MHD2017 磁気流体プラズマで探る
高エネルギー天体現象研究会
2017. 8. 30. JAMSTEC東京事務所

THE UNIVERSITY OF TOKYO

太陽プラズマの磁気流体数値計算

横山央明
東京大学地惑

共同研究
東京大学横山研の大学院生ほか
特に飯島陽久（名古屋大学）

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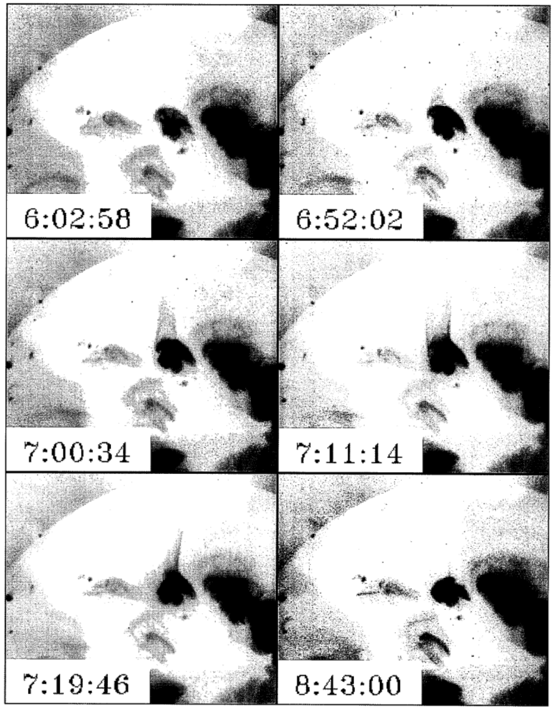
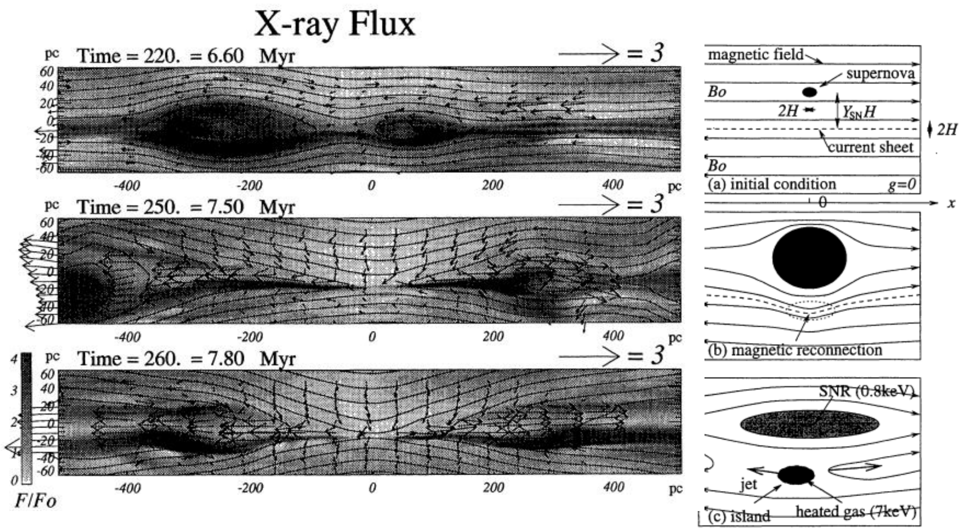
捻れた磁場による太陽彩層ジェットのシミュレーション

　飯島陽久（2016 博士論文）、Iijima & Yokoyama (2017)

わたしと松元さん

- 最初の出会い 1992年？月
  - ✓ 松元さん・柴田先生・横山の3人で核融合研（当時、名古屋大キャンパス内）の大型計算機利用に出かけた。当時D1で天文業界に入門したばかりの私は、松元さんの研究への、疲れを知らない姿勢をみてひるむ。
  - ✓ 最初に研究に使ったコードは、松元さんが書いたもの（改良Lax-Wendroff＋Lapidus粘性）。
- 共著論文 2本
  - ✓ Shibata et al. (1994) 太陽コロナジェットの観測（！）
  - ✓ Tanuma et al. (1999) 銀河磁気リコネクションのシミュレーション





わたしと松元さん

- 2000-2002年度 JST「宇宙シミュレーション・ネットラボラトリーシステムの開発」
  - ✓ CANS開発と数値計算学校開催。いろいろ勉強になりました。当時は、「シミュレーション研究をする若い人がいなくなった」と話していましたが、このプロジェクトで盛り返したのではないでしょうか。CANSはその後、CANS+やpCANSという形で花開きました。オリジナル版は、いまも細々と改良を続けています。
- 科研費に研究分担者／連携研究者として参加。
  - ✓ 2004-2005、2008-2010、2011-2013年度
  - ✓ 2016-2018年度基盤B「巨大ブラックホール降着流におけるX線放射領域の形成と時間変動機構の解明」
  - ✓ できるだけお役に立てるようがんばります。

