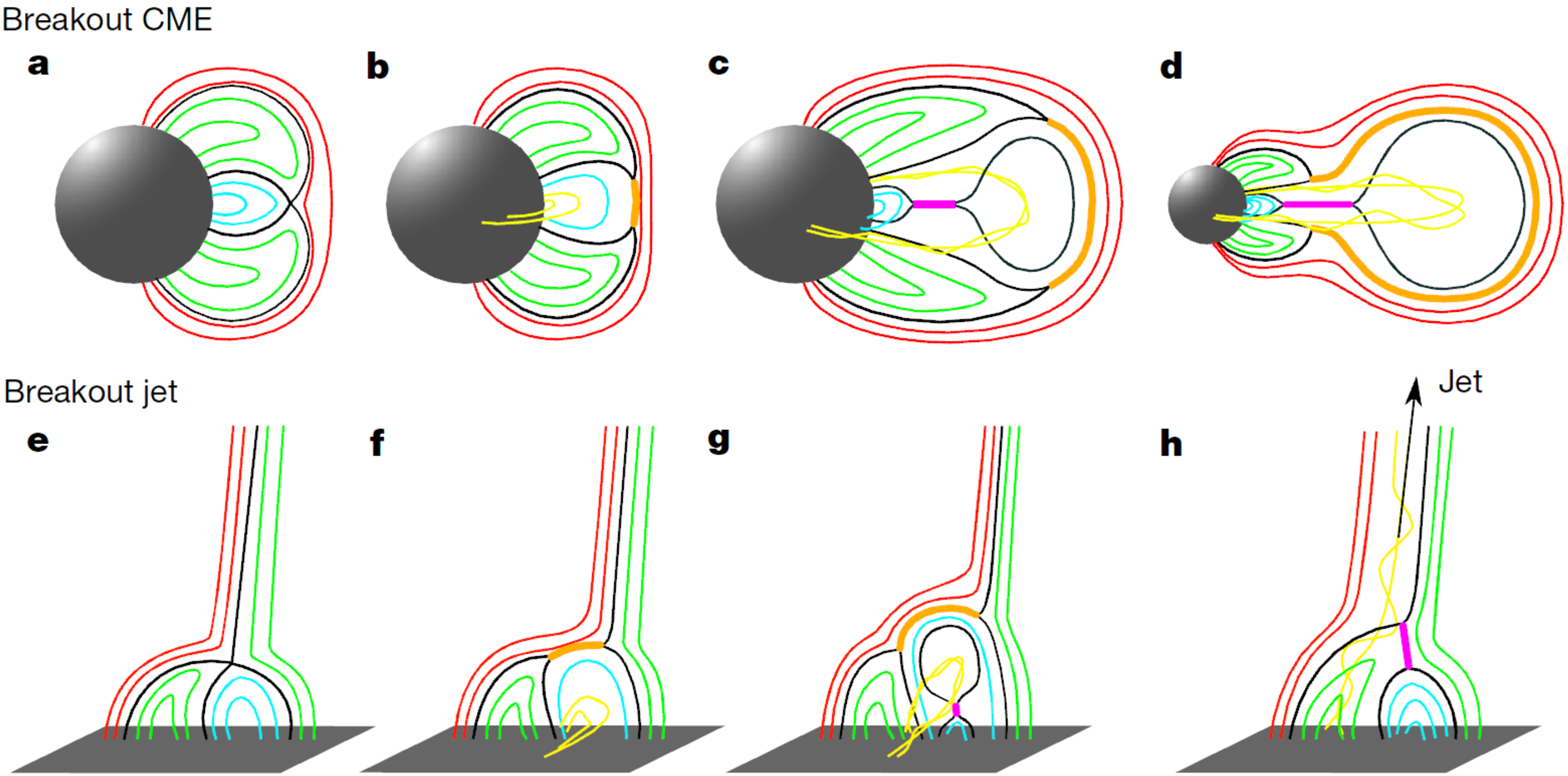

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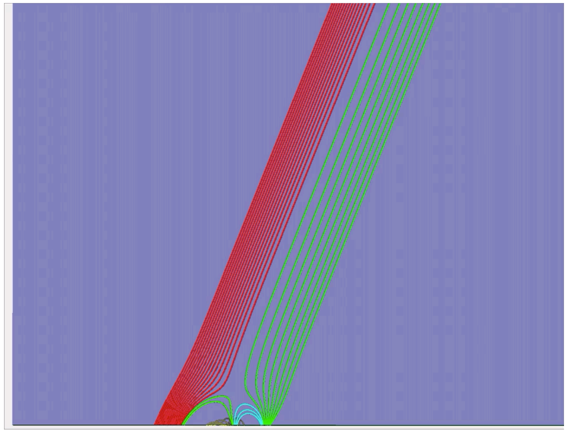

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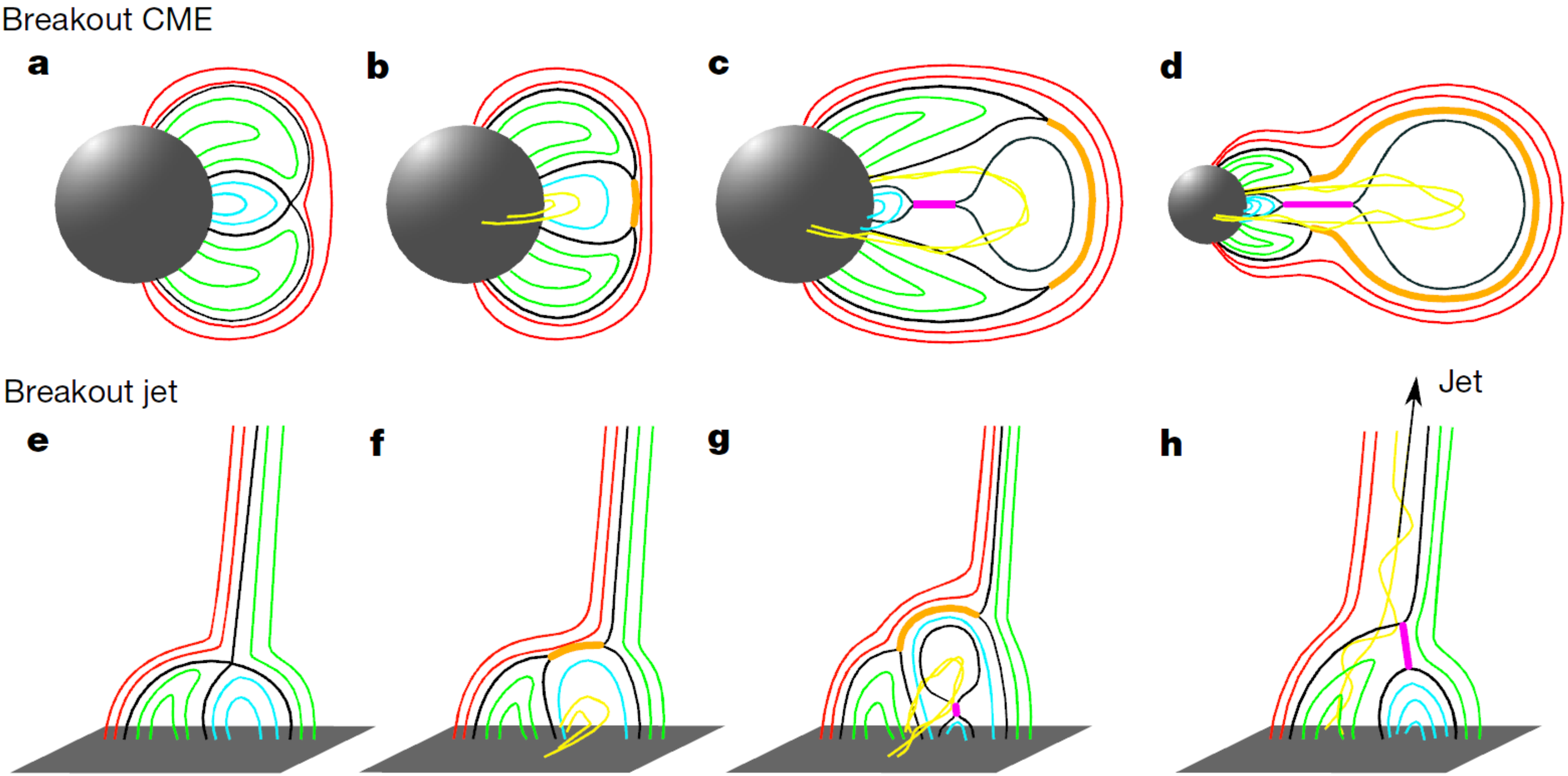

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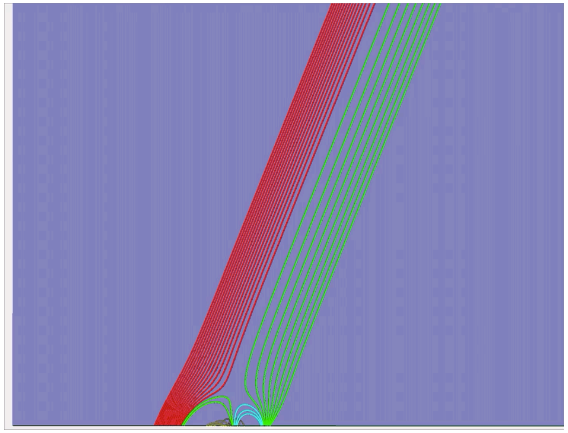

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Kelvin-Helmholtz instability

- Kelvin−Helmholtz instability (KHI) occurs when two parallel fluids with different velocities flow alongside each other, with a shear exceeding a critical value (Helmholtz 1868; Kelvin 1871).
- In non-viscous HD and MHD situations, dispersion equations (Chandrasekhar, 1961):

$$\omega = \frac{\mathbf{k} \bullet (\rho_1 \mathbf{V}_1 + \rho_2 \mathbf{V}_2) \pm i\sqrt{\rho_1 \rho_2 (\mathbf{k} \bullet \mathbf{V}_1 - \mathbf{k} \bullet \mathbf{V}_2)^2}}{\rho_1 + \rho_2}$$

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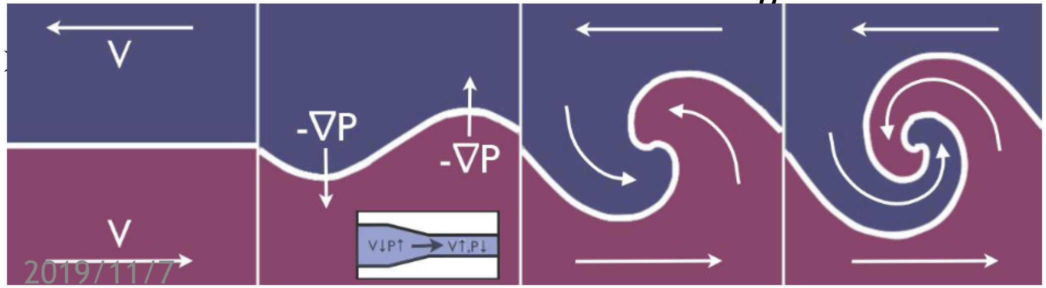
Instability occurs when Im{ω}>0

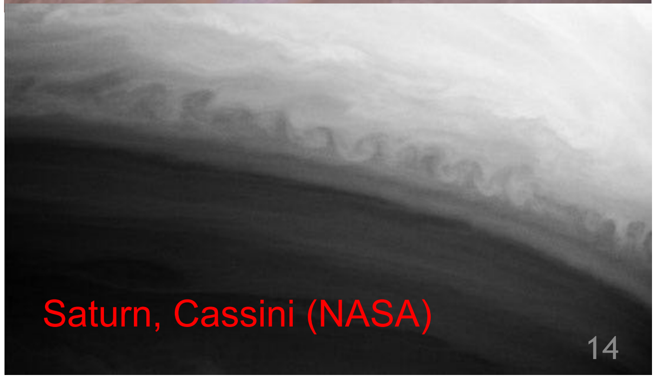
HD: $\mathbf{V}_1 \neq \mathbf{V}_2$

MHD:

$$\rho_1 \rho_2 (\mathbf{k} \bullet \mathbf{V}_1 - \mathbf{k} \bullet \mathbf{V}_2)^2 > \frac{(\rho_1 + \rho_2)[(\mathbf{k} \bullet \mathbf{B}_1)^2 + (\mathbf{k} \bullet \mathbf{B}_2)^2]}{\mu}$$




Jupiter, Voyager 2 (NASA)


Saturn, Cassini (NASA)