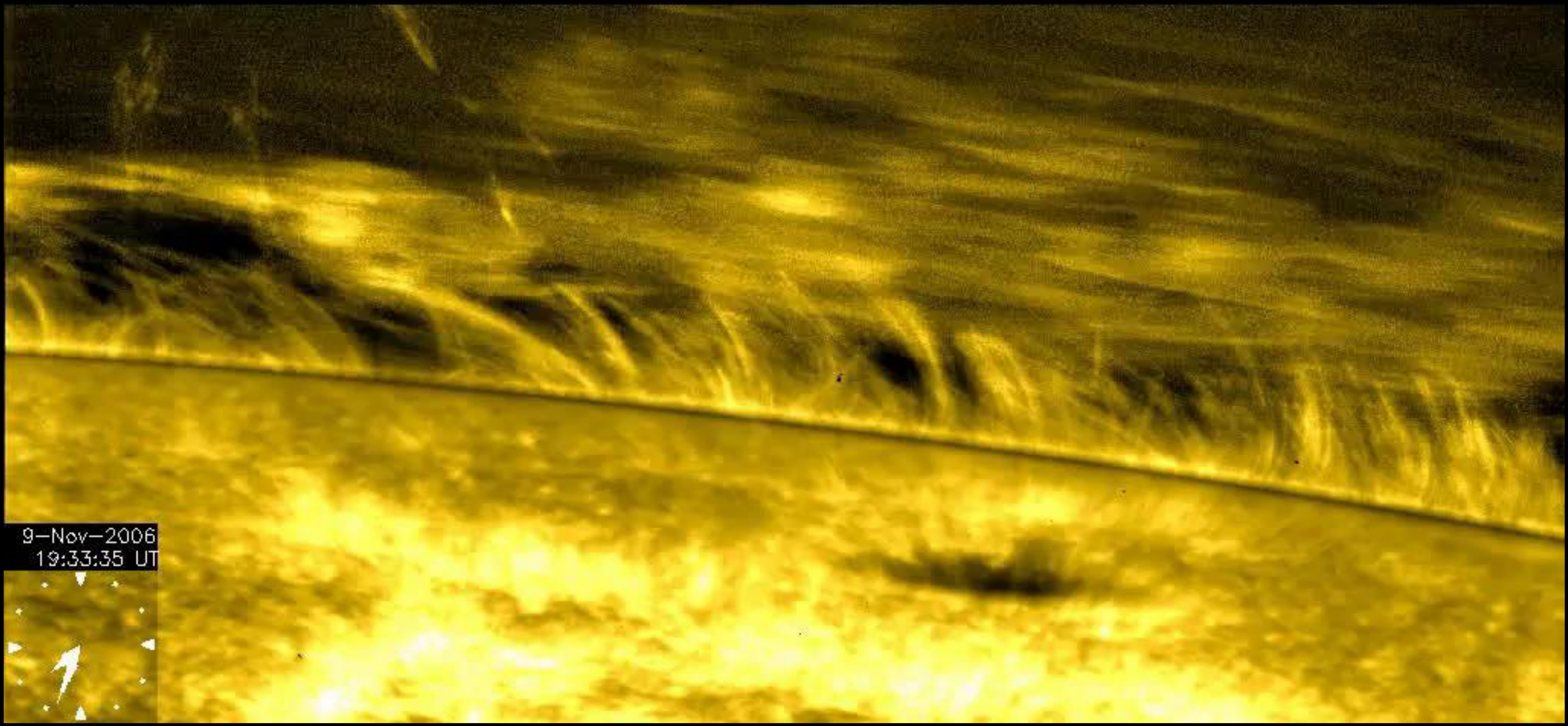
（千葉大学 JST宇宙ネットラボ ウェブページより）

JST計算科学プロジェクト天体シミュレーショングループ会議
花山 2001年11月

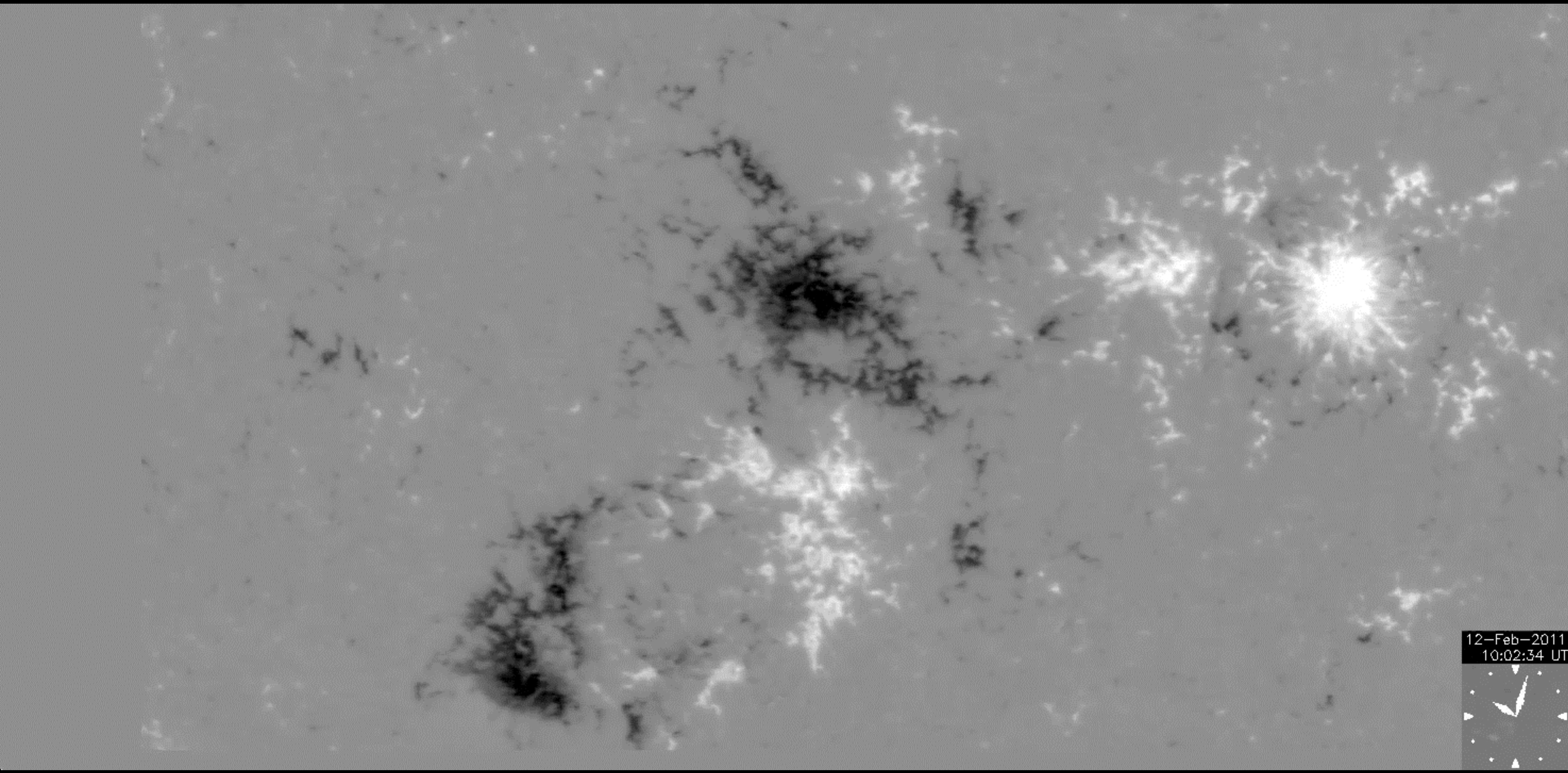
「学振日英共同研究」研究会 花山天文台 2004年7月

太陽プラズマの観測

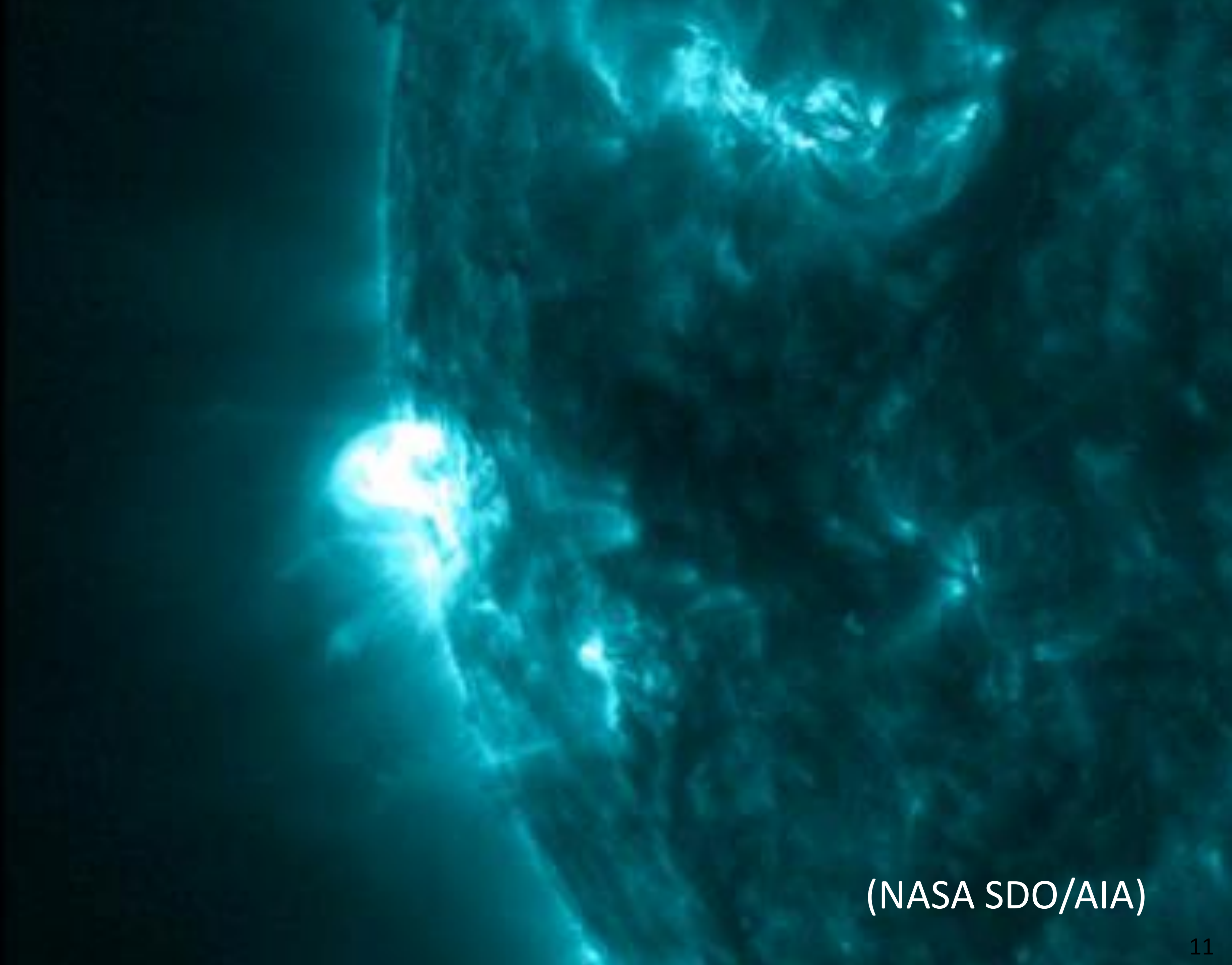
1992/01/12



（ひのでSOT、岡本丈典博士提供 JAXA、NAOJ）

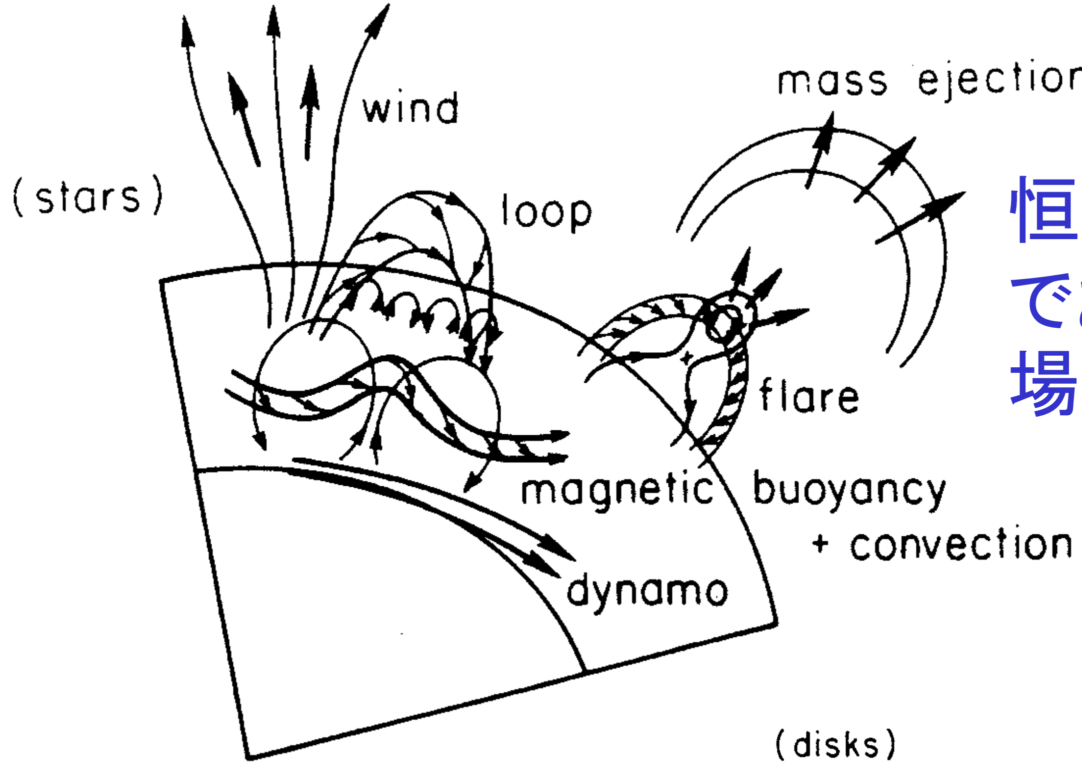


（ひのでSOT、岡本丈典博士提供 JAXA、NAOJ）



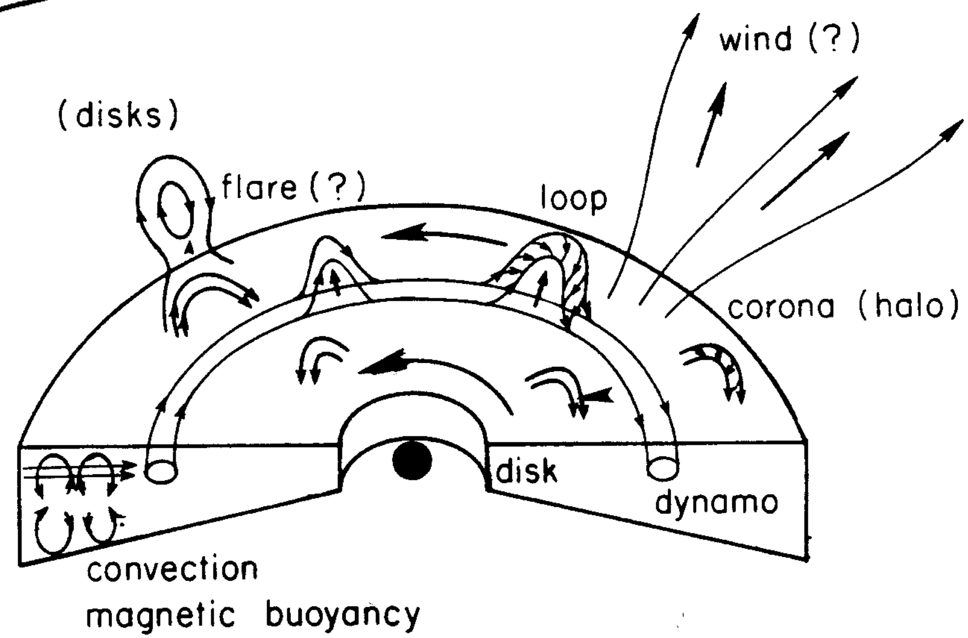
(NASA SDO/AIA)

太陽プラズマに関連するシミュレーション
松元さんたちの仕事と
私たちの仕事



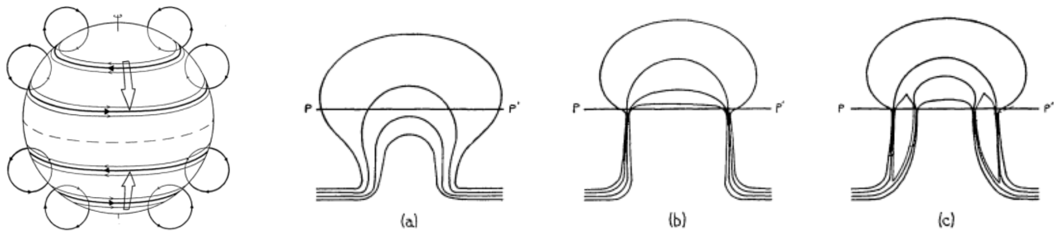
恒星・太陽や降着円盤でおこるさまざまな磁場・プラズマ相互作用

（図はTajima & Shibata 1997）

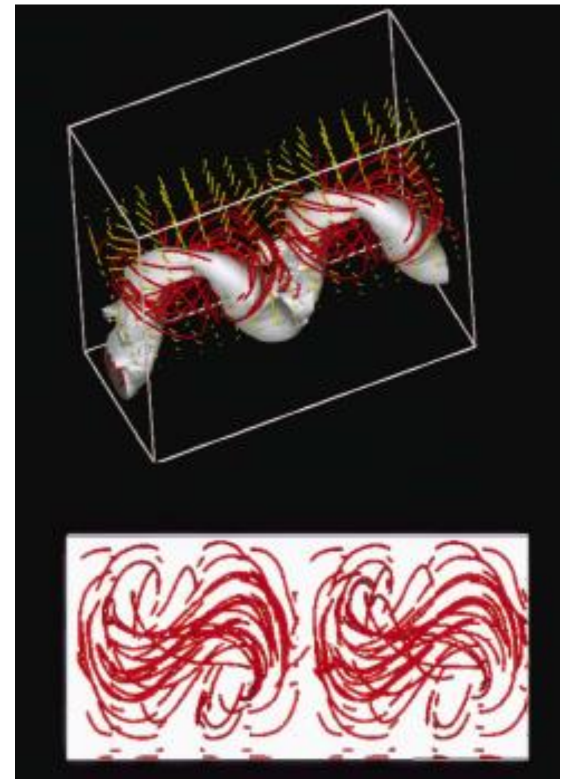


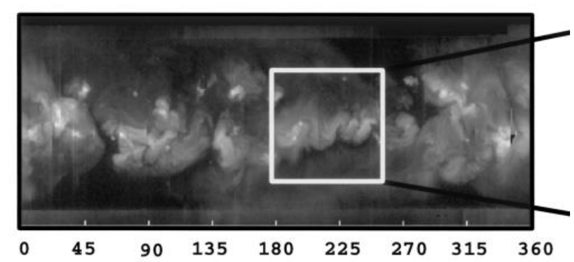
磁束浮上と活動領域形成

Parker (1955)

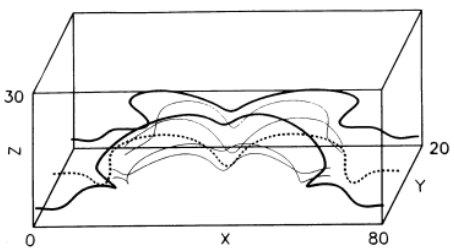


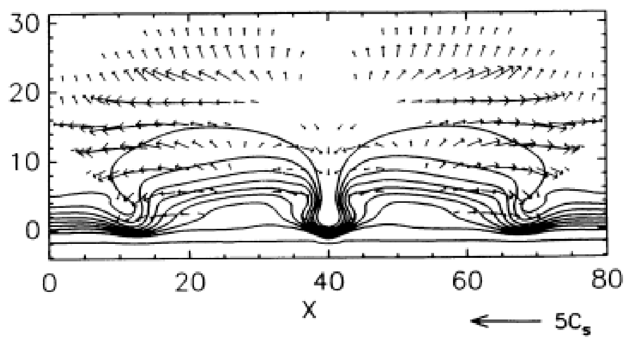
Matsumoto+(1998)

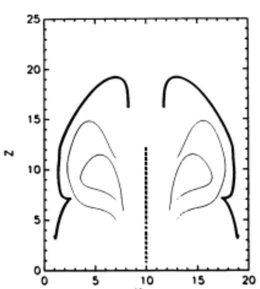


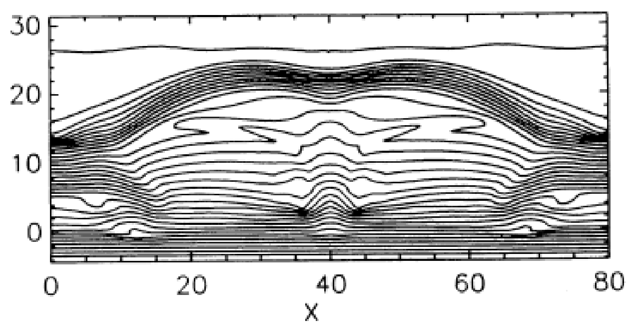


Matsumoto+(1993)



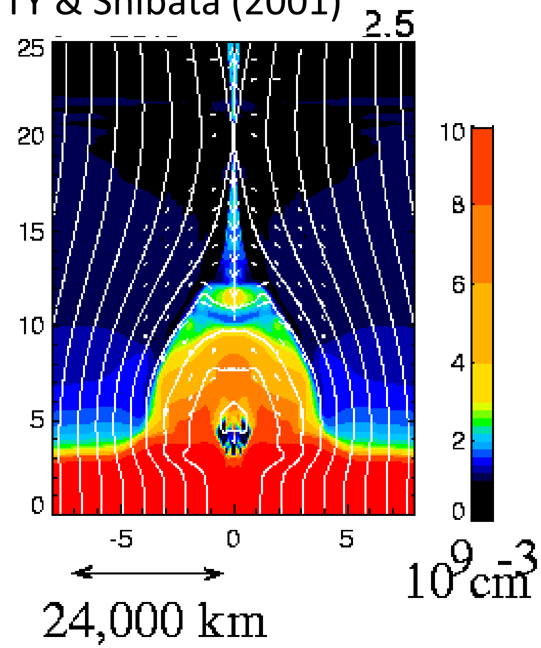


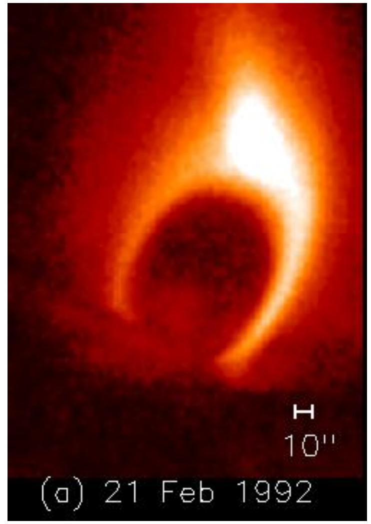




太陽・恒星フレア

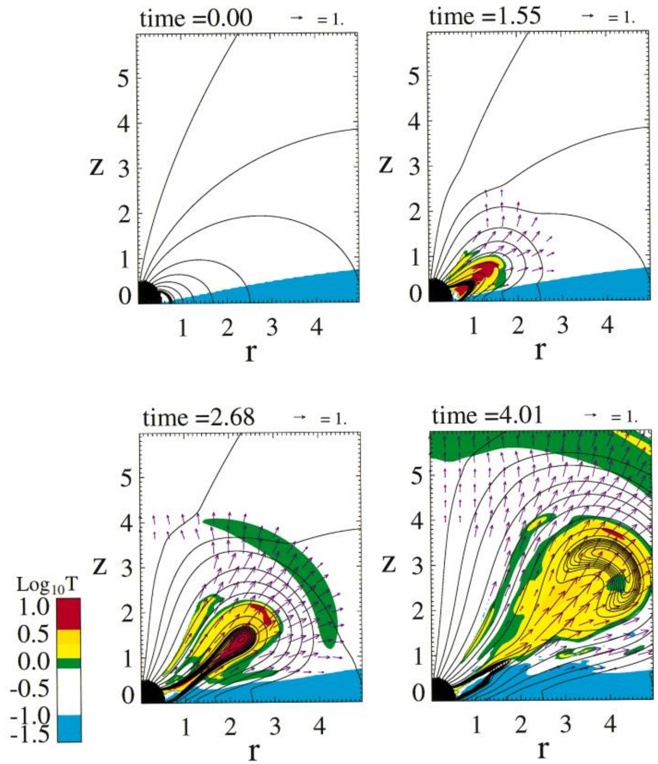
TY & Shibata (2001)



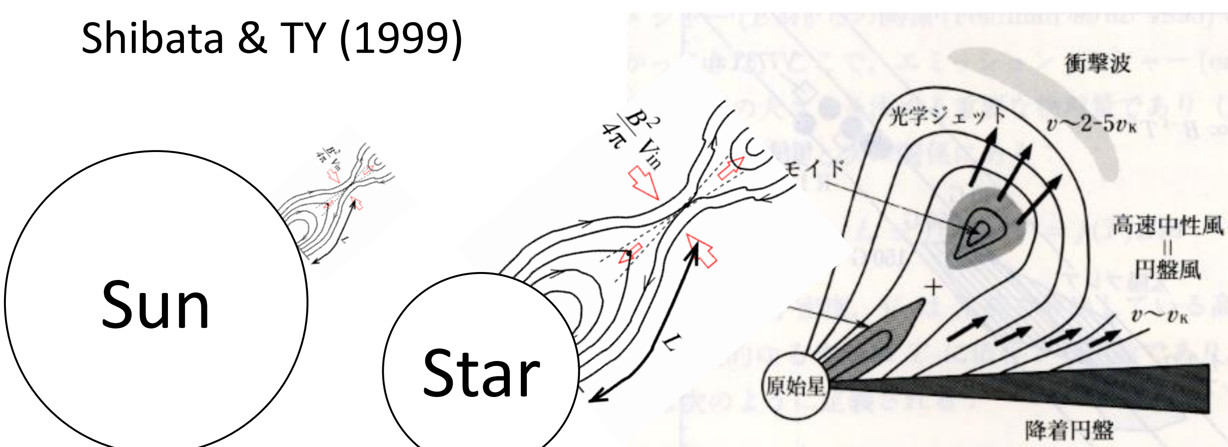


（ようこうSXT JAXA）

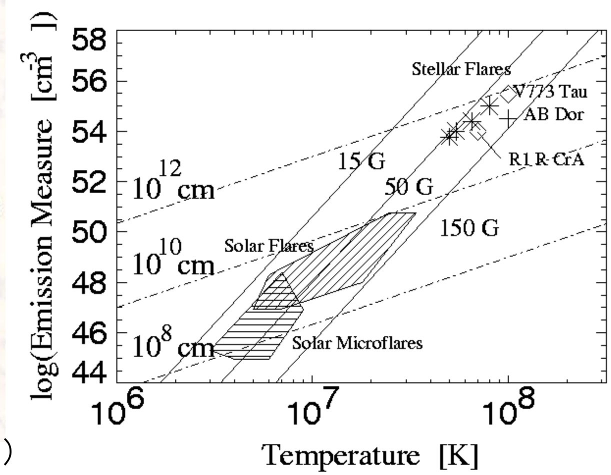
Hayashi, Shibata, Matsumoto (1996)



Shibata & TY (1999)

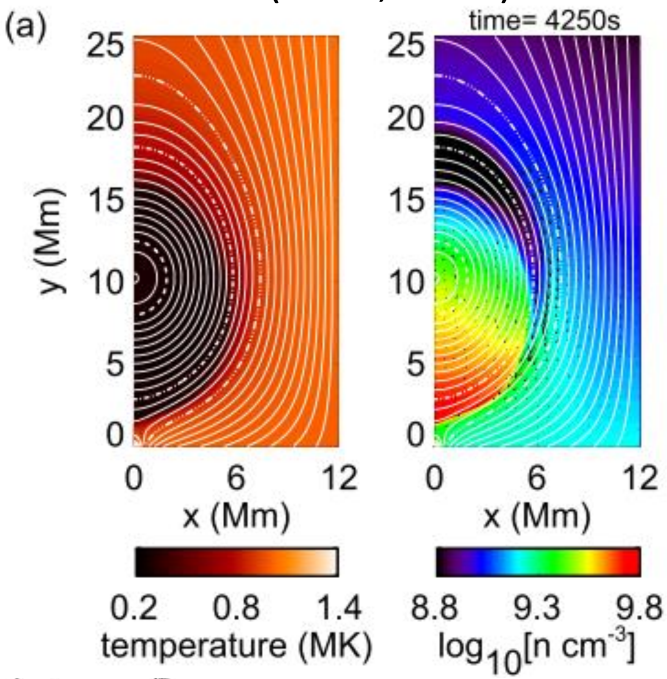


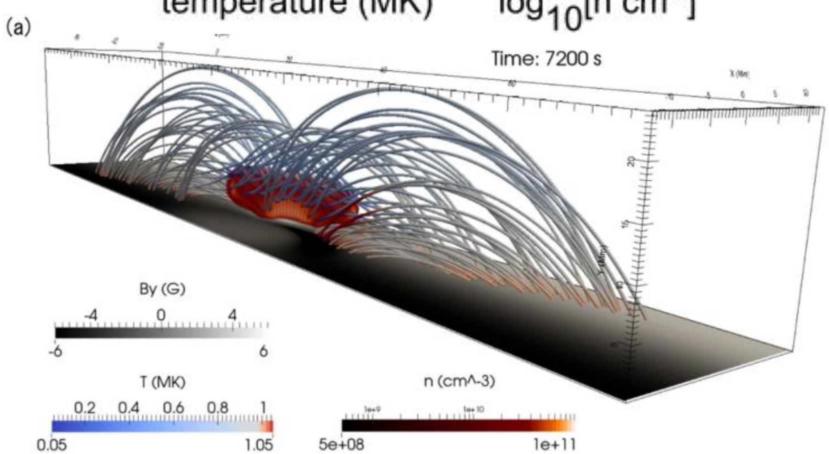
（図：柴田・福江・松元・嶺重1999より）



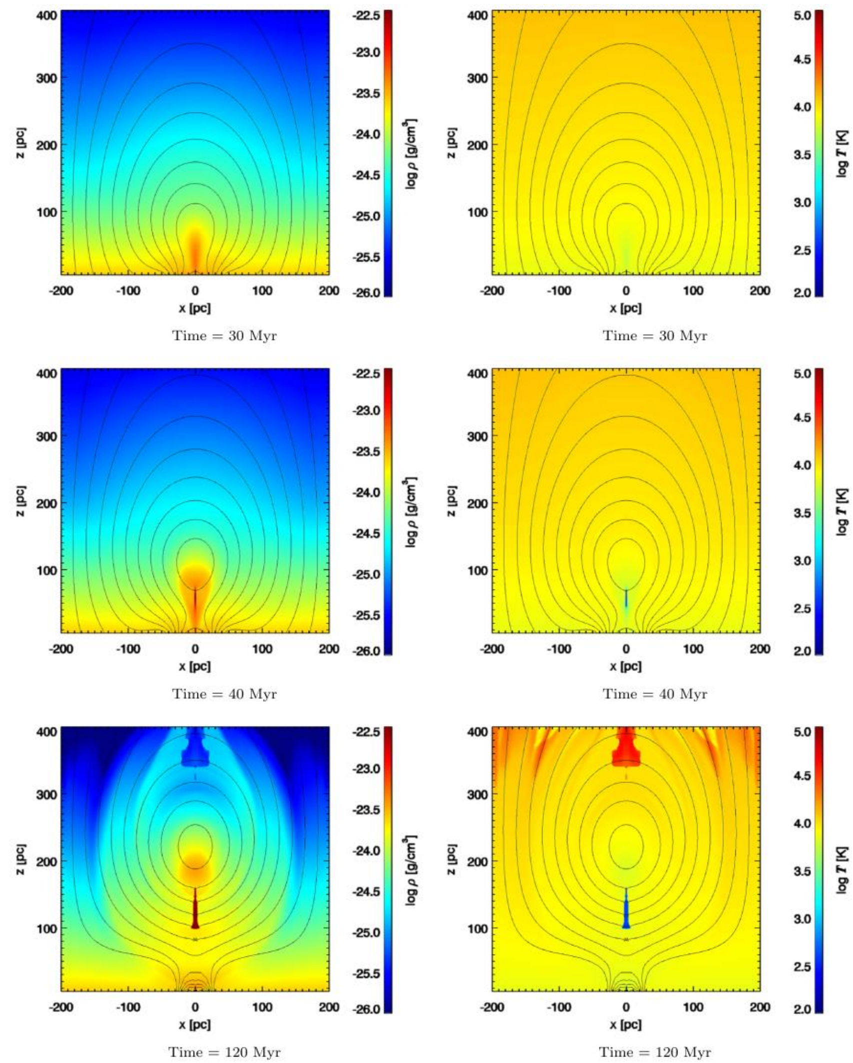
プロミネンス（熱い大気中の冷たいプラズマ雲）形成

Kaneko & TY (2015, 2017)

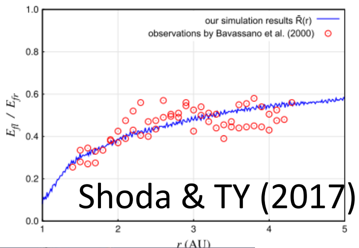




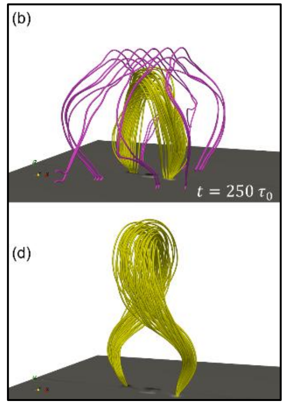
Peng & Matsumoto (2017)



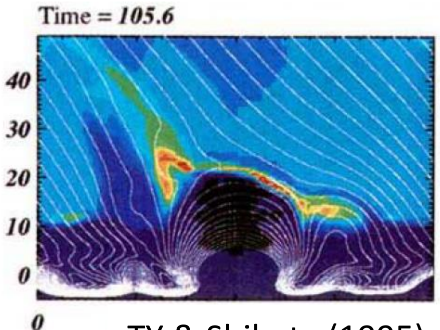
恒星・太陽でおこるさまざまな磁場・プラズマ相互作用



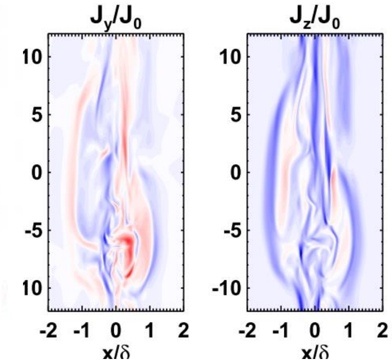
Shoda & TY (2017)



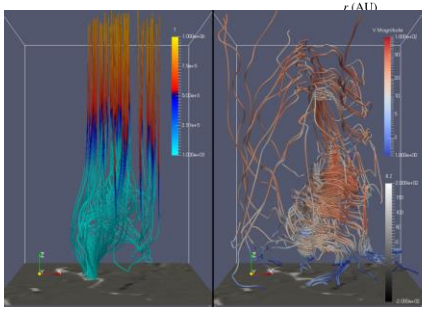
Oi, Toriumi, TY (2017)

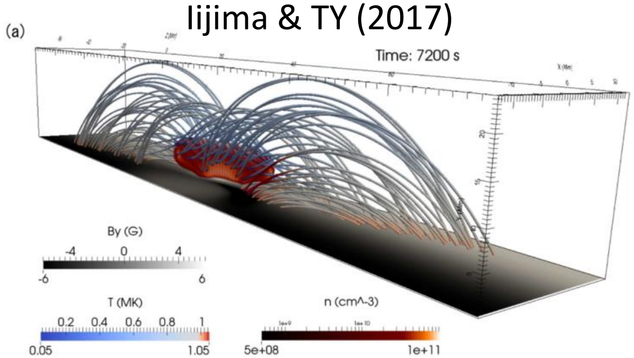


TY & Shibata (1995)

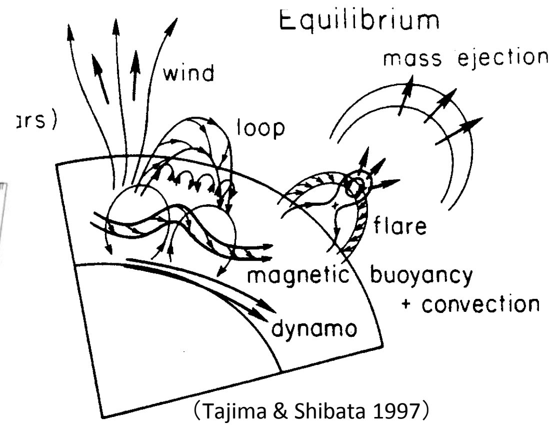


Wang, S.-Y. & TY (2017)