Kelvin-Helmholtz instability

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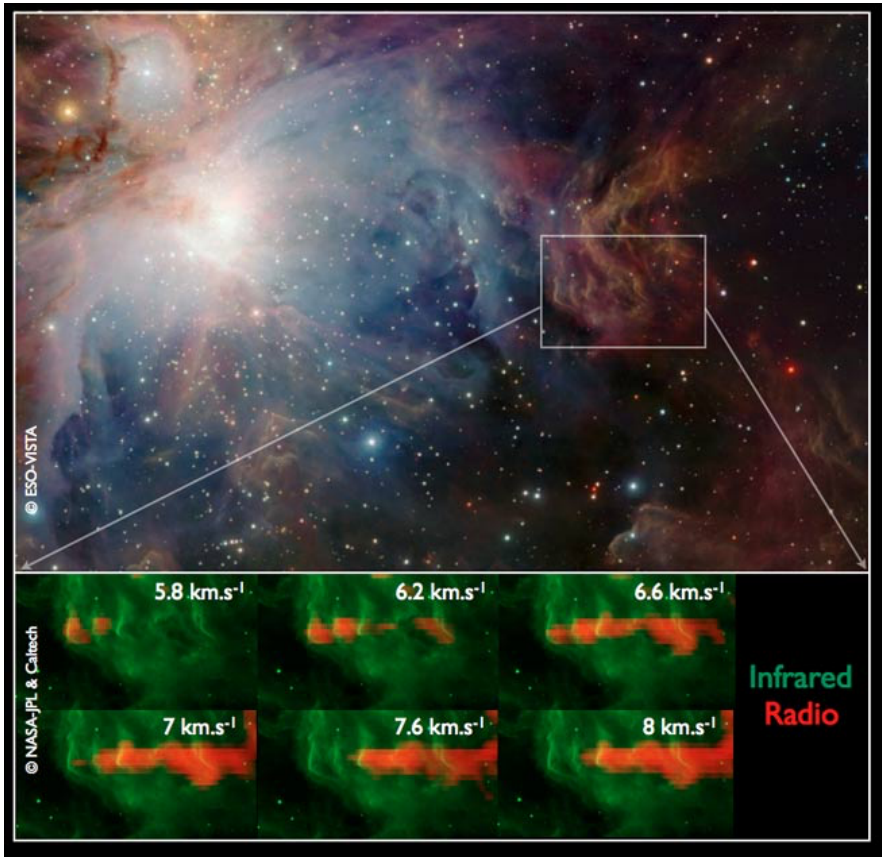

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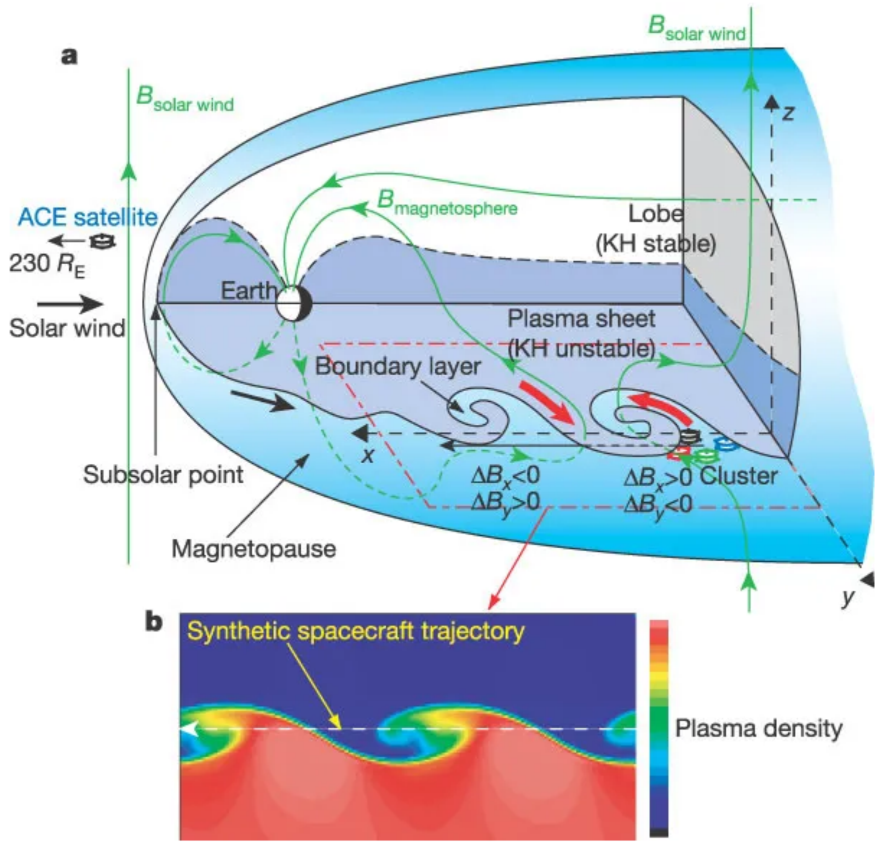
In astrophysics and space physics, the KHI has been observed in many phenomena including:

- ➢ astrophysical objects (Berné et al., 2010)
- ➢ Interface of the solar wind and Earth's magnetopause (Hasegawa et al. 2004)



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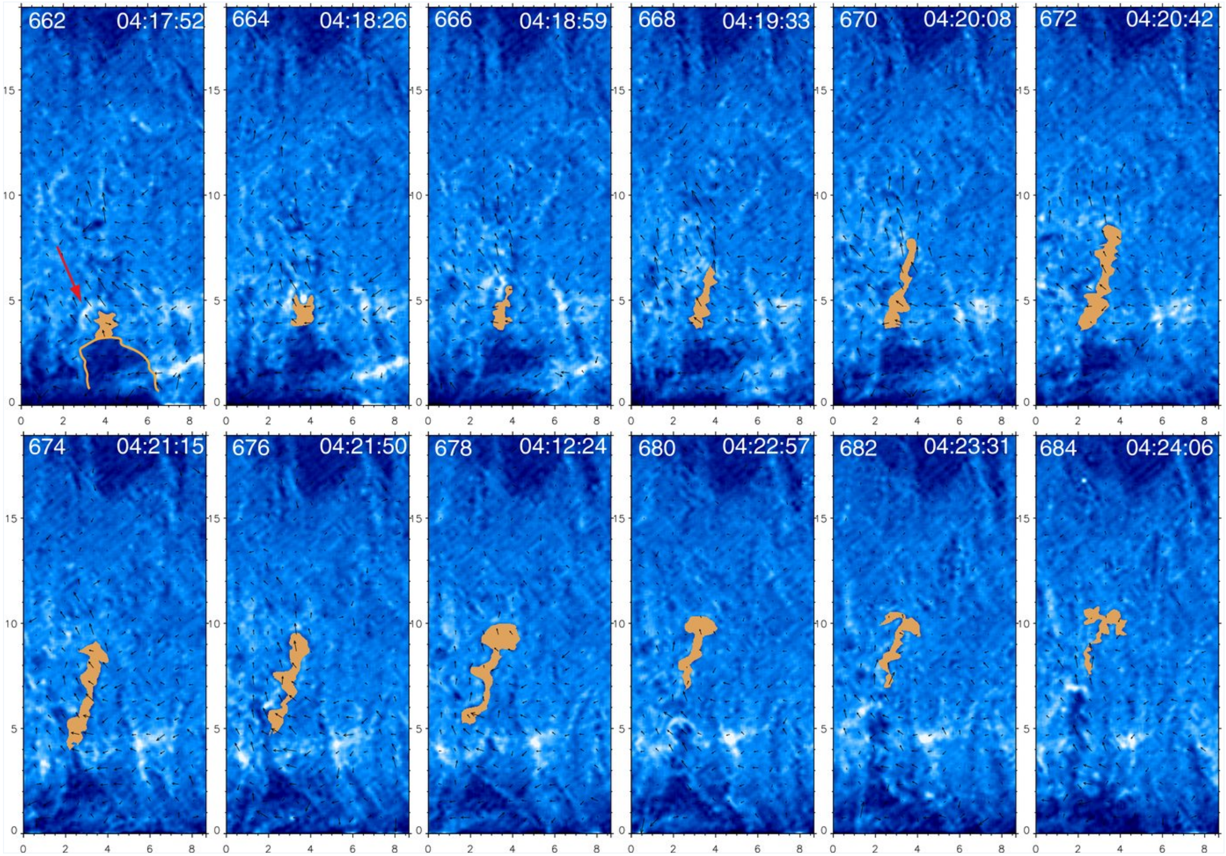
- ➢ Solar prominences (e.g., Berger et al. 2010; Ryutova et al. 2010)



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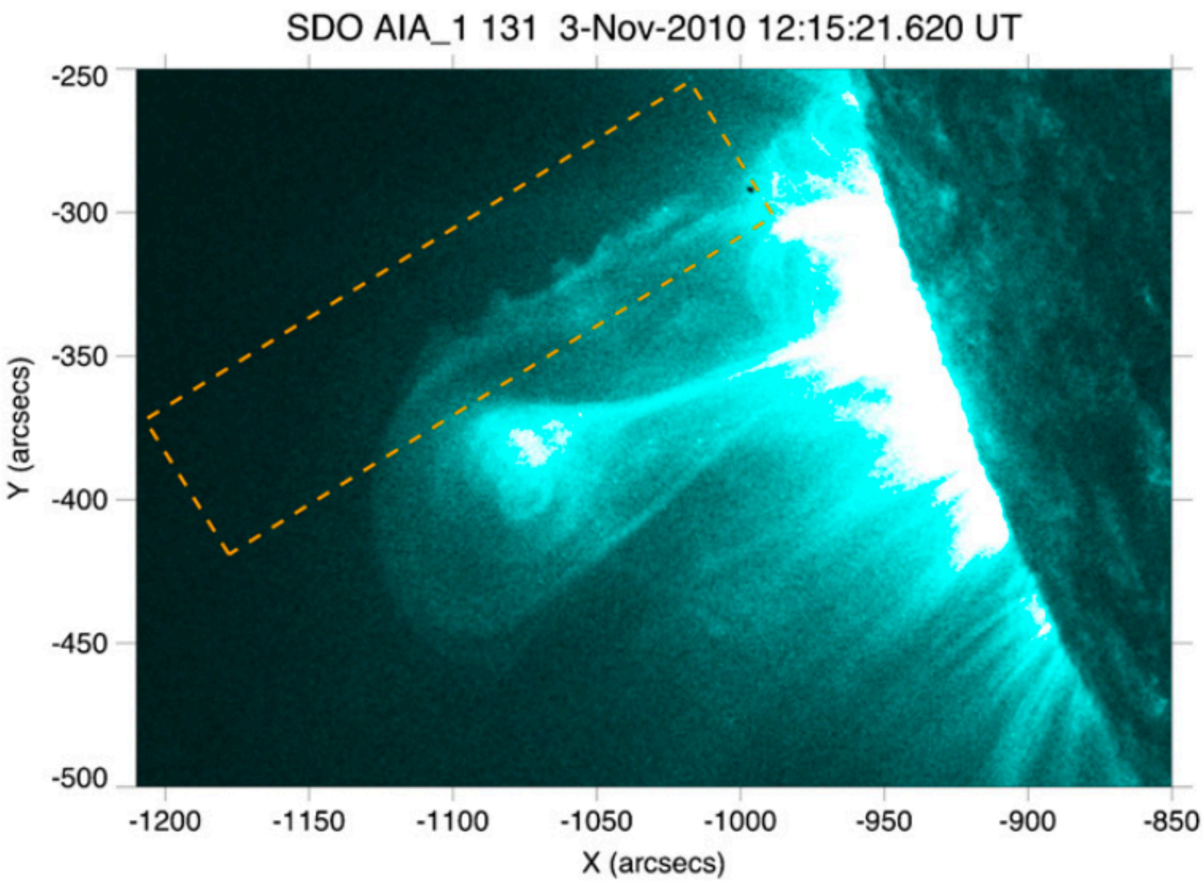
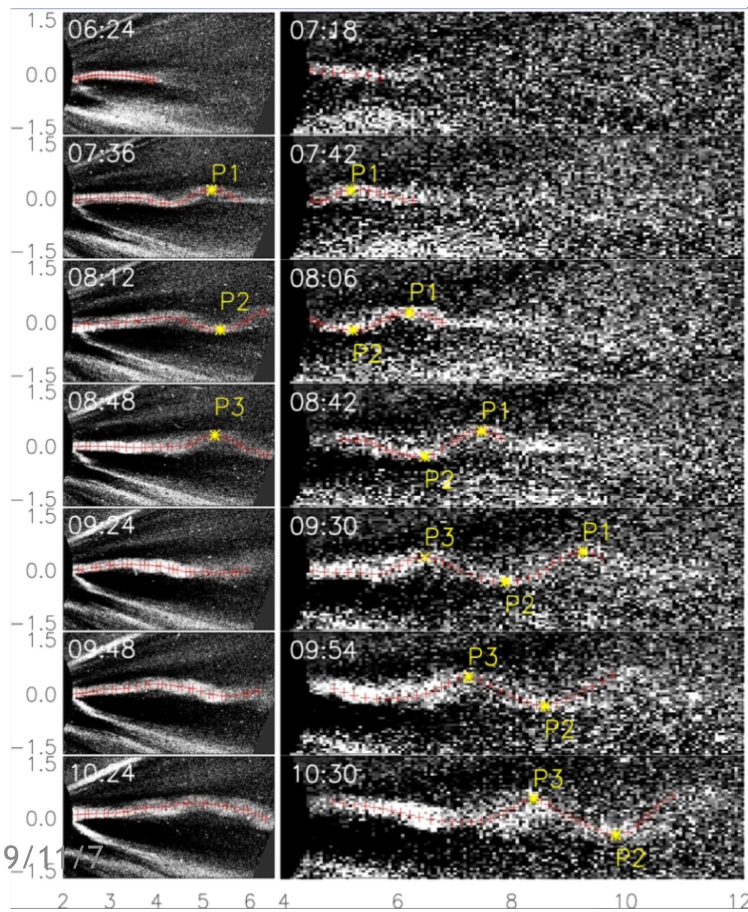
- ➢ Solar prominences (e.g., Berger et al. 2010; Ryutova et al. 2010)
- ➢ CME (e.g., Ofman and Thomson, 2011; Foullon et al., 2011; Möstl et al. 2013)