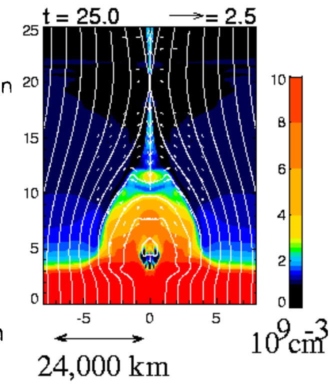

Iijima & TY (2017)



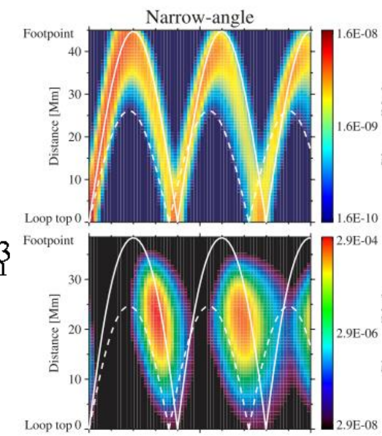
Kaneko & TY (2017)



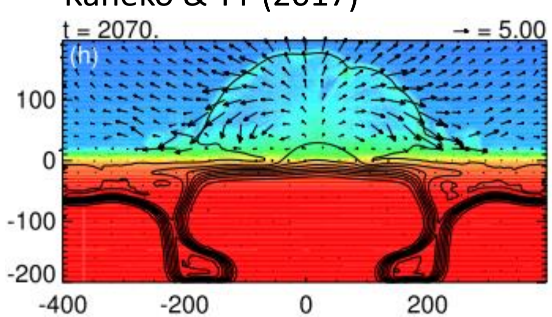
(Tajima & Shibata 1997)



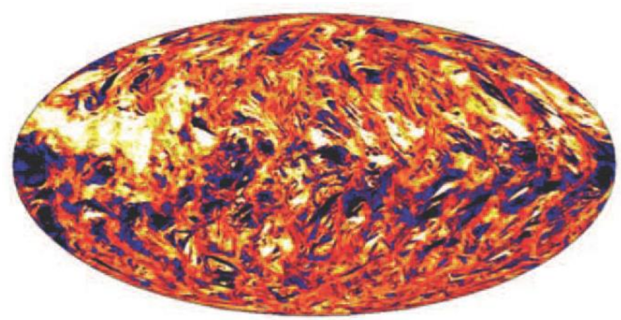
TY & Shibata (2001)



Minoshima & TY (2008)



Toriumi & TY (2010)


Hotta, Rempel, TY (2016)

3D MHD simulations of chromospheric jets launched by twisted magnetic field lines

Haruhisa Iijima

Nagoya University

Takaaki Yokoyama

The University of Tokyo

based on

Iijima, H., 2016, PhD thesis, UTokyo

Iijima & TY, 2015, ApJL, 812, L30

Iijima & TY, 2017, ApJ, submitted

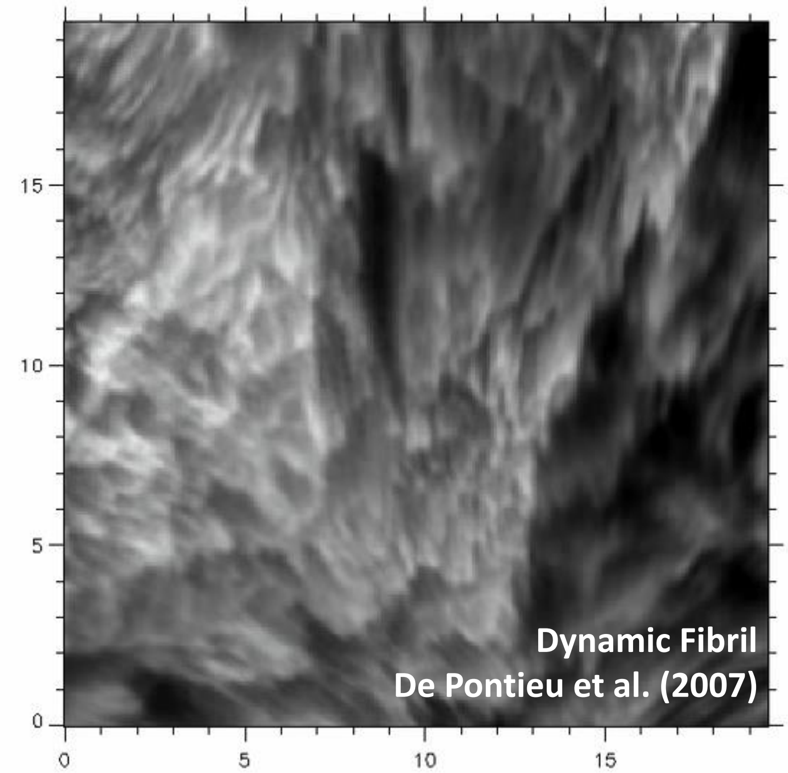
Chromospheric jets

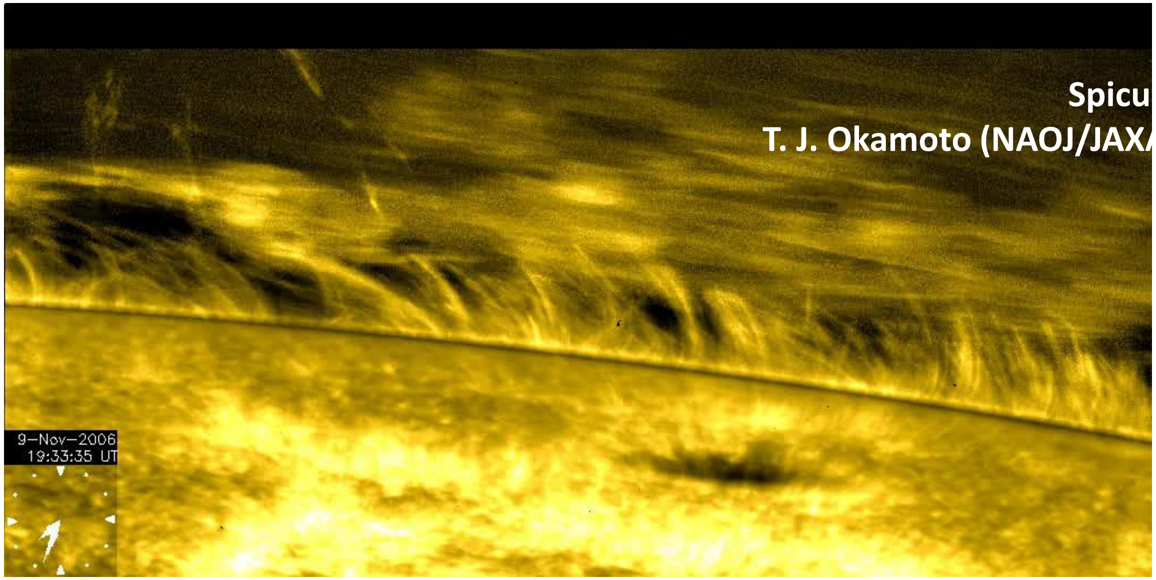
- dynamic fibrils in active regions
  (length ~ 3 Mm)
- spicules in quiet regions and
  coronal holes (length ~ 5–15 Mm)

One of the basic elements of the chromosphere.

For generation of the jets, involved processes
- MHD shocks and waves:
  mode conversion,
  nonlinear amplification
  amplification under strong stratification
  high β -> very low β

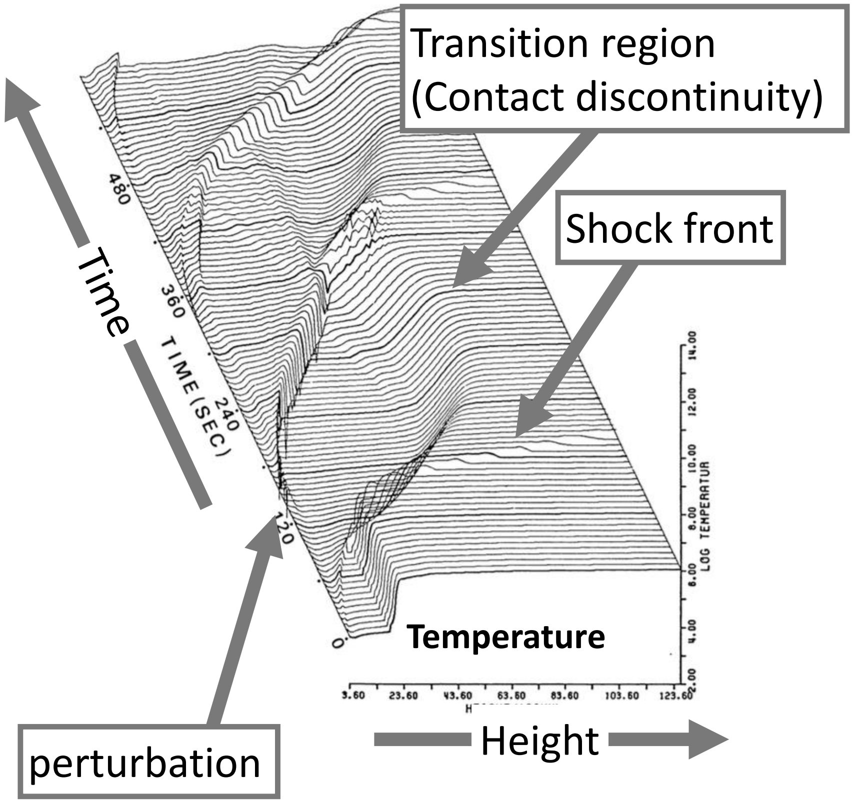
- Radiation
- Partial ionization



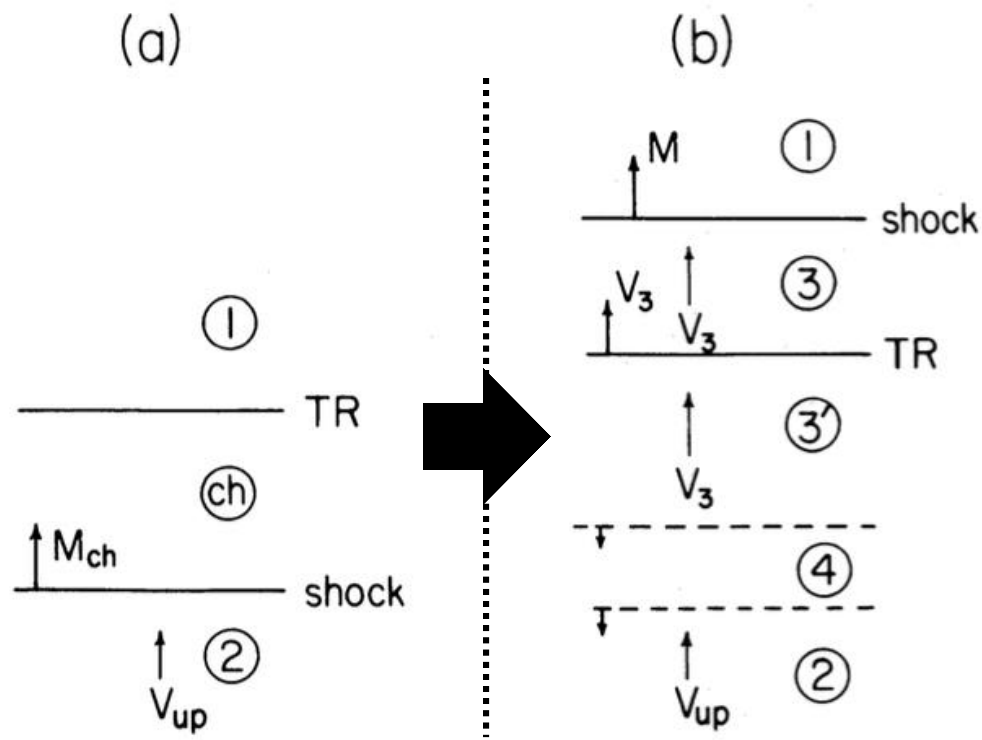


Shock transition-region interaction

(Hollweg, 1982)



1D hydrodynamic simulation
(Suematsu et al., 1982)

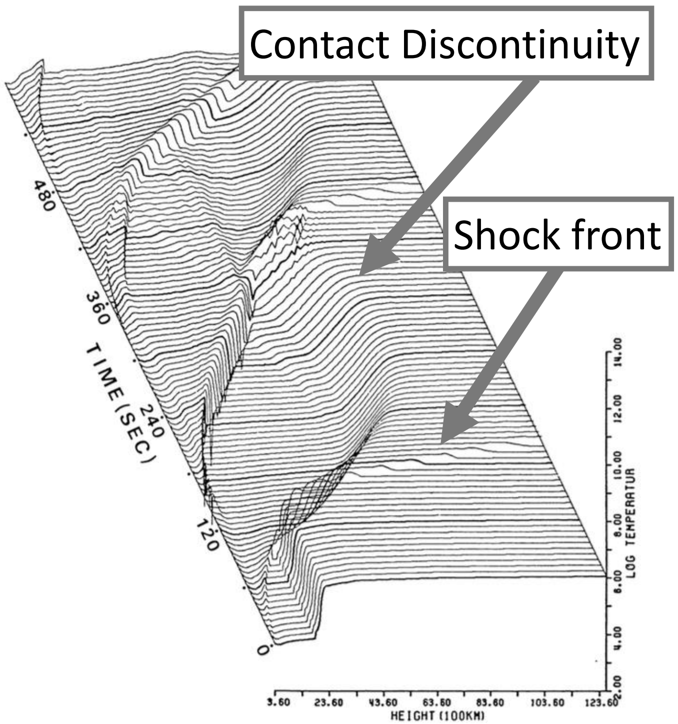


$$V_{\rm jet} = V_3 \propto V_{\rm up} = V_{\rm shock}$$

Shock formation -> Shock–TR interaction -> jets

Previously proposed driving mechanisms (via shock evoking)