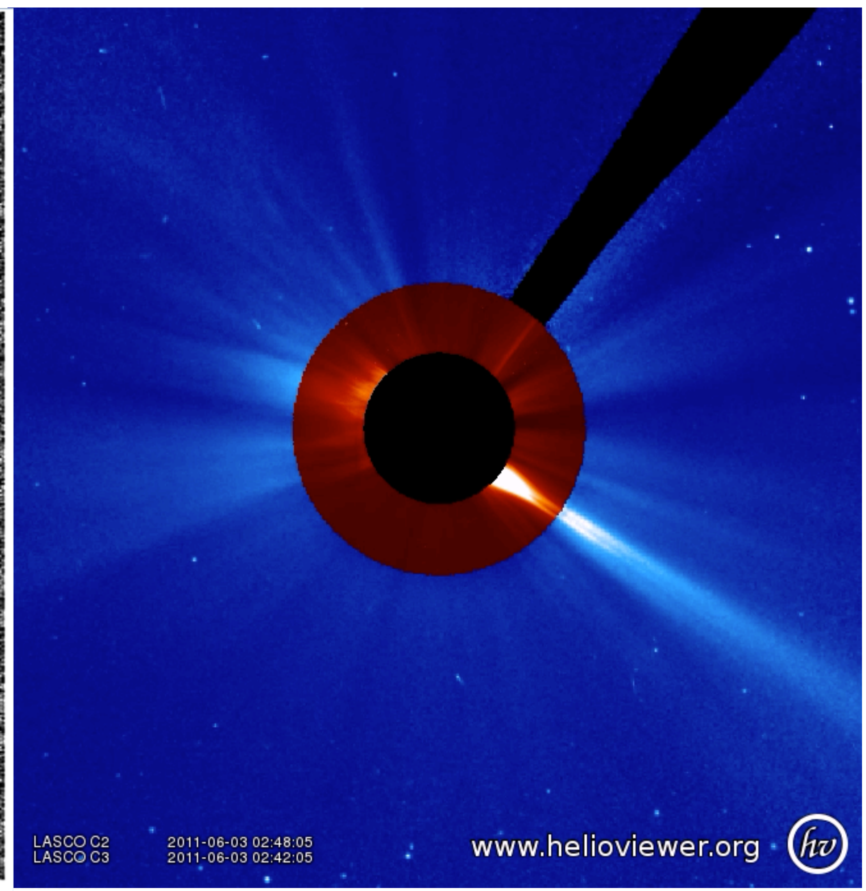


Kelvin-Helmholtz instability

In astrophysics and space physics, the KHI has been observed in many phenomena including:

- ➢ astrophysical objects (Berné et al., 2010)
- ➢ Interface of the solar wind and Earth's magnetopause (Hasegawa et al. 2004)
- ➢ Solar prominences (e.g., Berger et al. 2010; Ryutova et al. 2010)
- ➢ CME (e.g., Ofman and Thomson, 2011; Foullon et al., 2011; Möstl et al. 2013)
- ➢ Solar streamer (Feng et al. 2013)





Rayleigh-Taylor instability

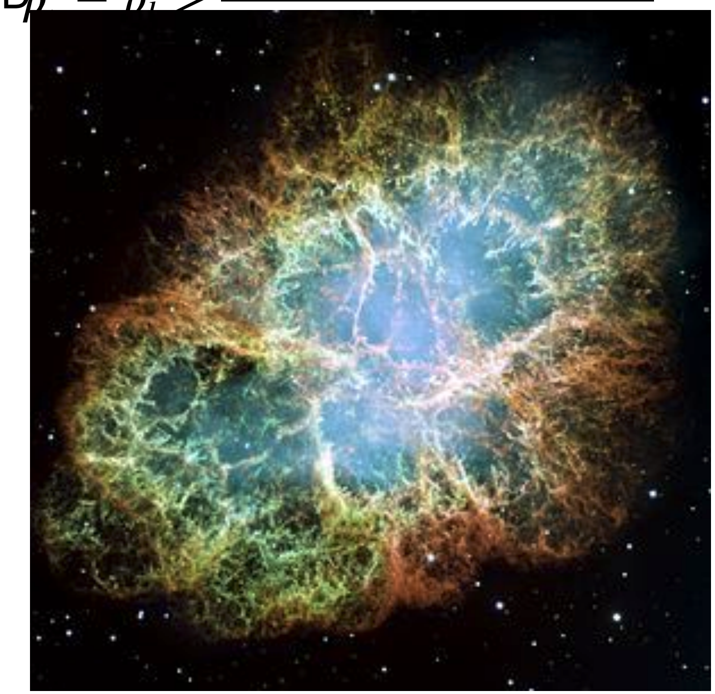
- Raleigh-Taylor instability (RTI) occurs at the interface between two fluids of different densities when a dense fluid is supported against gravity above a lighter fluid (Taylor 1950; Sharp 1984).
- Without background flow, dispersion equations:

$$\omega = i\sqrt{\frac{kg(\rho_u - \rho_l)}{\rho_u + \rho_l}} \quad \text{(HD)}$$

$$\omega = i\sqrt{\frac{kg(\rho_u - \rho_l)}{\rho_u + \rho_l} - \frac{(\mathbf{k}\bullet\mathbf{B}_1)^2 + (\mathbf{k}\bullet\mathbf{B}_2)^2}{\mu(\rho_u + \rho_l)}} \quad \text{(MHD)}$$

Instability occurs: $\rho_u > \rho_l$; $\rho_u - \rho_l > \frac{(\mathbf{k}\bullet\mathbf{B}_1)^2 + (\mathbf{k}\bullet\mathbf{B}_2)^2}{}$

mushroom clouds from atmospheric nuclear explosions



finger-like structures in Crab Nebula (Hester et al. 1996)

Rayleigh-Taylor instability

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Rayleigh-Taylor instability

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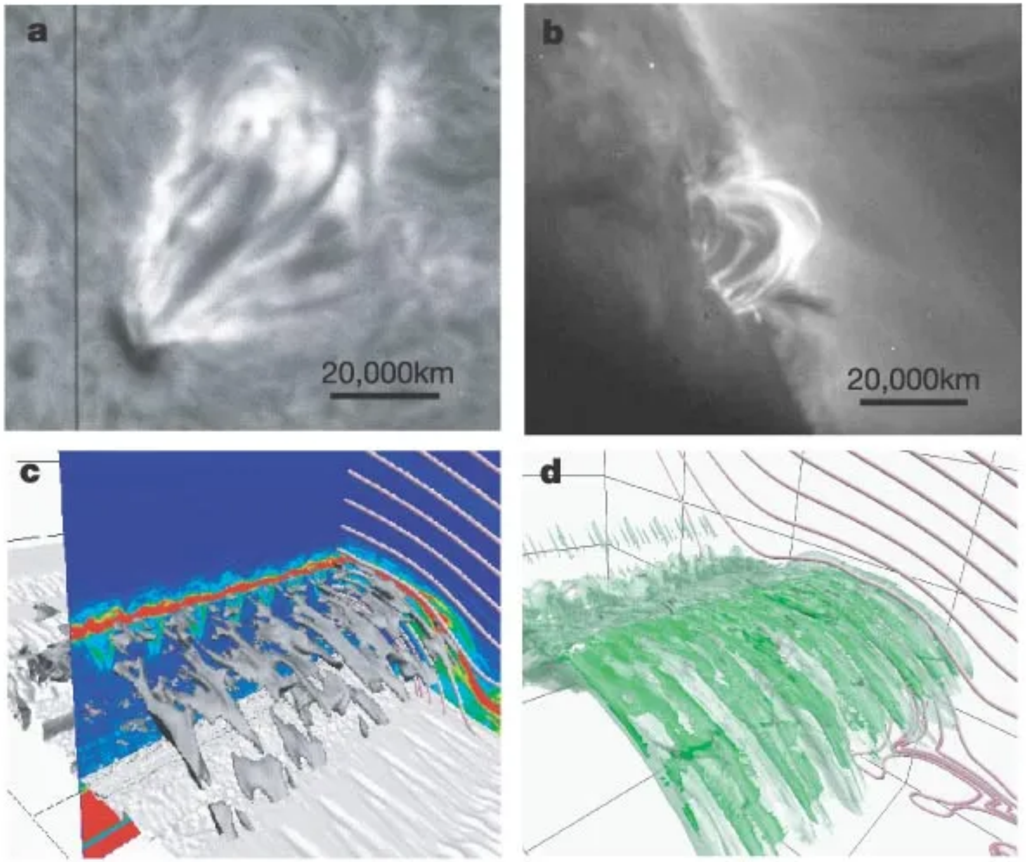

Rayleigh-Taylor instability

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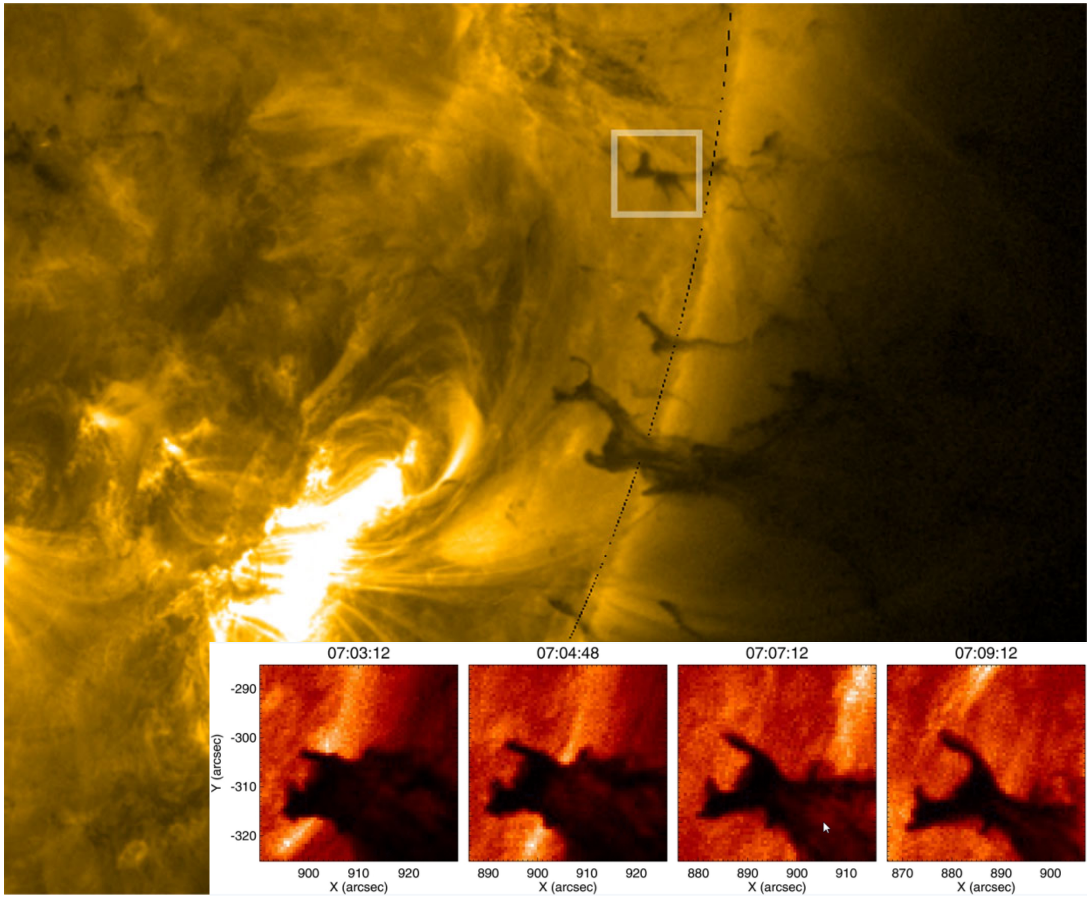
- ➢ filamentary structure arises during the flux emerging (Isobe et al. 2005)
- ➢ breakup of the prominence material as it fell back to the solar surface (Innes et al. 2012; Carlyle et al. 2014)