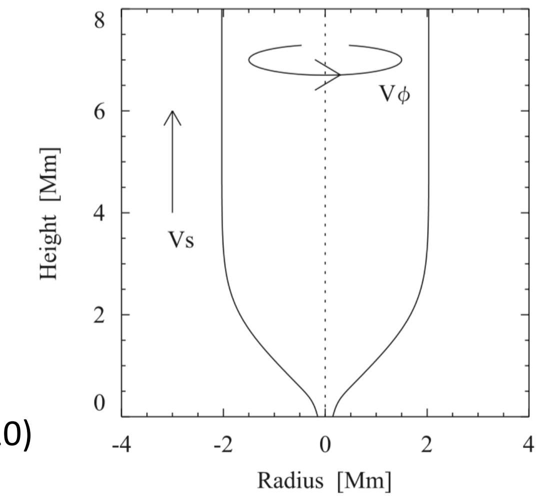
Acoustic wave model
Sound wave
-> (amplification)
-> Shock wave



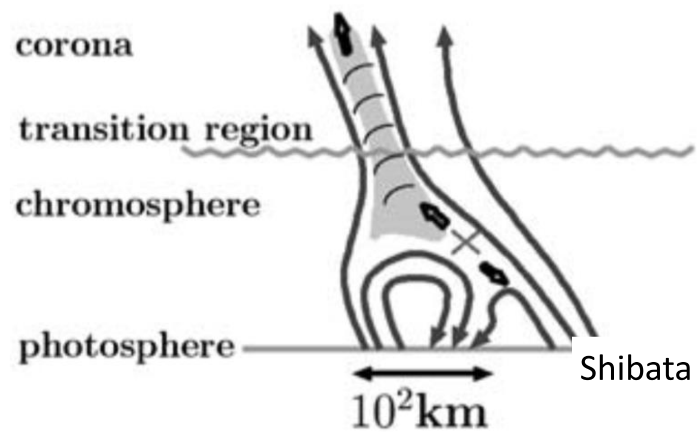
Hollweg (1982)
Suematsu et al. (1982)

Alfven wave model:
Alfven wave ->
(mode conversion)
-> Shock wave

Kudoh & Shibata (1999)
Matsumoto & Shibata (2010)



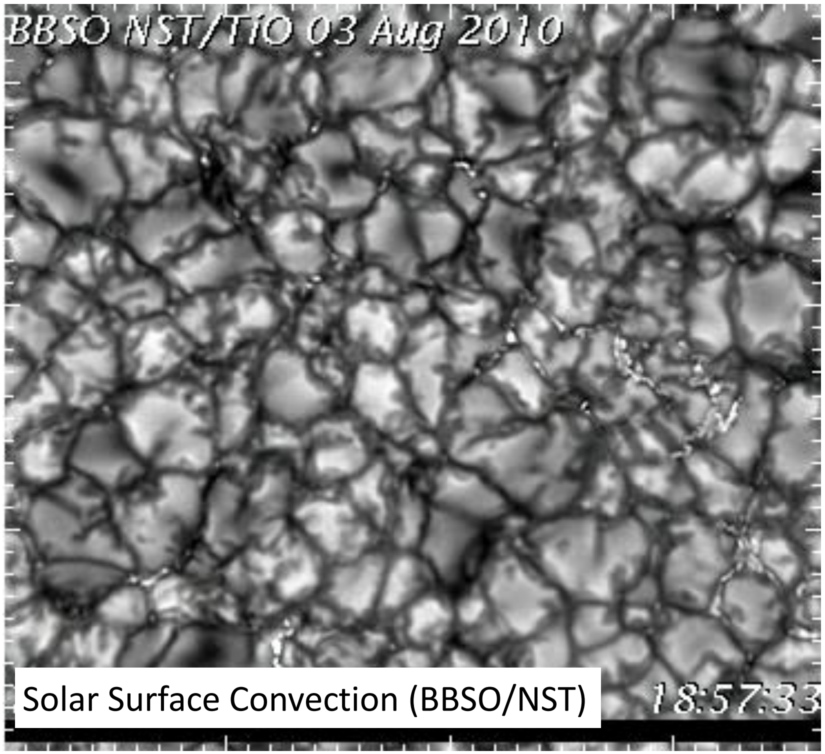
Reconnection model:
Reconnection out flow -> Shock wave



Shibata et al. (2007)

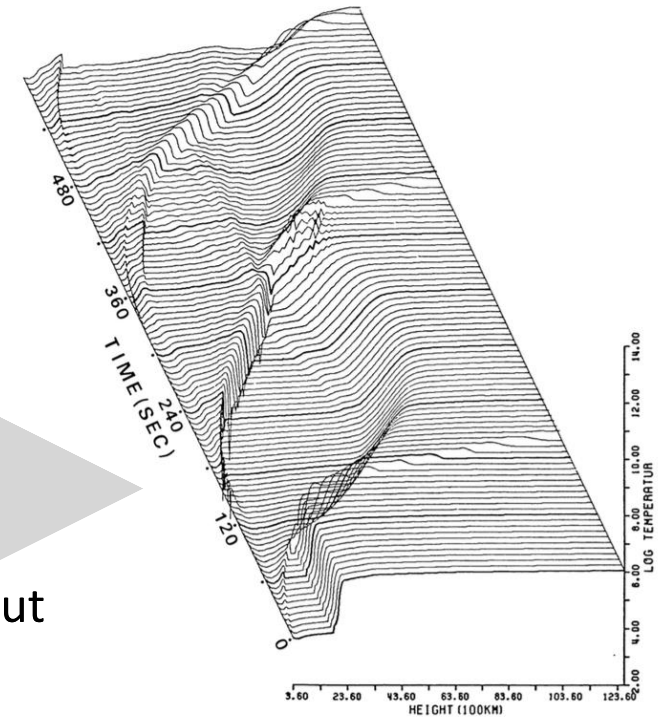
Basically, the background magnetic field is given and fixed.

Open issues for jet generation



Solar Surface Convection (BBSO/NST)

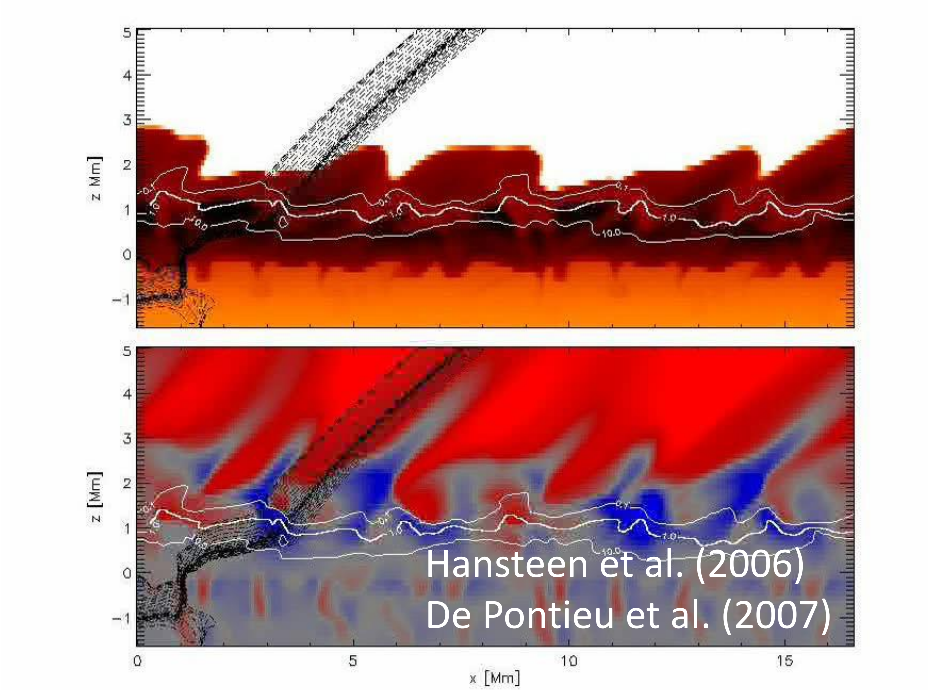
Energy input



Suematsu et al. (1982)

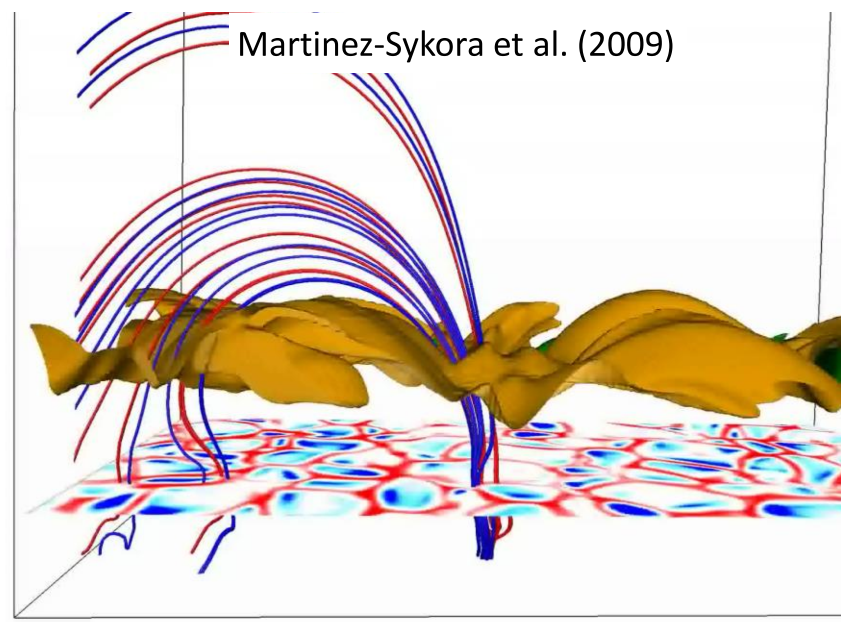
Which mechanism is more dominant ? Need to solve the energy input processes self-consistently.

Radiation MHD (RMHD) models



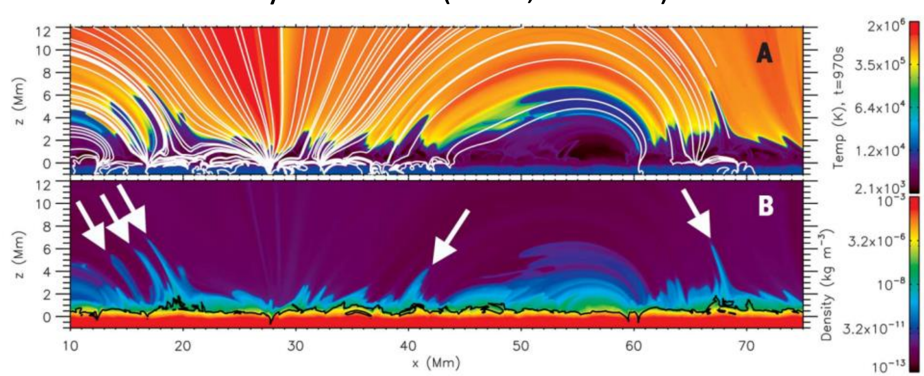
Hansteen et al. (2006)
De Pontieu et al. (2007)

By the radiation MHD approach, the energy input at the photosphere and the non-linear interaction with the background magnetic fields are self-consistently treated.



Martinez-Sykora et al. (2009)

Martinez-Sykora et al. (2017, Science)



Our approach

We numerically solve the RMHD equations in multi-dimension (2D & 3D) from the upper convection zone to the lower corona.

The simulation self-consistently includes the energy input, originated from the convection, to the upper layer and the non-linear interaction with magnetic field.

This allows us to investigate the formation and dynamics of chromospheric jets more quantitatively.

We developed a new code, RAMENS.

RAMENS

RAdiation Magnetohydrodynamics Extensive Numerical Solver

Magnetohydrodynamics

New high resolution CT scheme
Fifth-order WENO-Z reconstruction
Third-order SSP Runge-Kutta method

Radiative Energy Transfer

Non-local RT with Short Characteristic method
OPAL Rosseland mean Opacity
Effectively optically thin radiative loss