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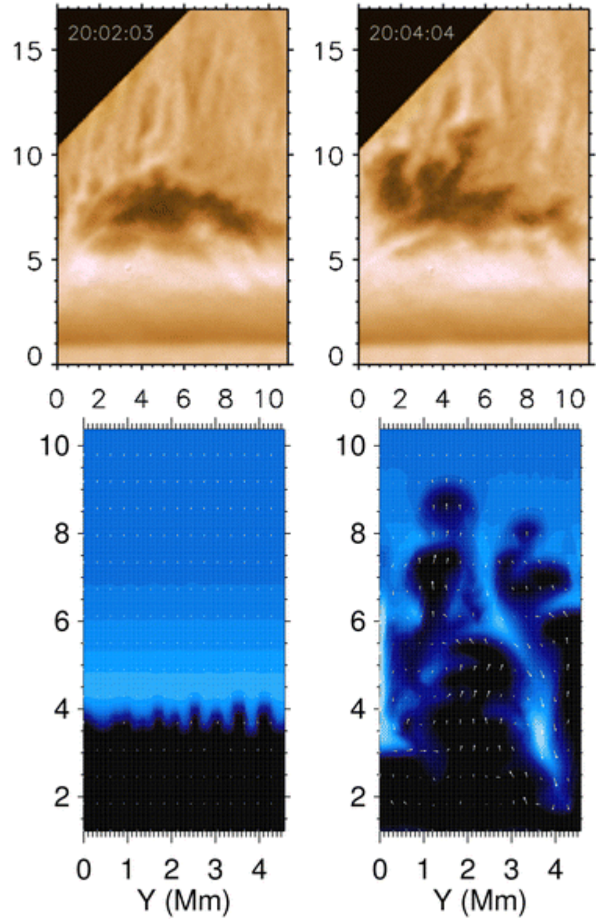
- ➢ breakup of the prominence material as it fell back to the solar surface (Innes et al. 2012; Carlyle et al. 2014)
- ➢ the formation of the plumes in quiescent prominences (Ryutova et al. 2010; Hiller et al. 2018))



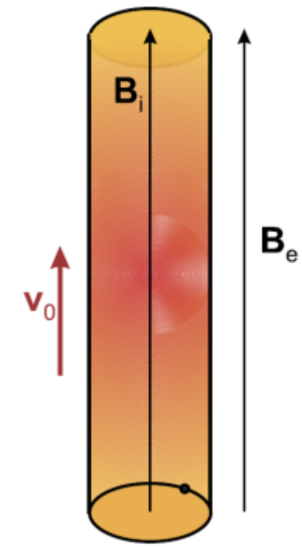
KHI in solar jets: theory

- The observations of the KHI in the solar atmosphere stimulated the modeling of instability in magnetic flux tubes (e.g., Zaqarashvili et al. 2010, 2011,2014; Zhelyazkov et al. 2012). The occurrence of the KHI in solar jets are studied by regarding the jet as a flux tube.

- Methods: use the linearized incompressible MHD equations in cylindrical geometry under different situations to get the dispersion relation, then the dispersion relation is solved analytically and numerically to find thresholds for KHI.

- As demonstrated before, the jets have axial, transverse and untwisting motion. The KHI can be developed by velocity discontinuity at boundaries of magnetic flux tubes owing to the relative motion of the tubes with regard to the background or neighboring tubes. However, the flow-aligned magnetic field can exert a restoring force, and KHI would happen only in super-Alfvénic flows (Alfvén Mach number >1).

- The magnetic field configurations of the jet and surrounding environment are crucial for possible onset of the instability.



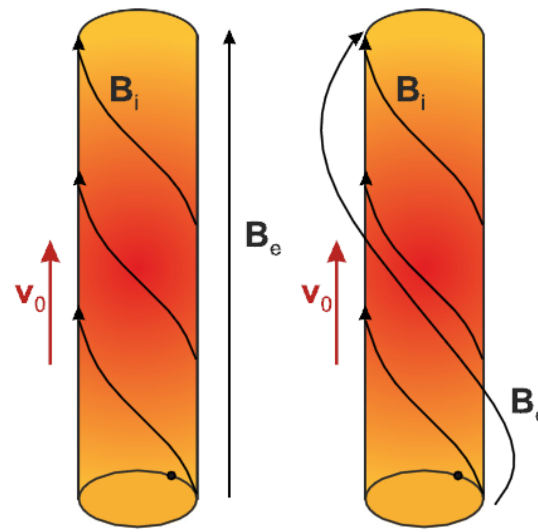
(Zhelyazkov et al. 2016)

KHI in solar jets: theory

- Zaqarashvili et al. (2015) studied the KH instability of twisted and rotating jets caused by the velocity jumps near the jet surface. In the incompressible approximation they obtained the result that twisted and rotating jets are unstable when the kinetic energy of rotation is higher than the magnetic energy of the twist. KH vortices may lead to an enhanced turbulence development and heating of surrounding plasma, therefore rotating jets may provide energy for chromospheric and coronal heating.

- Zhelyazkov et al. (2015) investigated the KHI in surges (cool jets) by modeling the surge as a moving twisted magnetic flux tube in homologous and twisted magnetic field. Their numerical studies showed that KHI occurred in magnetic field configurations for MHD waves propagating in axial direction, and the critical velocity for emerging KHI was remarkably lower than Alfvén speed when both magnetic fields were twisted.

- In general, any velocity component across the magnetic fields inside and outside a jet may lead to the fast development of KHI.



(Zhelyazkov et al. 2015)

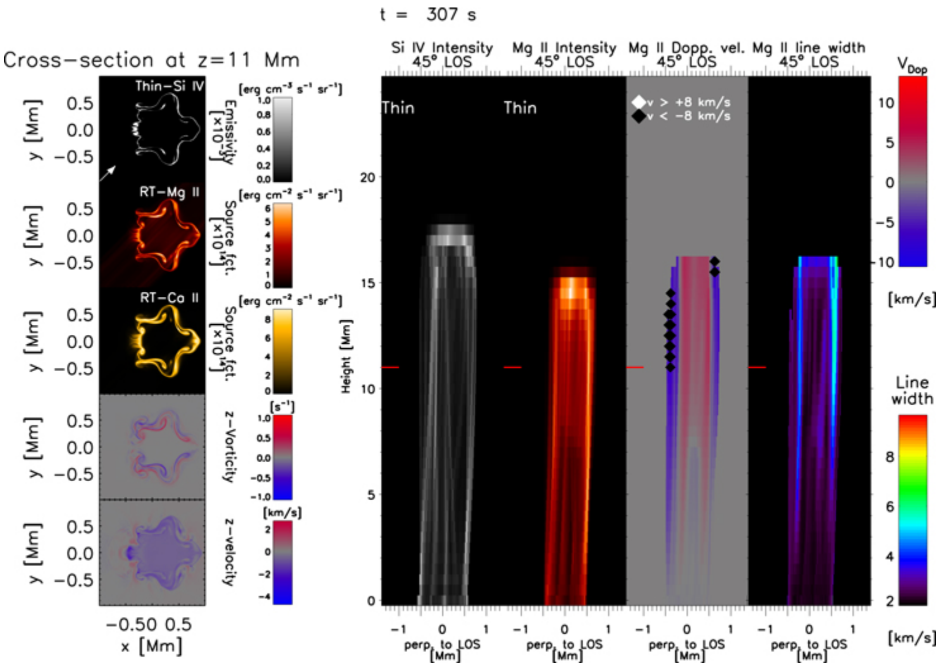
- Other parameters that influence the occurrence of the KHI: compressibility (Sen 1964) , viscosity (Ruderman et al. 1996) ……

KHI in solar jets: simulations

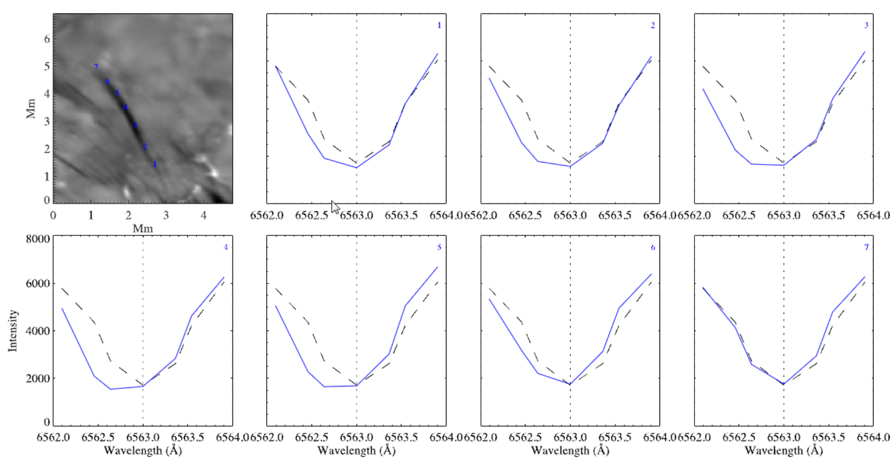
- ➢ The transverse motion of non-twisted jets may result in the KHI for any value of speed, which may lead to the plasma turbulence and heating.

- ➢ 3D simulations showed that the transverse waves in the spicules would induce the KHI and vortices grow at the of the spicules (Antolin et al. 2018).

- ➢ Recently observed fast disappearance of rapid redshifted and blueshifted excursions (RREs, RBEs) in the Hα line has been interpreted by the heating of the structures due to the KHI at their boundary during transverse motion (Kuridze et al. 2015, 2016).



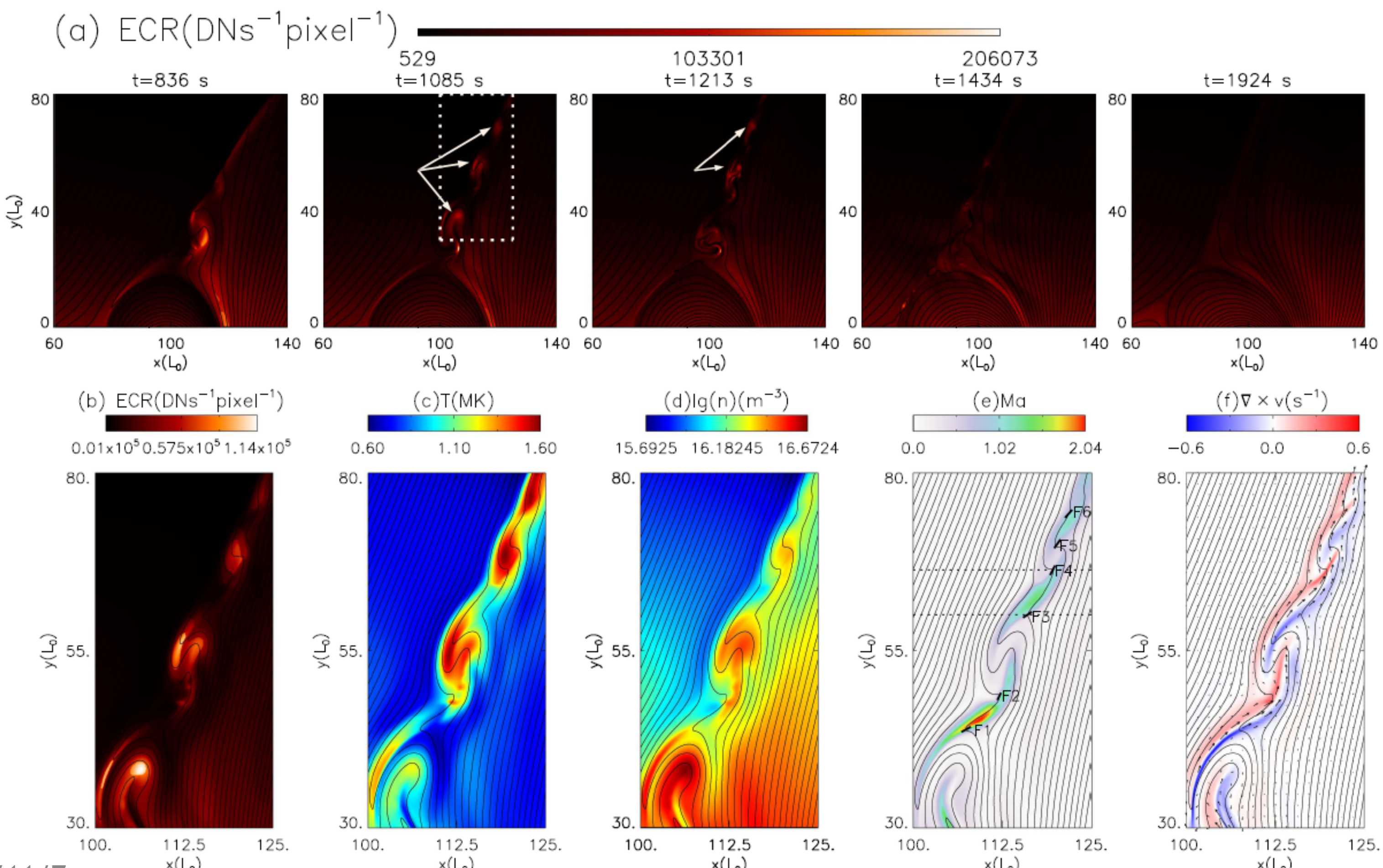
(Antolin et al. 2018)



(Kuridze et al. 2016)

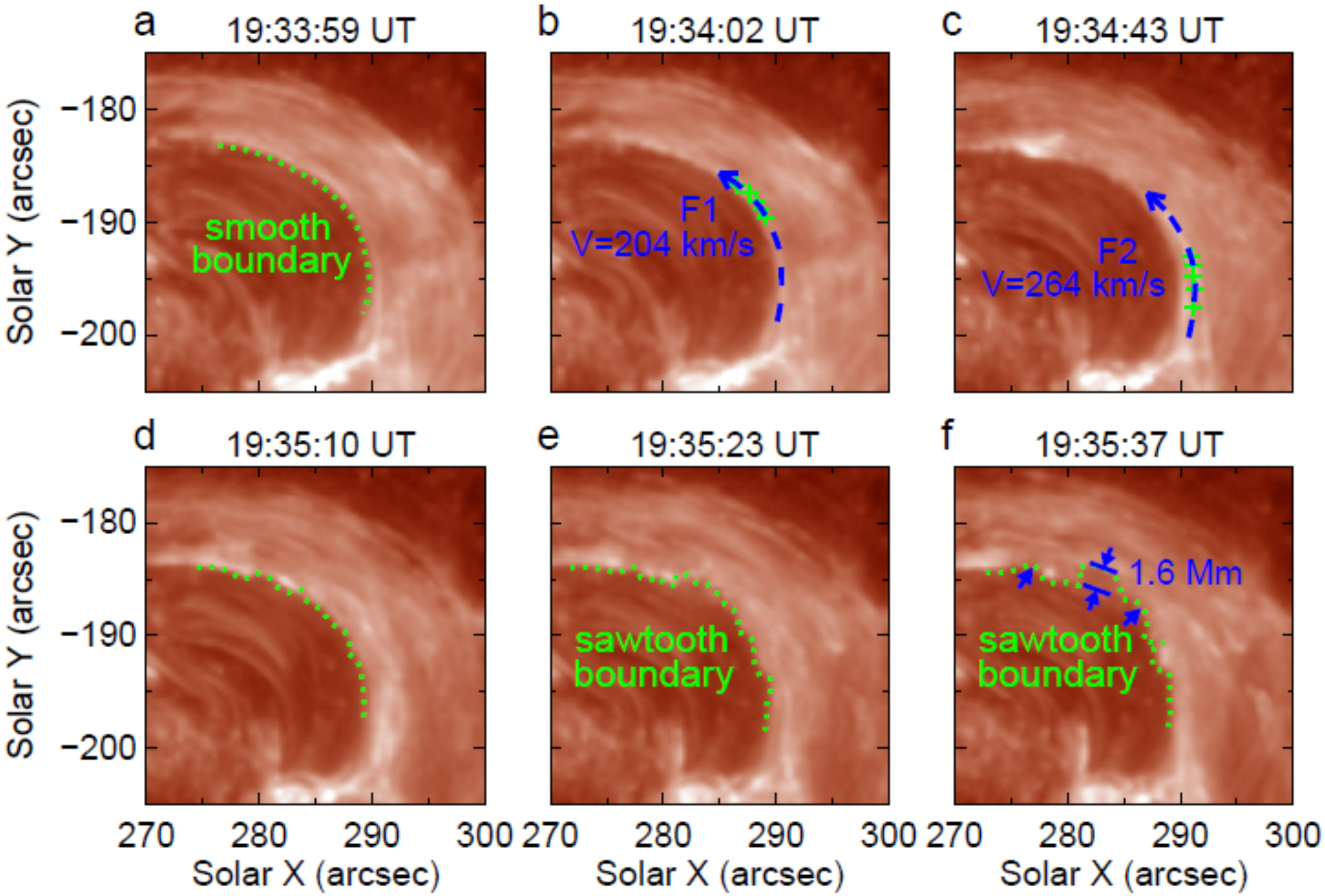
KHI in solar jets: simulations

Recent MHD simulations with high Lundquist number by Ni et al. (2017) supported the presence of KHIs in solar jets. In the case with high Alfvén Mach number, KHI appeared strong shear flows between the high-velocity jet and the roughly stationary ambient plasma and resulted in vortex-like high density and high temperature blobs, which were suggestive of accounting for the bright blobs observed in the EUV band.



KHI in solar jets: observations

Using the high resolution data obtained from IRIS (0.33″/pixel, ~ 3s), Li et al. (2018) found that the KHI developed at the boundary of a blowout jet due to the strong velocity shear (~ 204 km s^{-1}) between two flows.



IRIS 1400 Å images showing the KHI at the boundary of a jet

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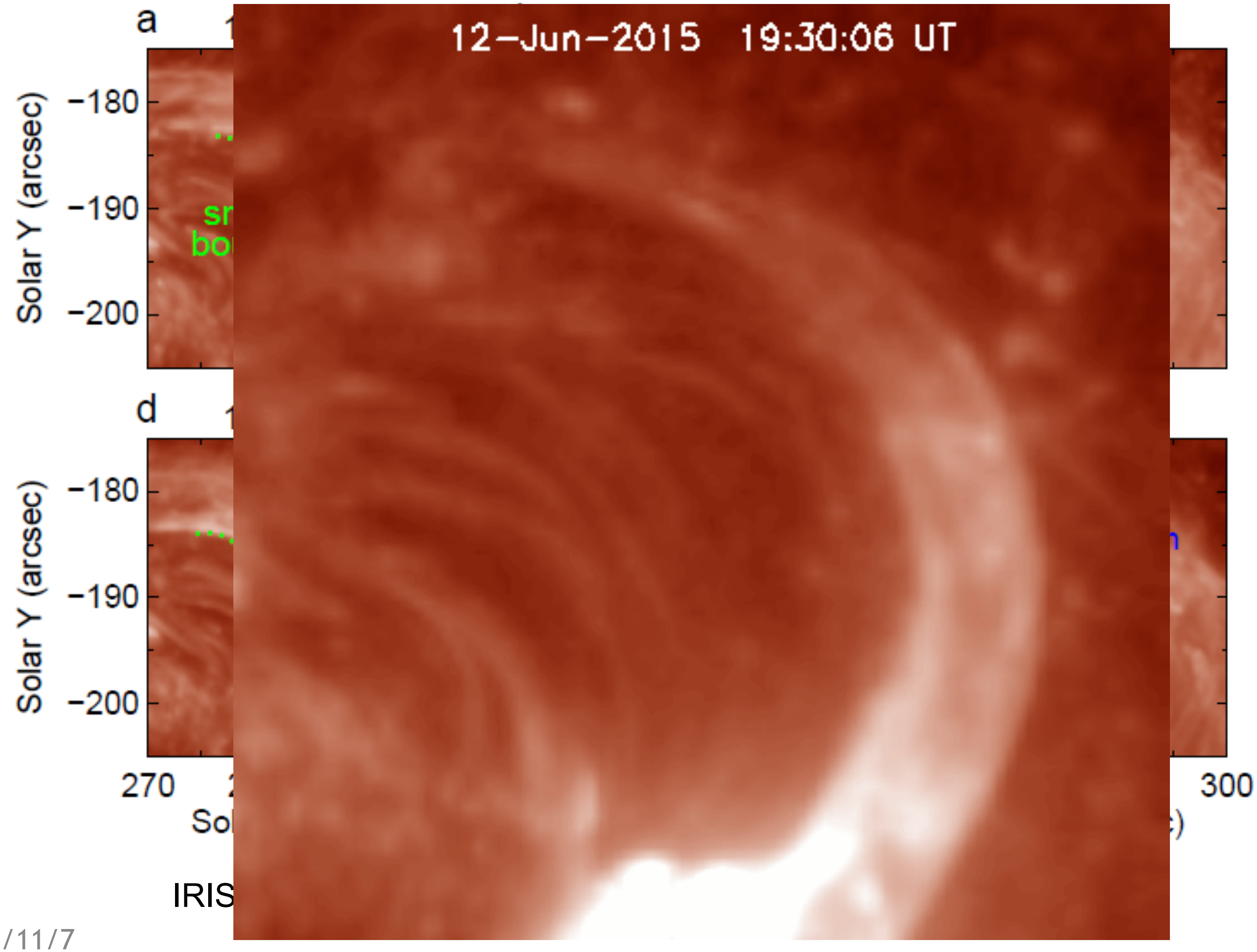

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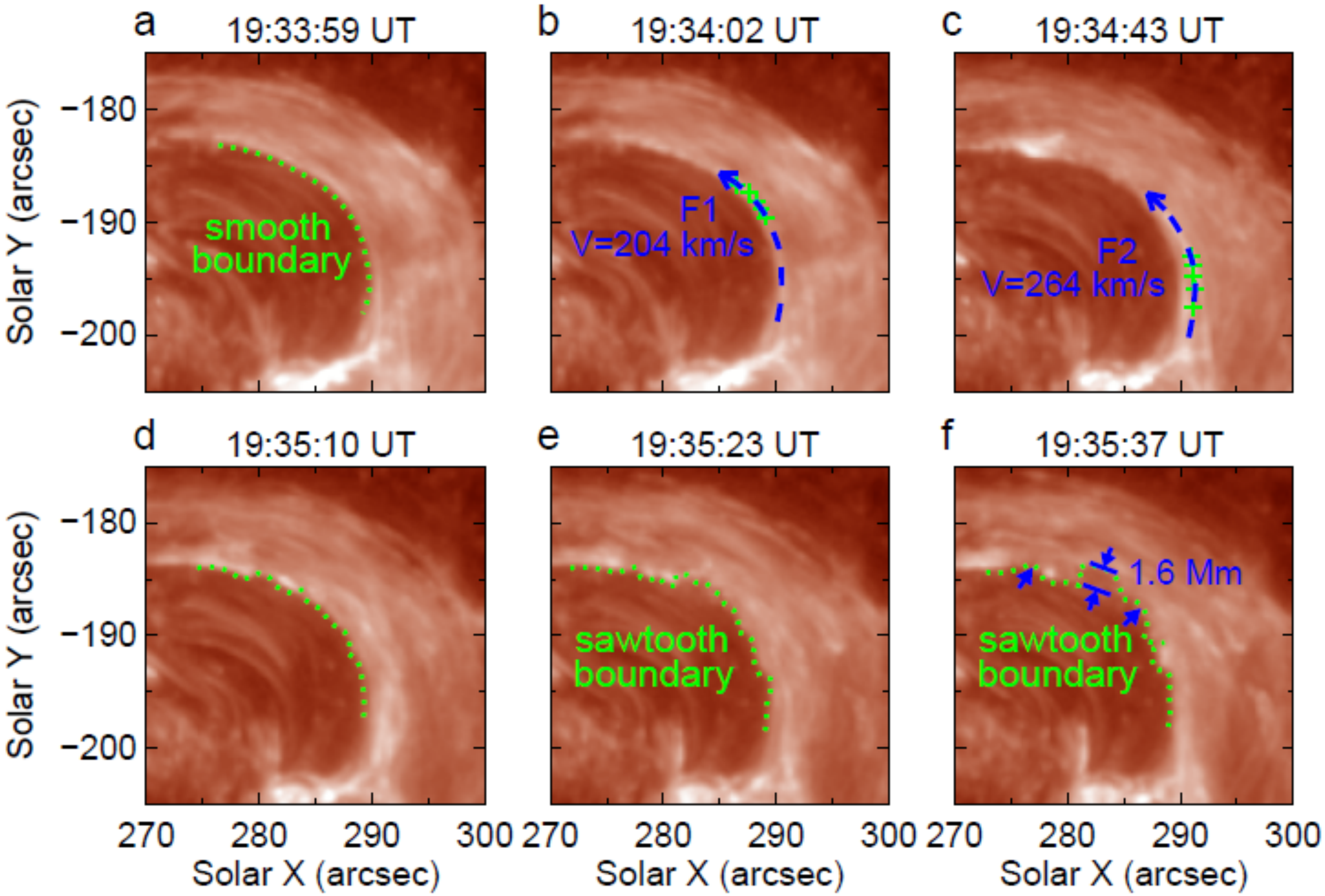