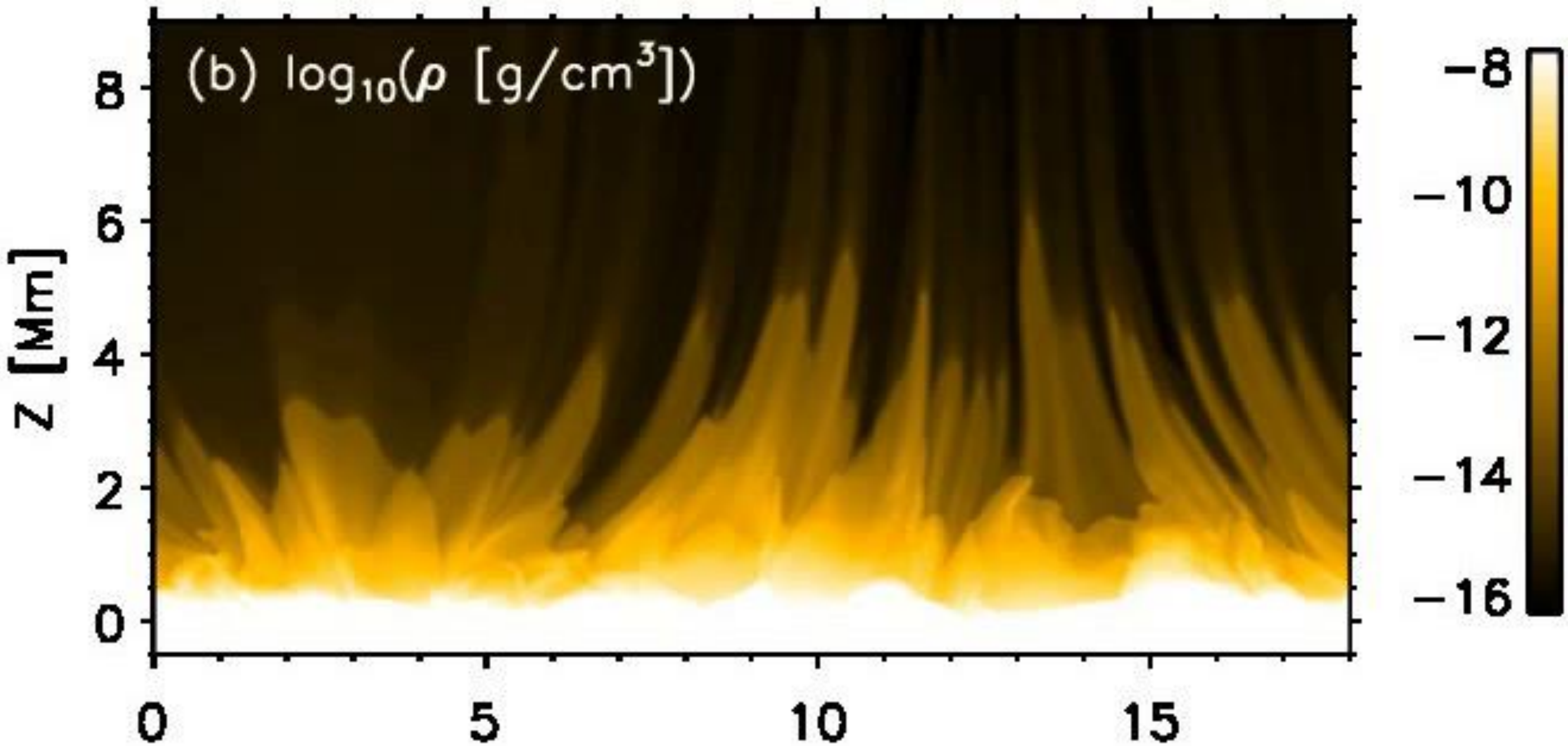
Spitzer thermal conduction

Flux limiter for preserving monotonicity
Second-order Super TimeStepping method
Second-order operator splitting

Equation of State

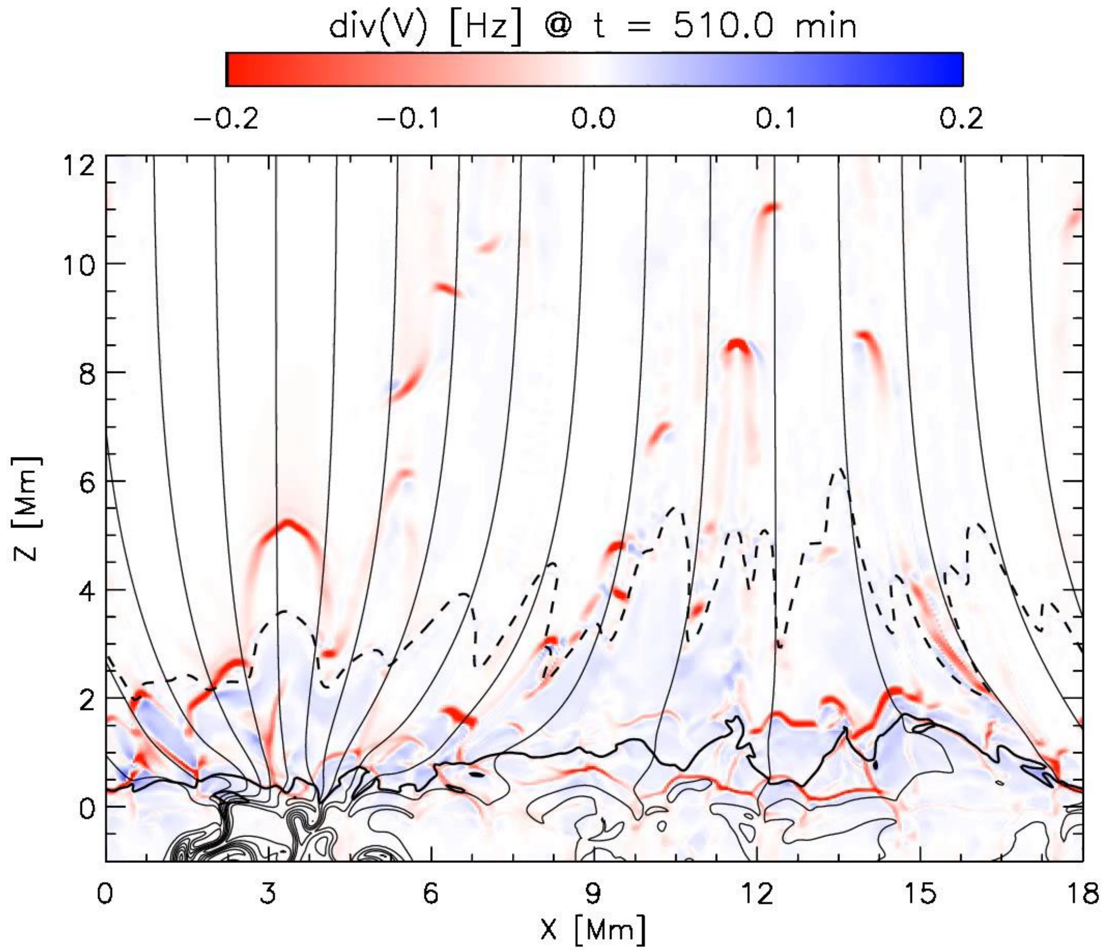
LTE with hydrogen molecule formation
6 most abundant species
Interpolation from numerical table

2D simulation



Statistical properties of the acoustically driven jets are in good agreement with those of the Bifrost simulations (Heggland+ 2011).

2D simulation



Statistical properties of the acoustically driven jets are in good agreement with those of the Bifrost simulations (Heggland+ 2011).

3D simulations setup

Numerical domain

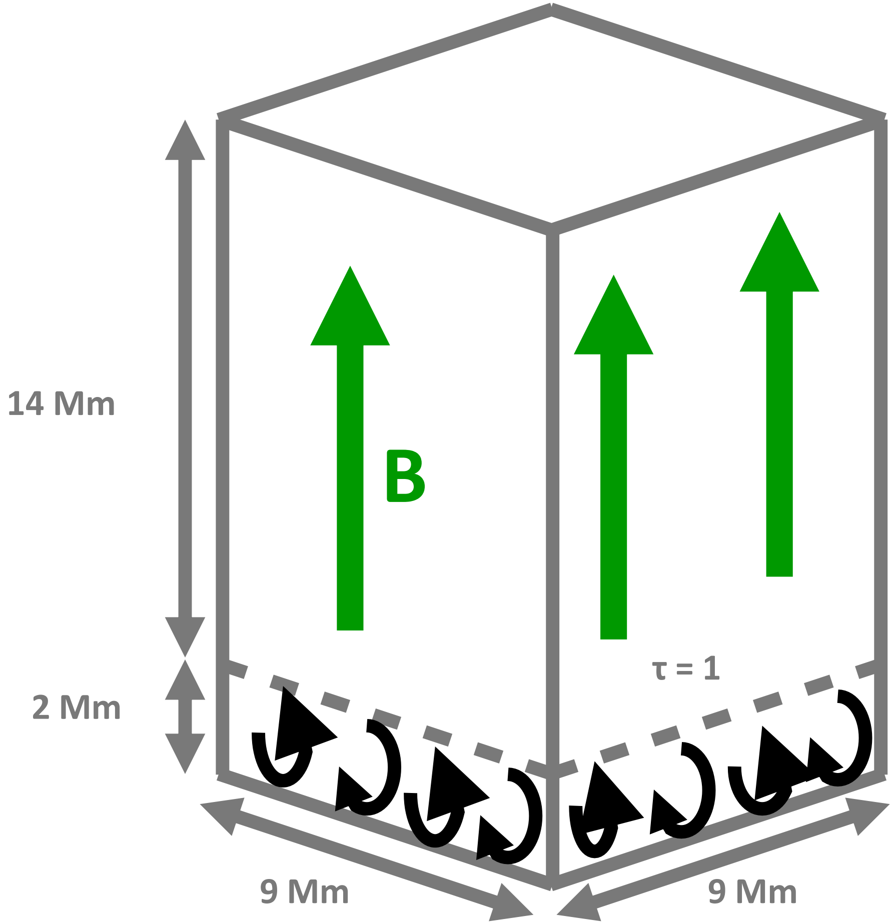
- Domain size: 9 x 9 x 16 Mm^3
  from the upper convection zone
  to the lower corona
- Grid size: 42 x 42 x 32 km^3

Initial condition

- Impose uniform vertical magnetic field of **10** G on a sufficiently evolved non-magnetized convective atmosphere.

Boundary condition

- Top: Open for flow, conductive flux to maintain hot (**1** MK) corona
- Bottom: Open for flow, convective flux through the bottom boundary
- Horizontal: periodic



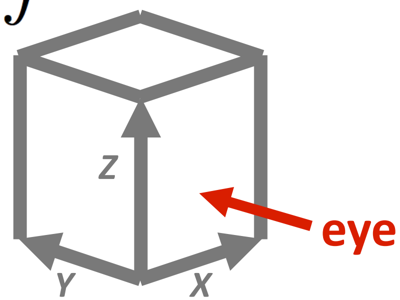
Morphology | Pseudo-emission

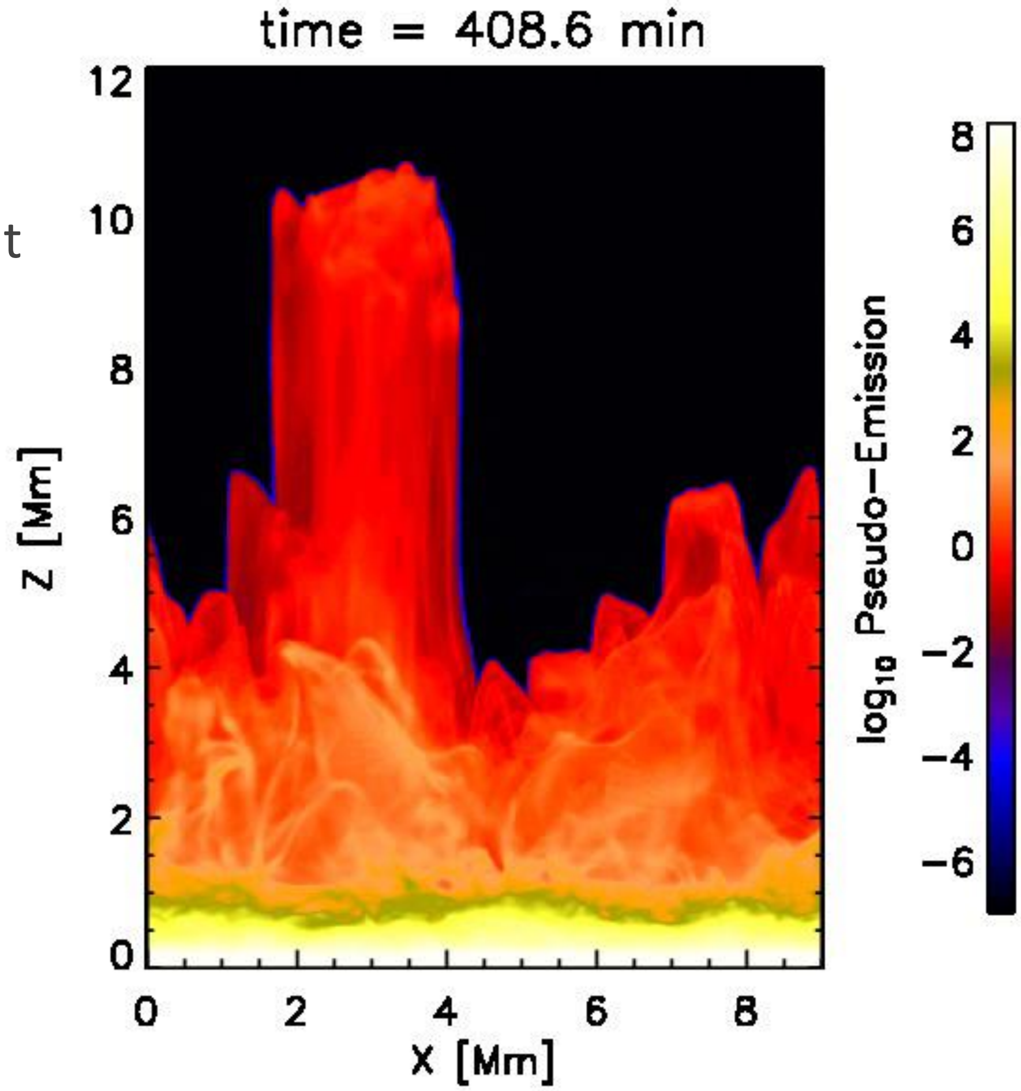
Succeeded to reproduce jets with 6-8 Mm height.