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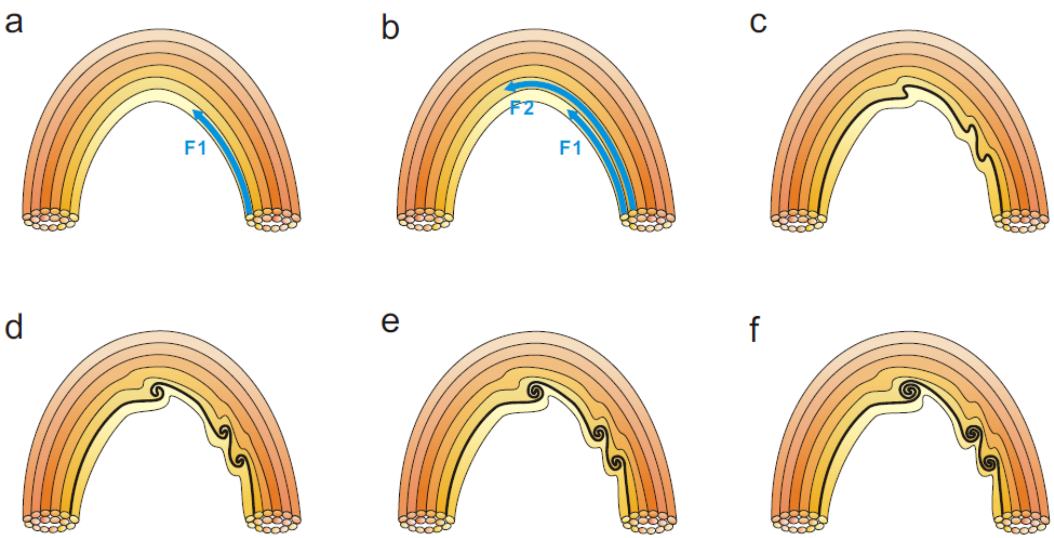
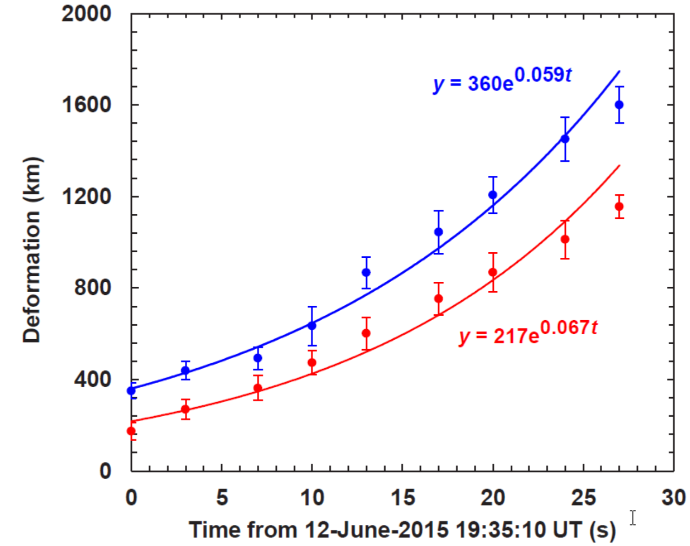
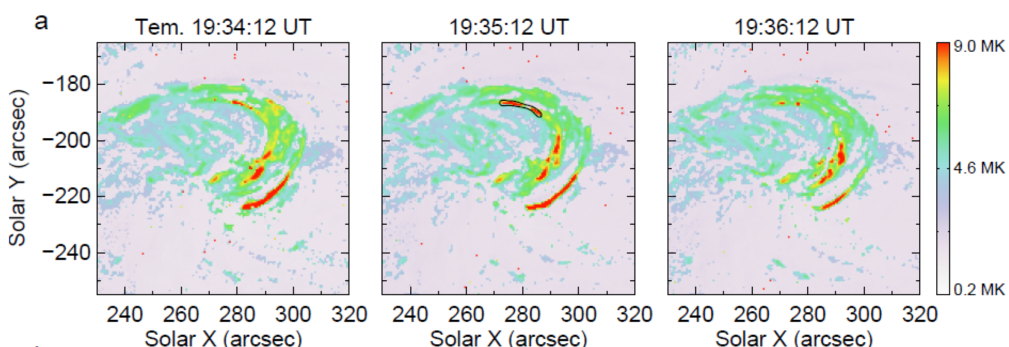
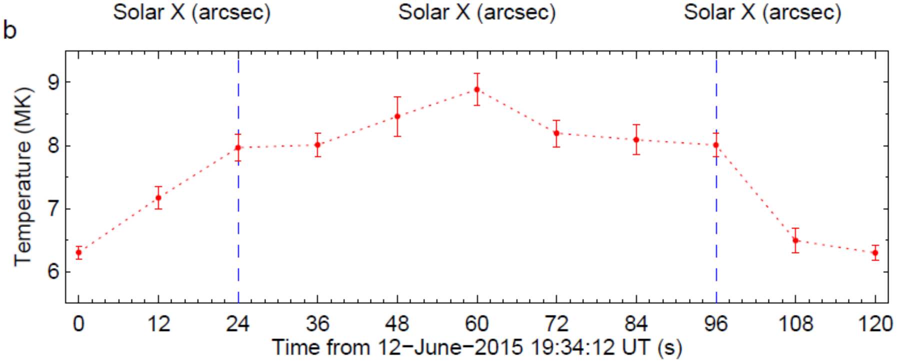








- $\mathbf{k} \parallel \mathbf{B}_1 \parallel \mathbf{B}_2$

$$\Delta V > \sqrt{\frac{(\rho_1 + \rho_2)\left(\mathrm{B}_1^{\,2} + \mathrm{B}_2^{\,2}\right)}{\mu \rho_1 \rho_2}}$$

$\mathbf{B}_1 = 11$ G $\quad \mathbf{B}_2 = 15$ G

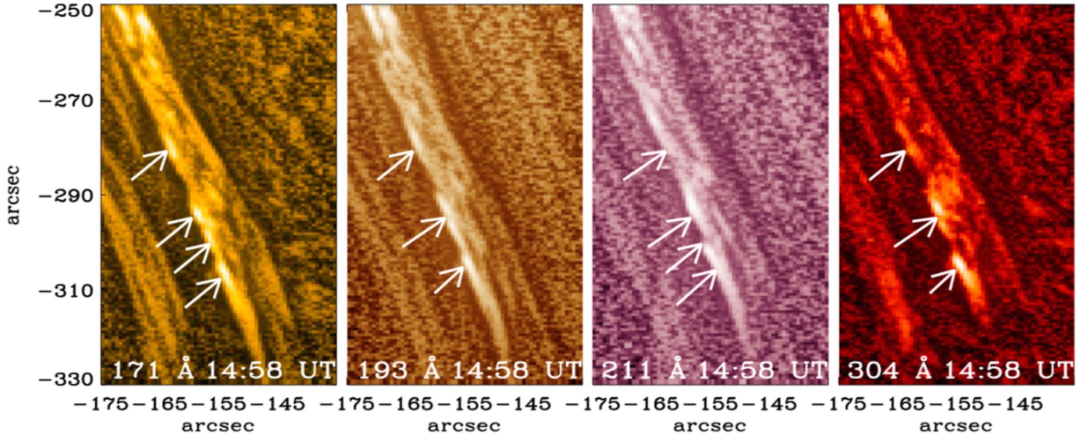
$n_1 = 4\times10^{16}\ \mathrm{m}^{-3}$

$n_2 = 4.5\times10^{16}\ \mathrm{m}^{-3}$

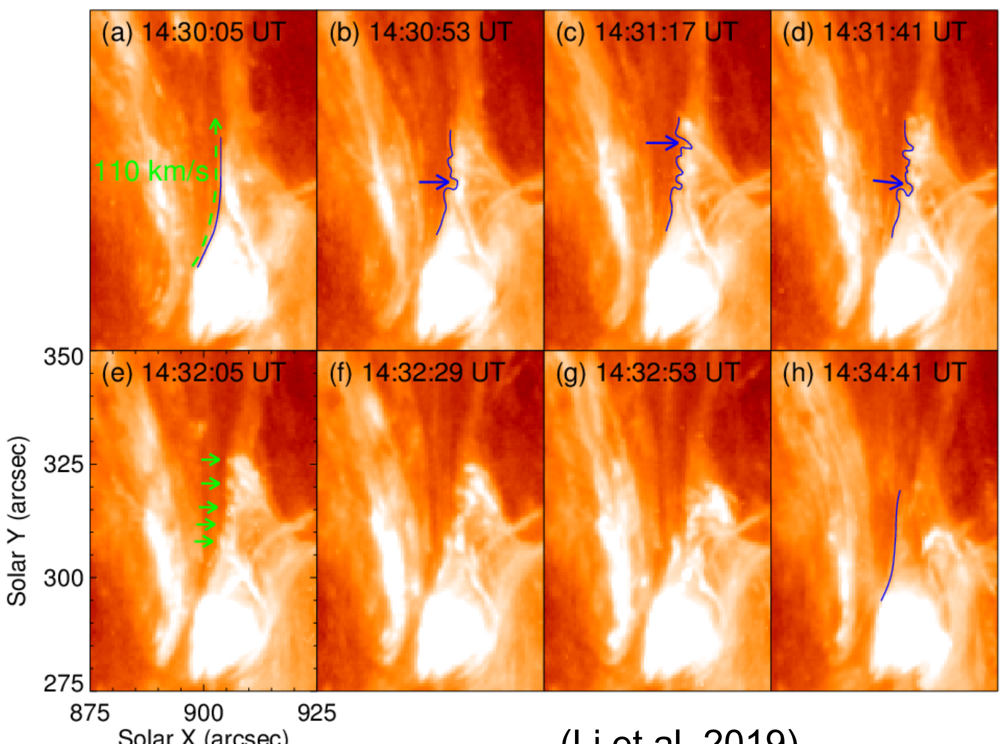
KHI would happen if $\Delta V > 279$ km s^{-1}

- Growth rate: 0.059 & 0.067
- Plasma heating of the KHI

KHI in solar jets: observations



(Bogdanova et al. 2018)



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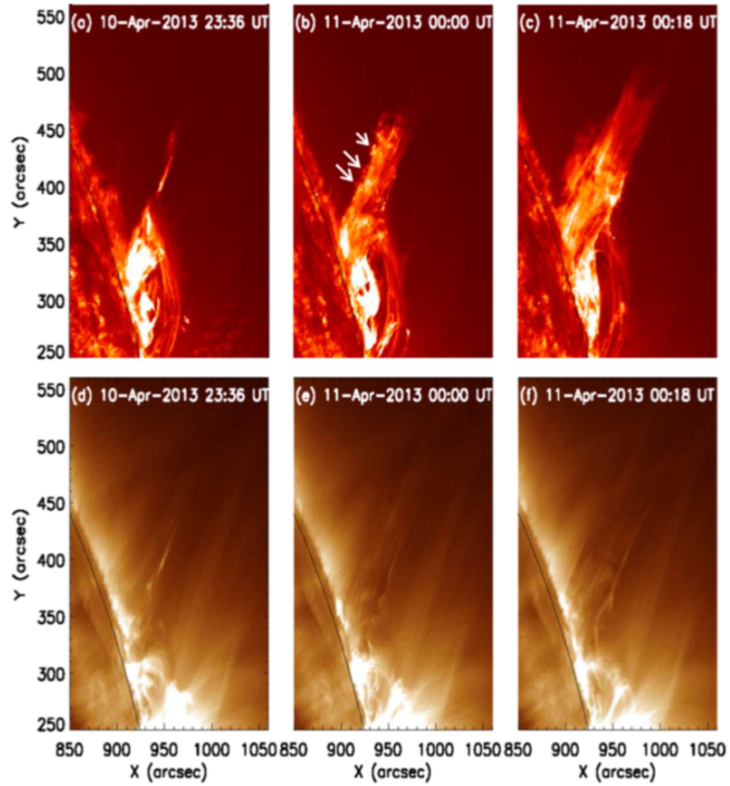


(Zhelyazkov & Chandra 2018)

SDO also observed the vortex-like structures in the upstream regime of the jet, which are interpreted as evidence of the KHI.

Combined KHI and RTI in solar jets

In the downstream regime of the jet, we observed numerous finger-like structures.

Pure RTI:

$$\rho_u - \rho_l > \frac{(\mathbf{k} \bullet \mathbf{B}_u)^2 + (\mathbf{k} \bullet \mathbf{B}_l)^2}{\mu k g}$$

$\mathbf{B}_u = \mathbf{B}_l = 3\mathrm{G} \quad \mathbf{k} \parallel \mathbf{B}_u \parallel \mathbf{B}_l$

corona: $n_l = 10^{15}\ \mathrm{m}^{-3}$

jet: $n_u = 10^{16}\ \mathrm{m}^{-3}$ (no RTI)

RTI would happen if

$n_u > 10^{18}\ \mathrm{m}^{-3}$

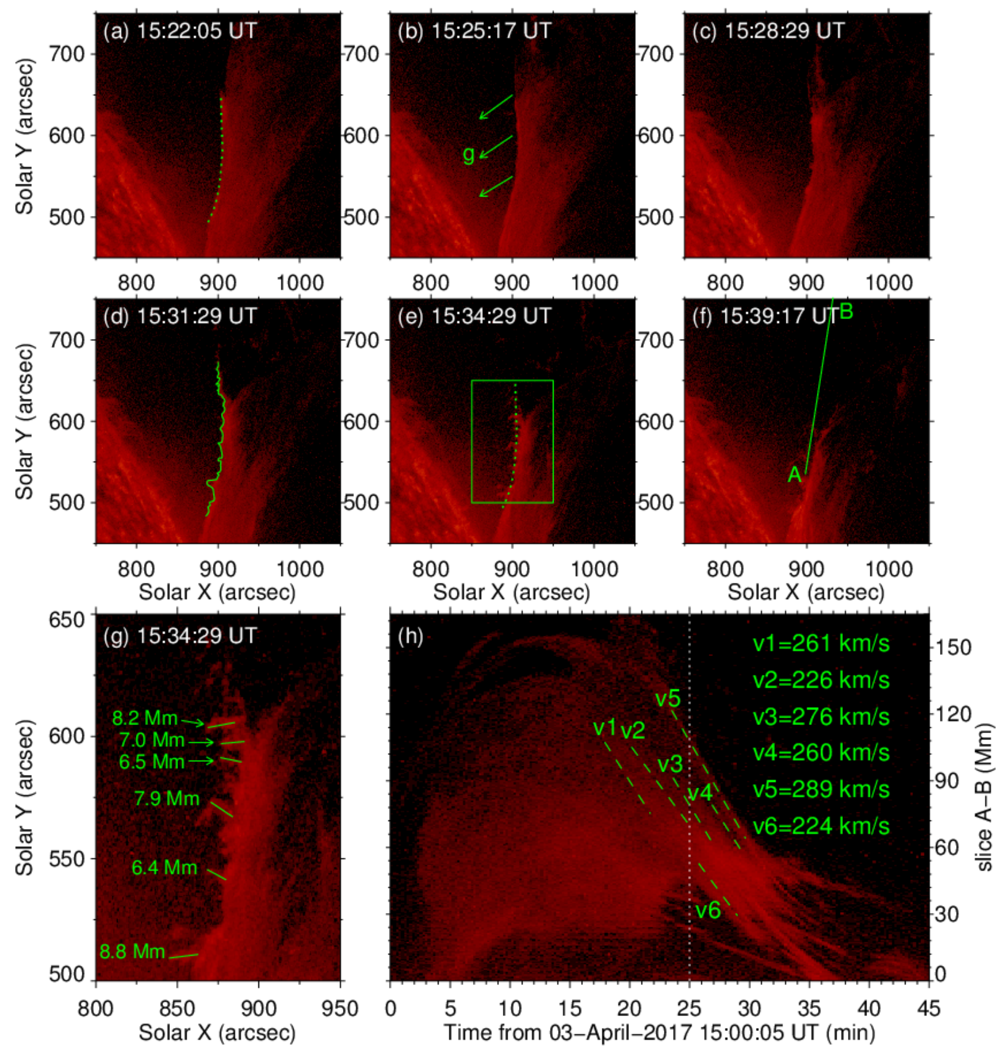
Both the gravity and velocity difference are included:

$$Im(\omega) = \sqrt{\frac{kg(\rho_u - \rho_l)}{\rho_u + \rho_l} + \frac{\rho_l \rho_u (\mathbf{k} \bullet \mathbf{V}_u - \mathbf{k} \bullet \mathbf{V}_l)^2}{(\rho_u + \rho_l)^2} - \frac{(\mathbf{k} \bullet \mathbf{B}_u)^2 + (\mathbf{k} \bullet \mathbf{B}_l)^2}{\mu(\rho_u + \rho_l)}}$$

Instability would happen if

$$\Delta V > \sqrt{\frac{(\rho_u + \rho_l)\left(\mathrm{B}_u^{\ 2} + \mathrm{B}_l^{\ 2}\right)}{\mu \rho_u \rho_l} - \frac{g(\rho_u + \rho_l)(\rho_u - \rho_l)}{k \rho_u \rho_l}}$$

Combined KHI and RTI!



(Li et al. 2019)

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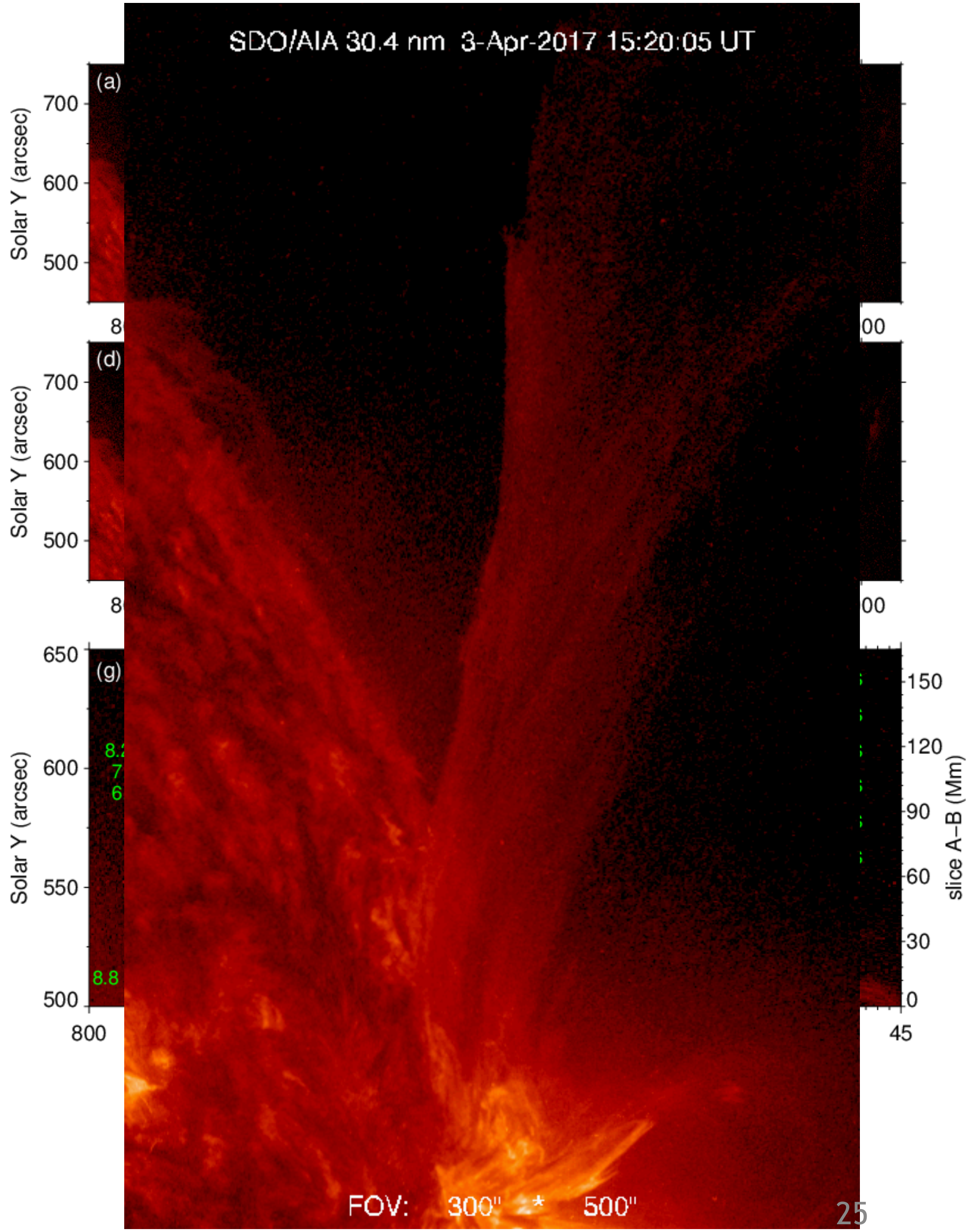

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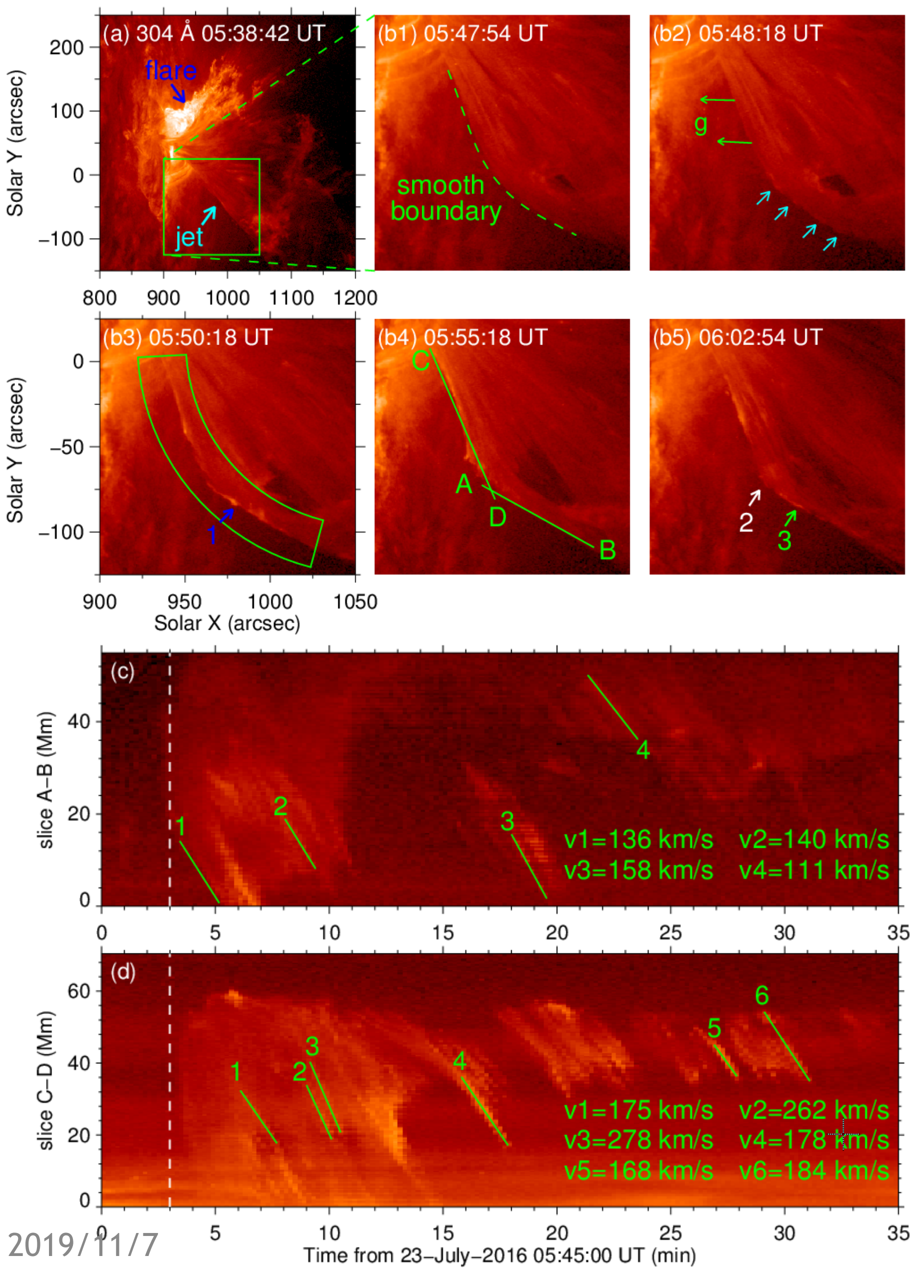
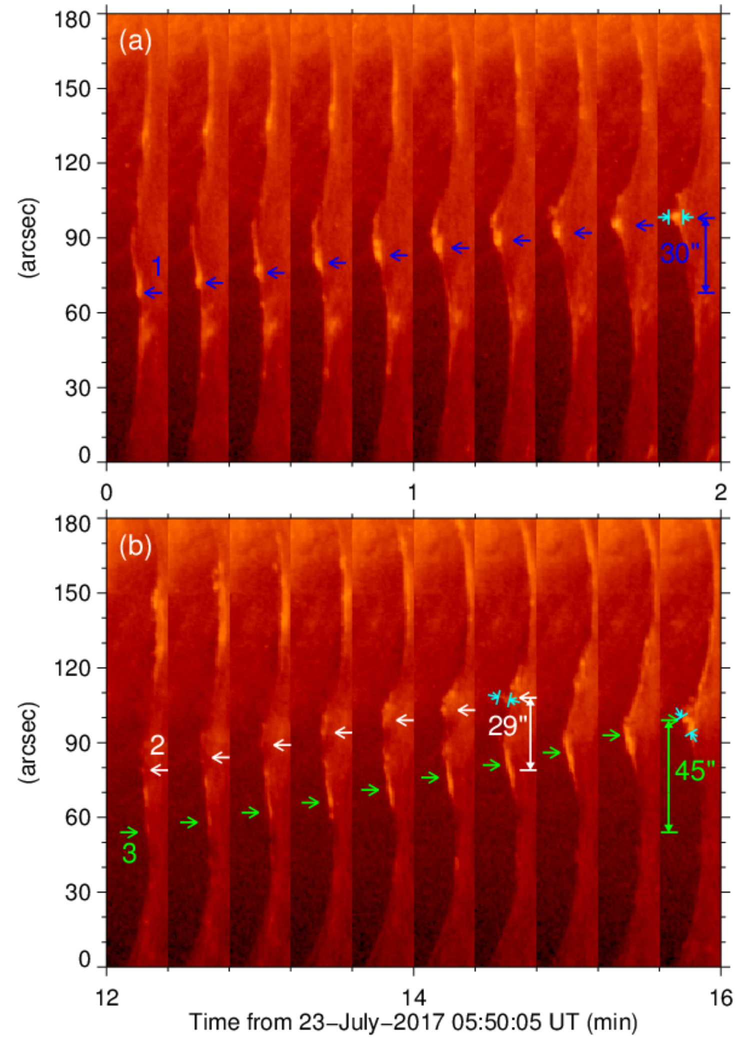