A very tall jet with 10 Mm height is also generated

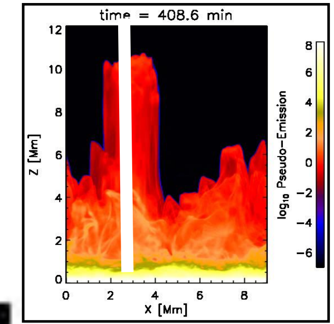
For visualization, we calculate the optically thin emission with the contribution function G(T) that mimic the chromospheric line emission.

$$\epsilon = \int n_{\mathrm{e}} n_{\mathrm{H}} G(T) \mathrm{d}l$$





Temporal evolution along the tall jet



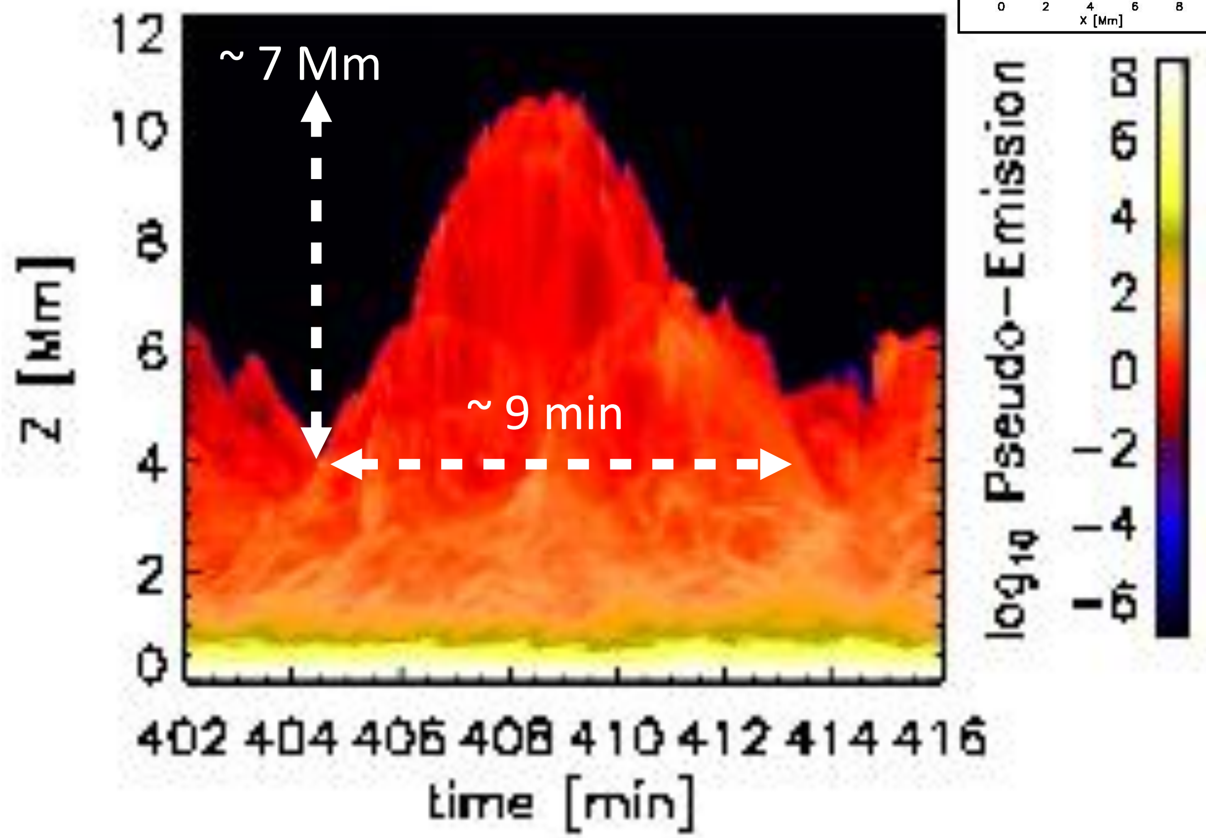
t_{Life}~ 9 min

L ~ 7 Mm

Assuming parabolic motion,

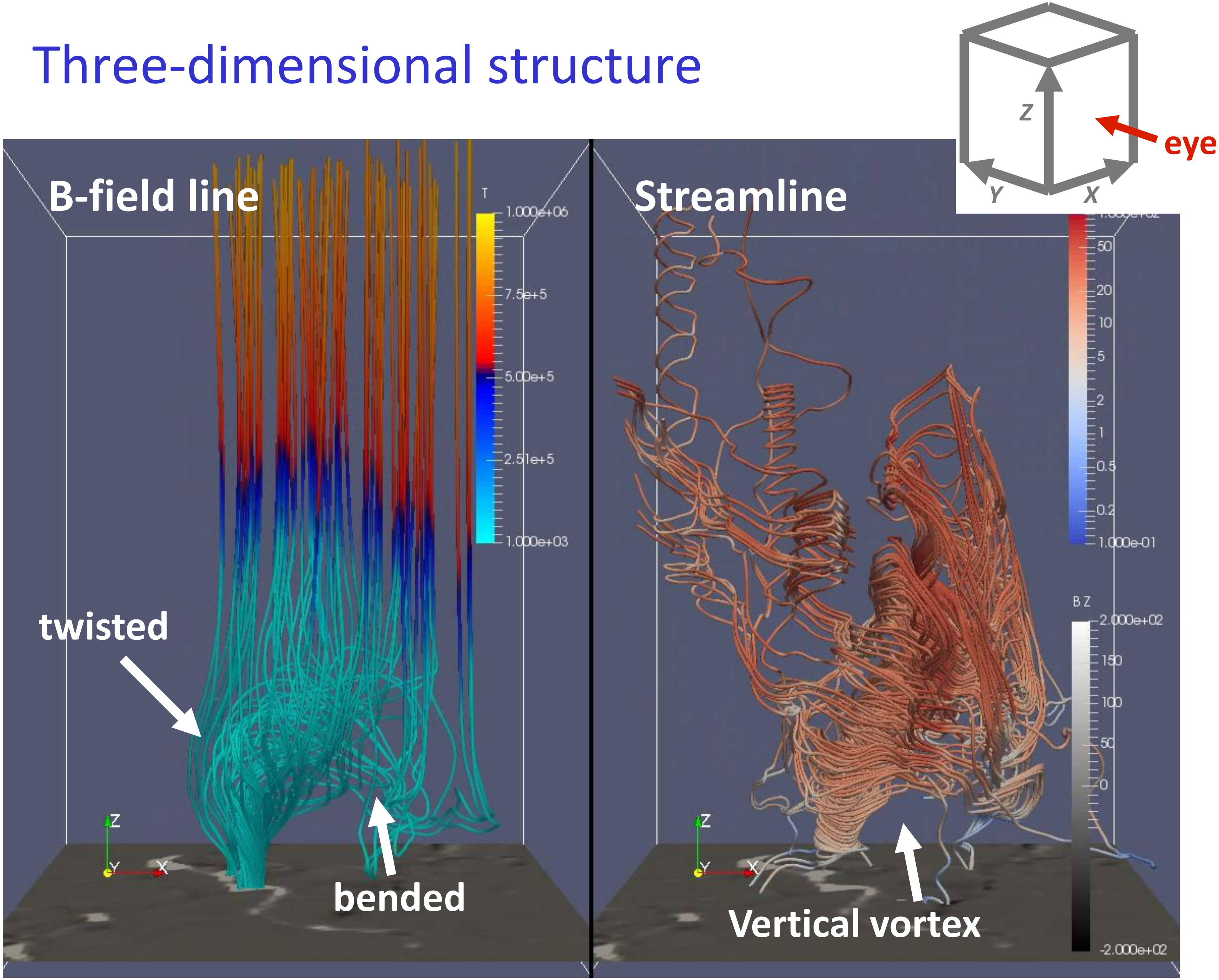
V~ 50 km/s

d~ 200 m/s^2



These parameters are consistent with the observations of spicules in quiet regions.

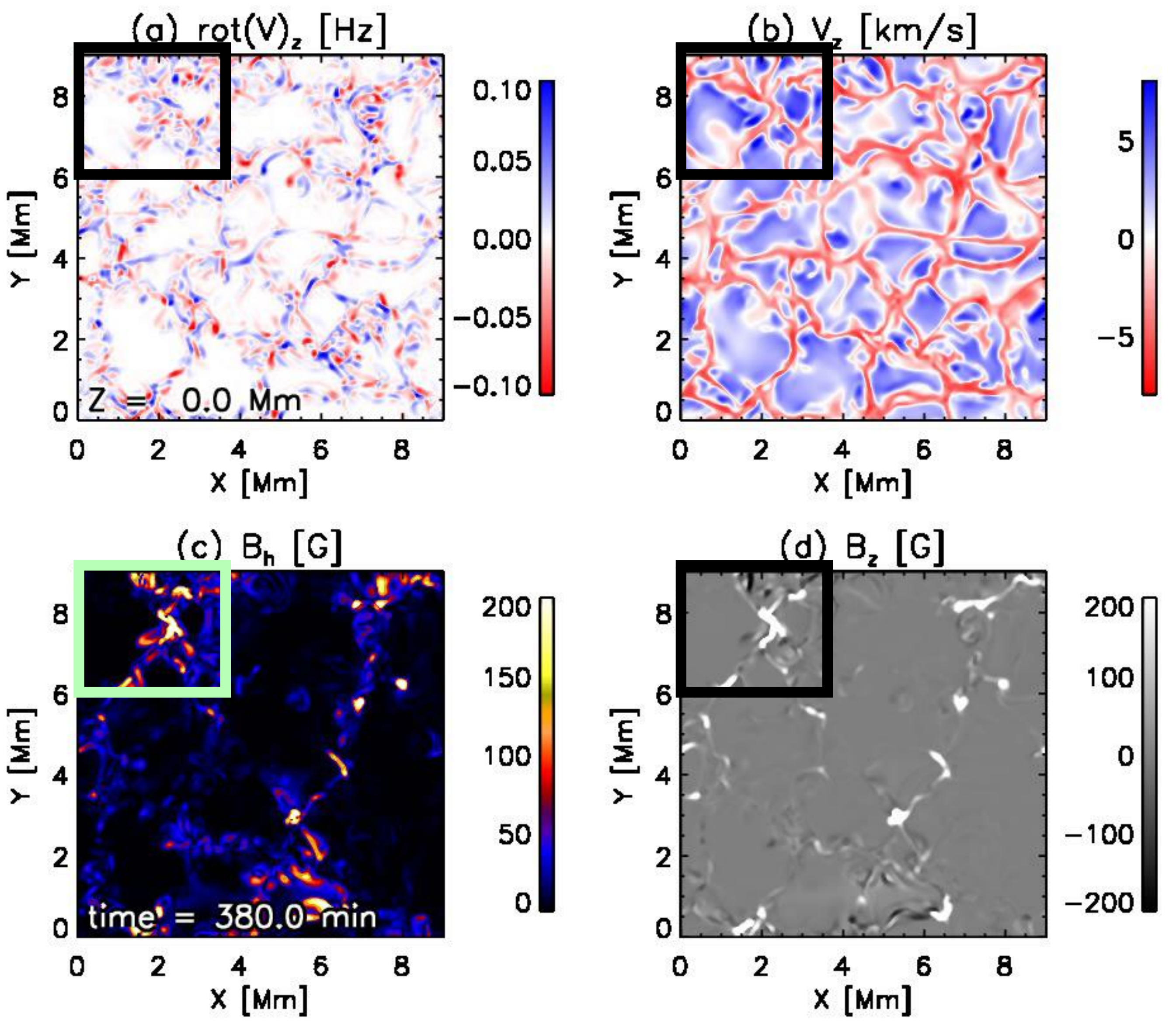
Three-dimensional structure



Vortex and magnetic concentration at the root of the jet in the photosphere

Small-scale vortex is generated at the boundary of convective cells.

Vertical magnetic field is also gathered in the cell boundary by the horizontal flow.

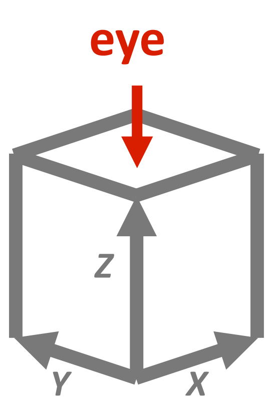


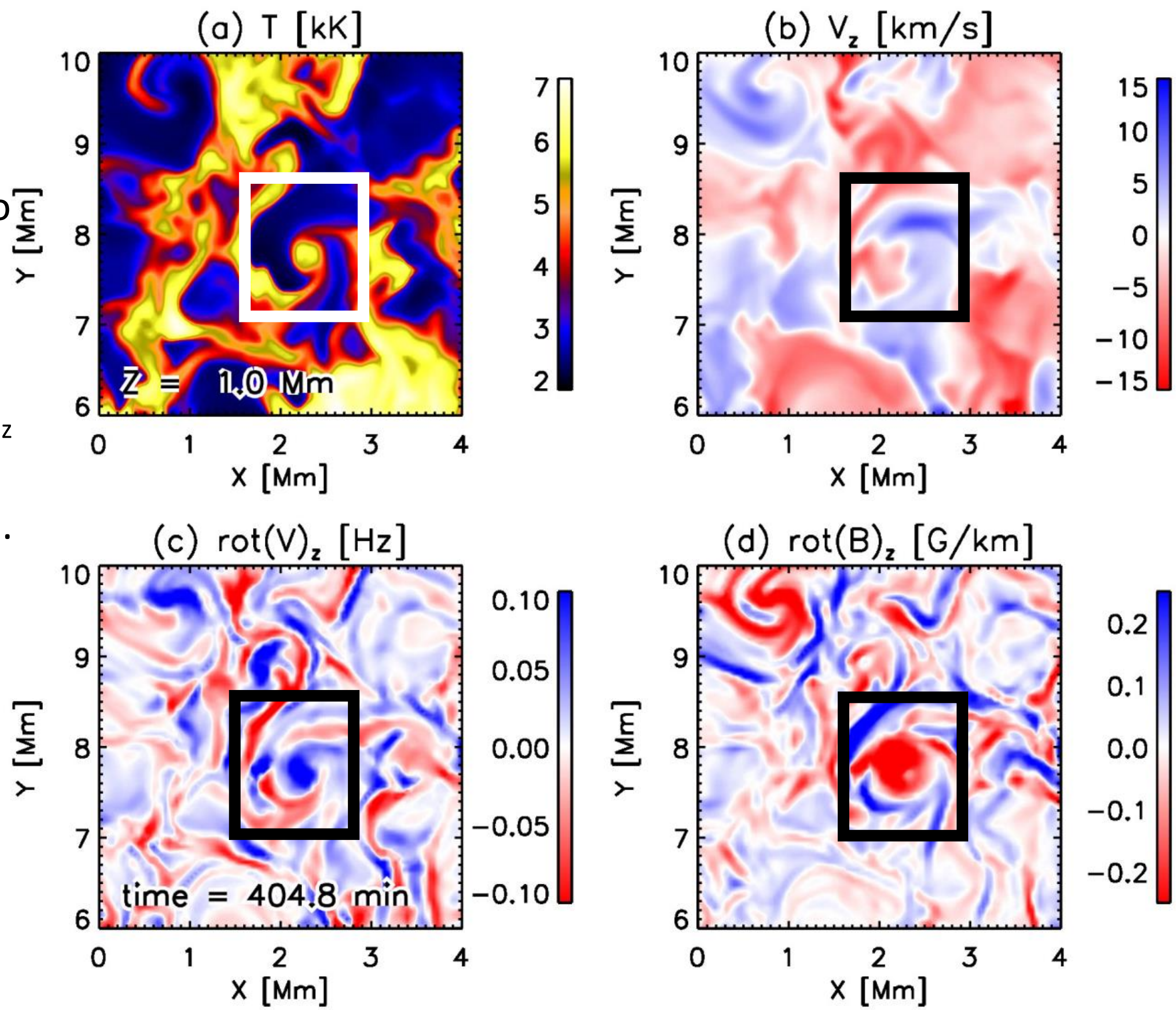
Vortex at the root of the tall jet in the chromosphere