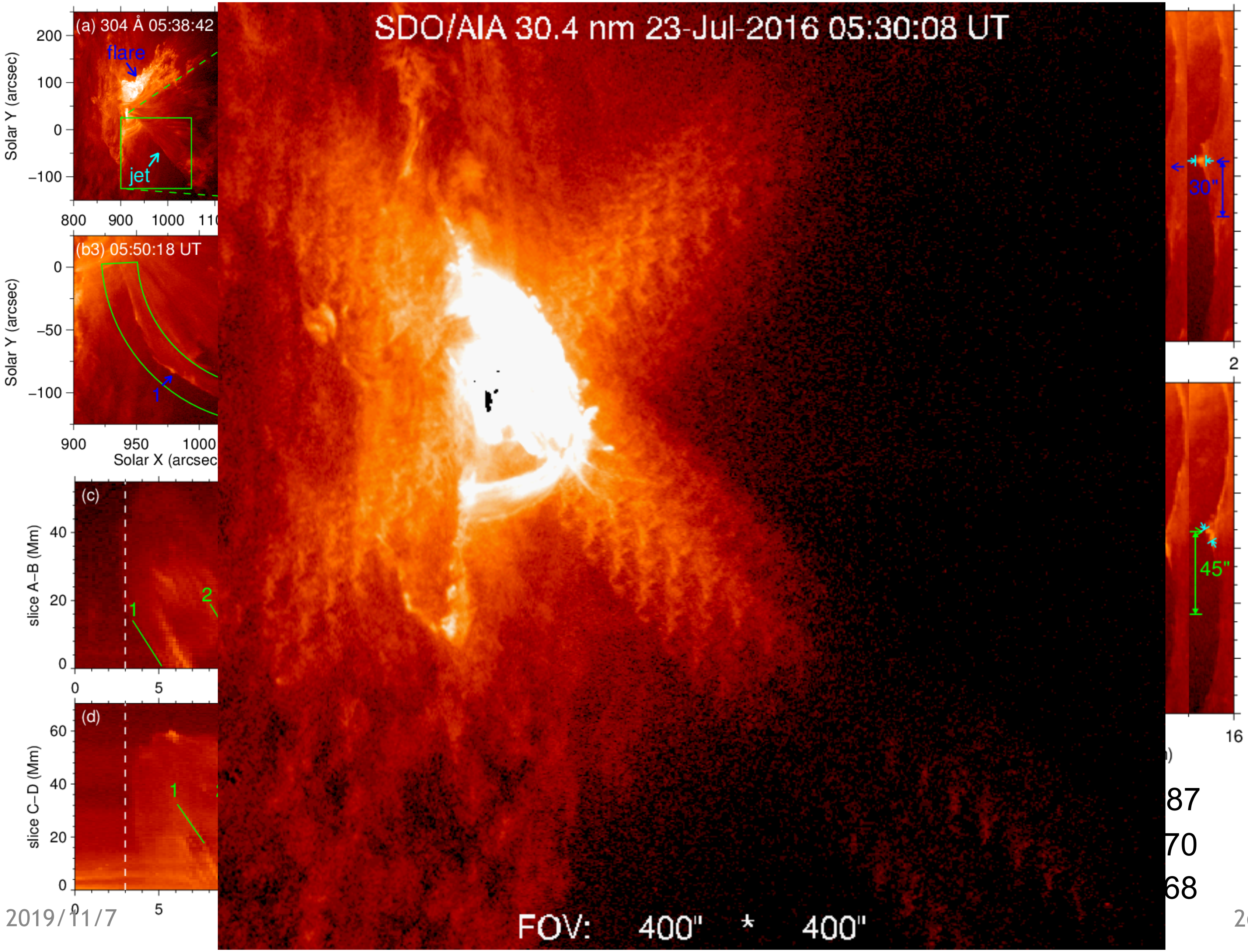
1： 4.2 Mm 175 km s^{-1} 0.0087

2： 3.4 Mm 125 km s^{-1} 0.0070

3： 5.0 Mm 131 km s^{-1} 0.0068

(Li et al. 2019)

Combined KHI and RTI in solar jets



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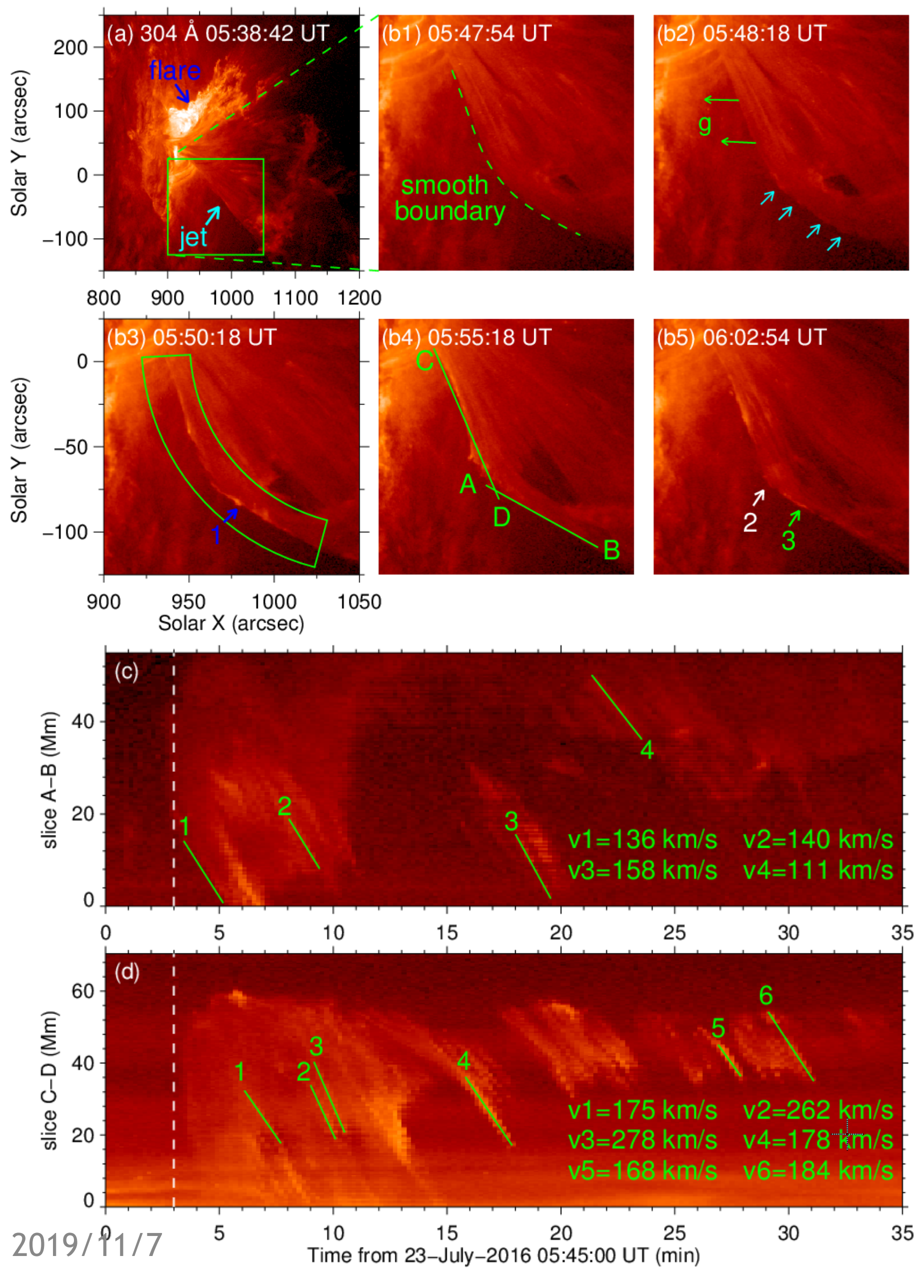

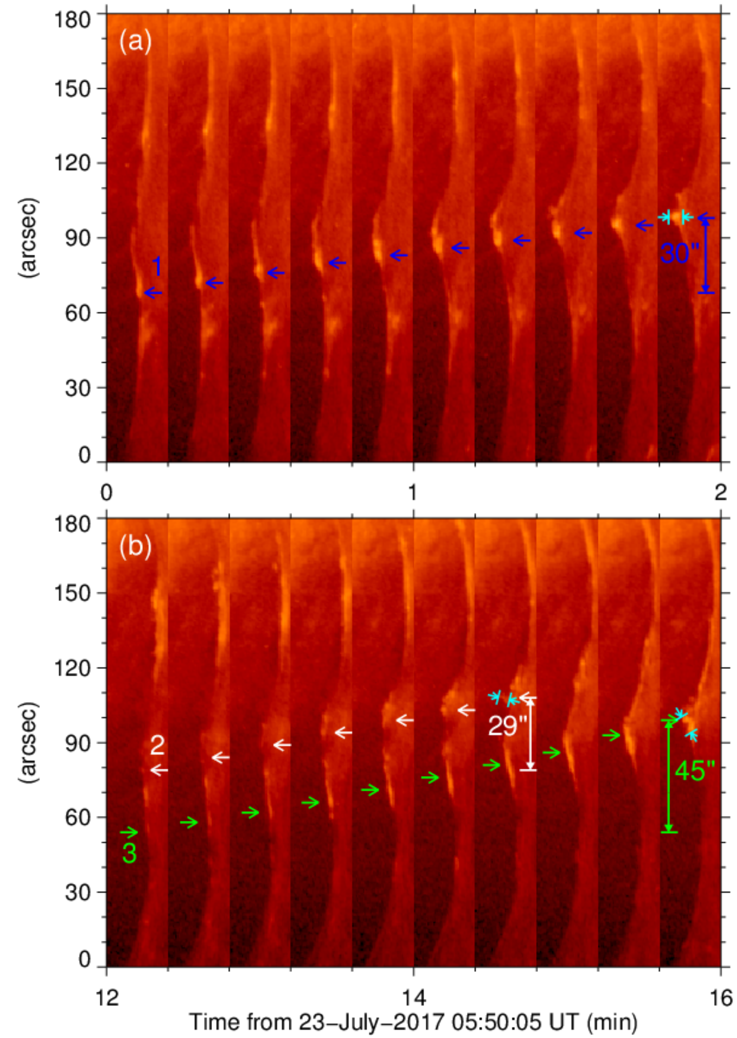

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Outline

1. Brief introduction of solar jets
2. Instabilities in the solar jets
3. Summary and outlook

Summary

Solar jets:

- Characteristics:
  1. Location, length, width, density……
  2. Temperature: consist of both cool and hot plasma flows
  3. Dynamic: untwisting motions
  4. Associated with photospheric magnetic activities
  5. JBP and a bright spire
- Models
  1. Standard model
  2. Blowout model
  3. Minifilament eruption model
  4. Breakout model

Instabilities in solar jets:

- KHI and RTI in the solar atmosphere
- KHI in the solar jets: theory, simulation, observations (vortex-like structures in the upstream regime of solar jet)
- Combined KHI and RTI: vortex-like structures in the downstream regime of solar jet

Outlook

Solar jets:

- The distribution along the longitude and latitude
- Relationship between the jet and other solar activities
- Density and temperature
- Material transfer and energy conversion processes

……

Instabilities in solar jets:

- Temperature increase caused by the KHI is reliable?

  more example & more reliable temperature measurement method
- If it is real, the exact mechanism of plasma heating and the contribution to the coronal heating
- Other instability?
- Instabilities in other astrophysical jets

……

Thanks for your attention！

Any questions:

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