At Z=1Mm

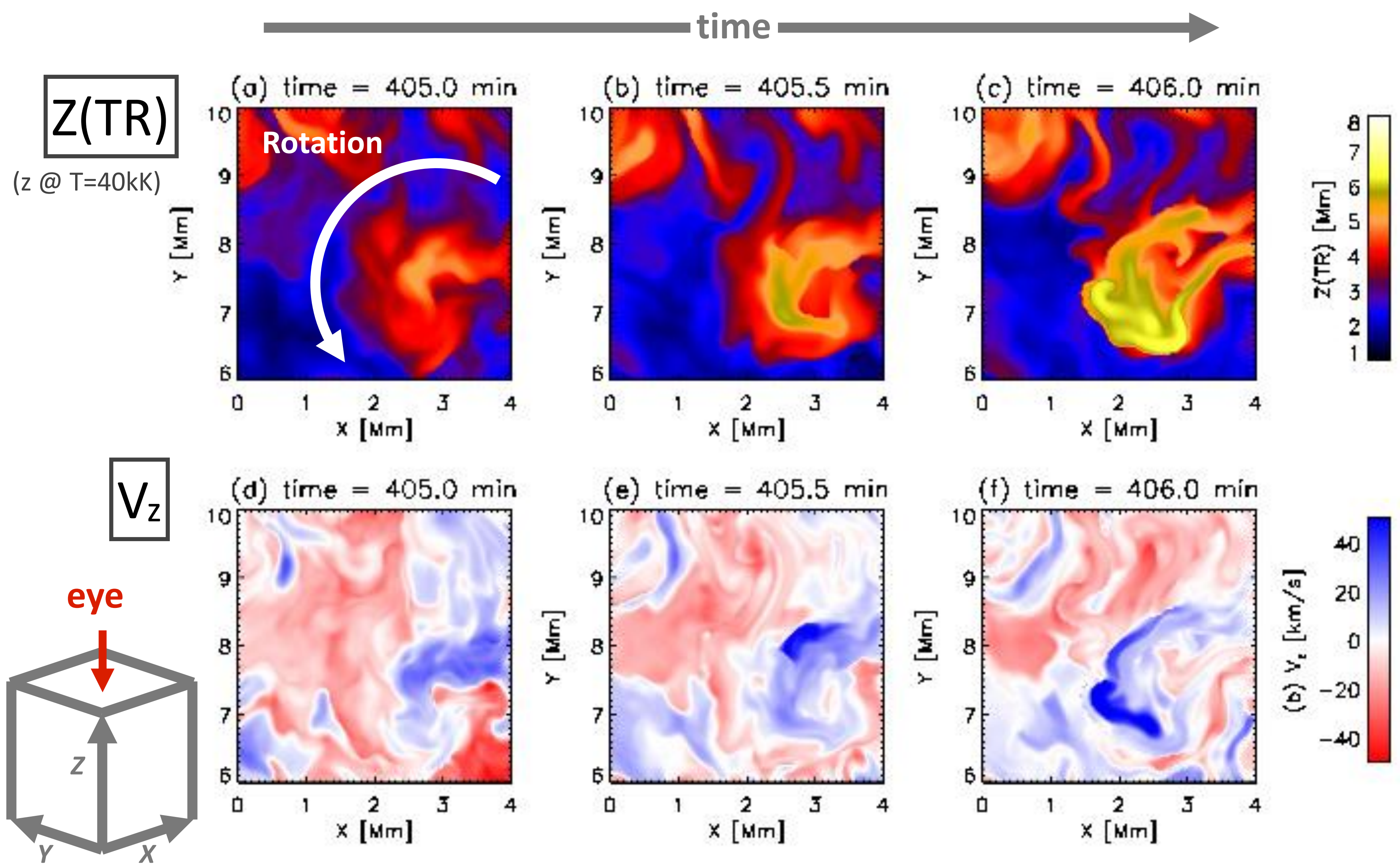
In the chromosphere, it is also found a vortex that persists during the emergence phase of the jet.

The signs of $rot(V)_z$ and $rot(B)_z$ can be interpreted as the upward torsional Alfven wave.

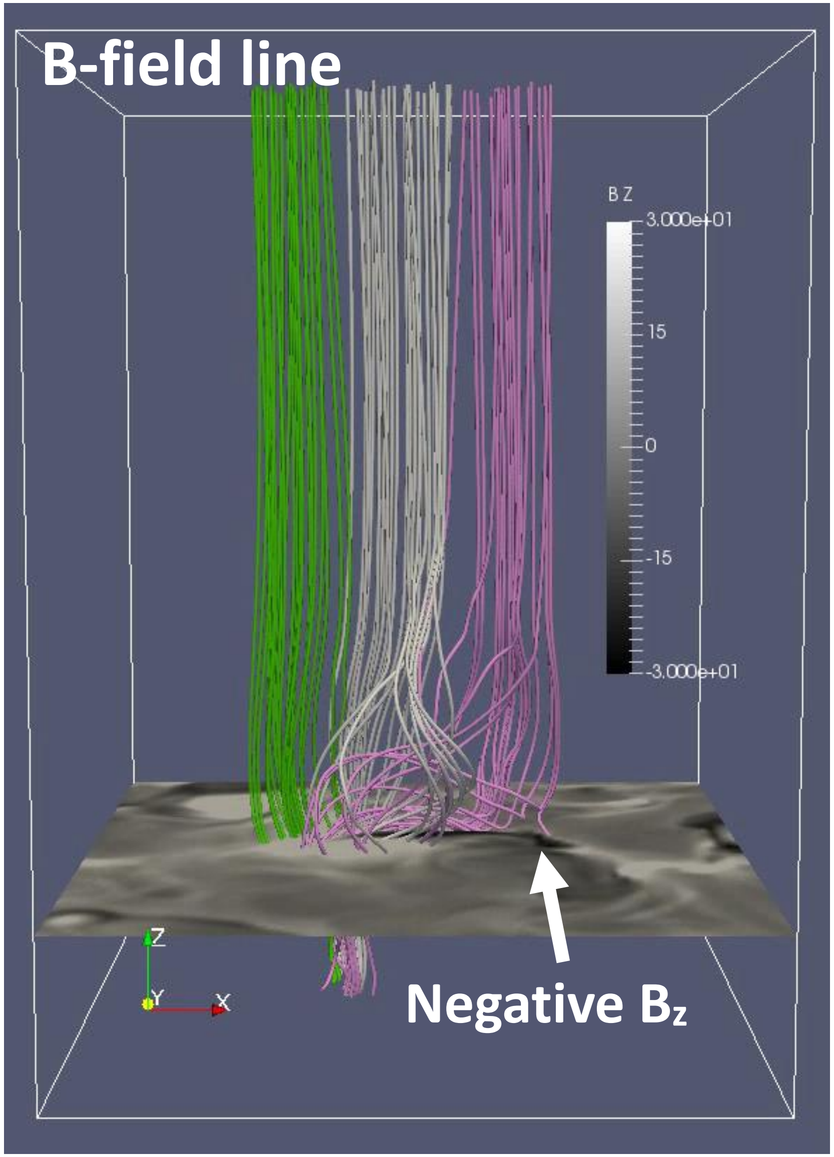


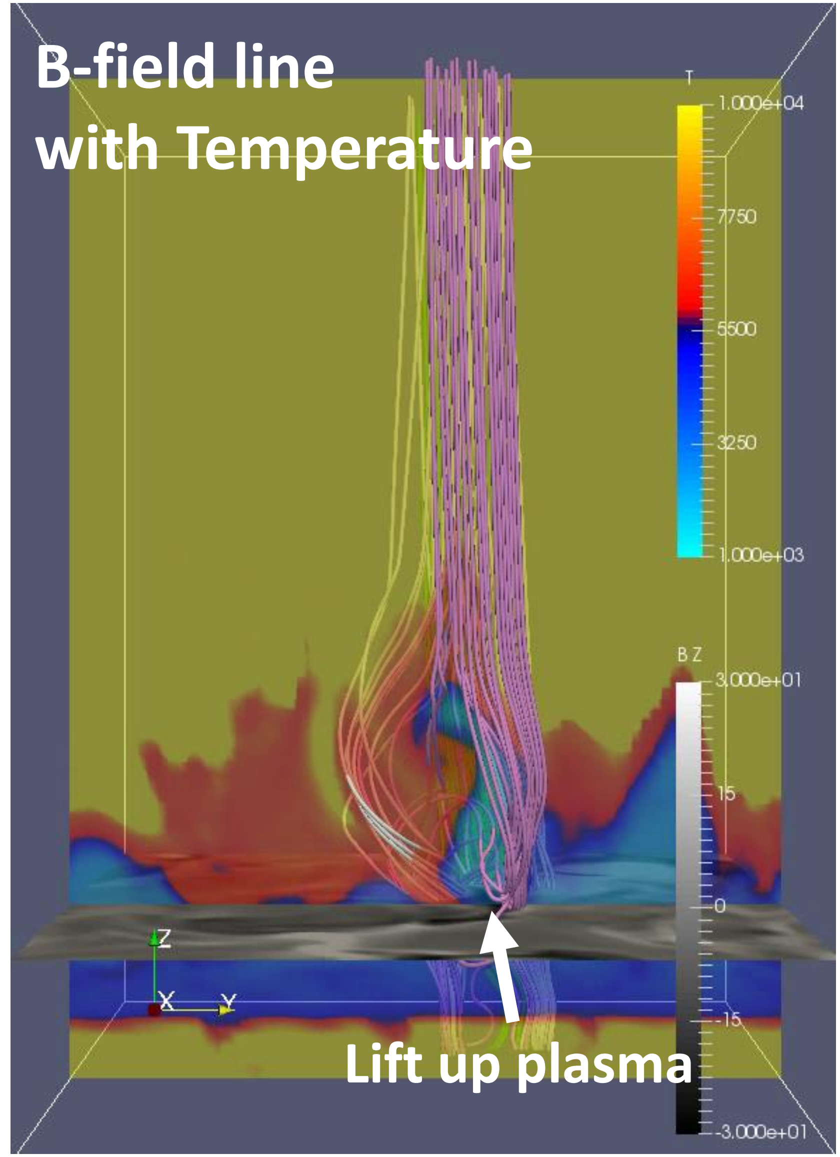


Twist and ejection of the jet



Acceleration of chromospheric plasma





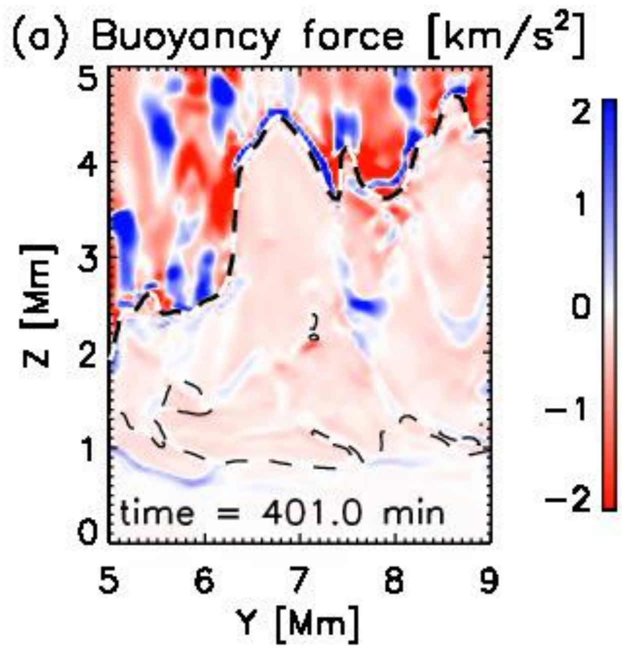
Vertical forces on (Y, Z)-slice at X = 3 Mm

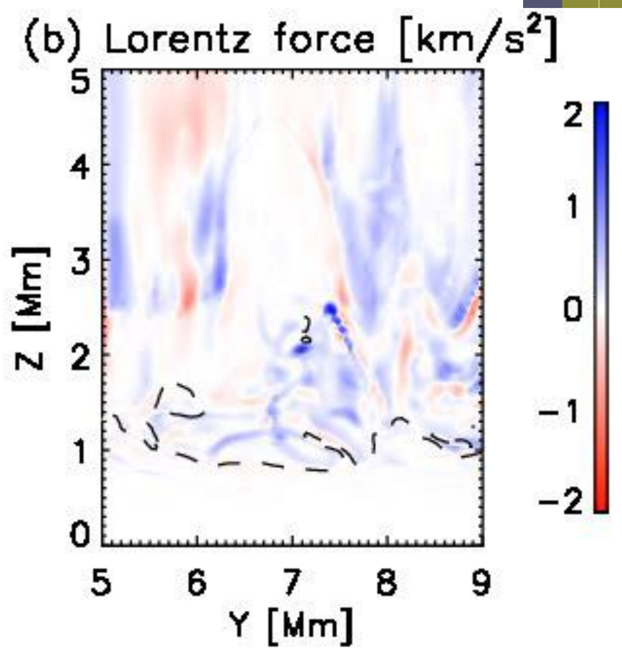
Buoyancy force
=> weak, downward

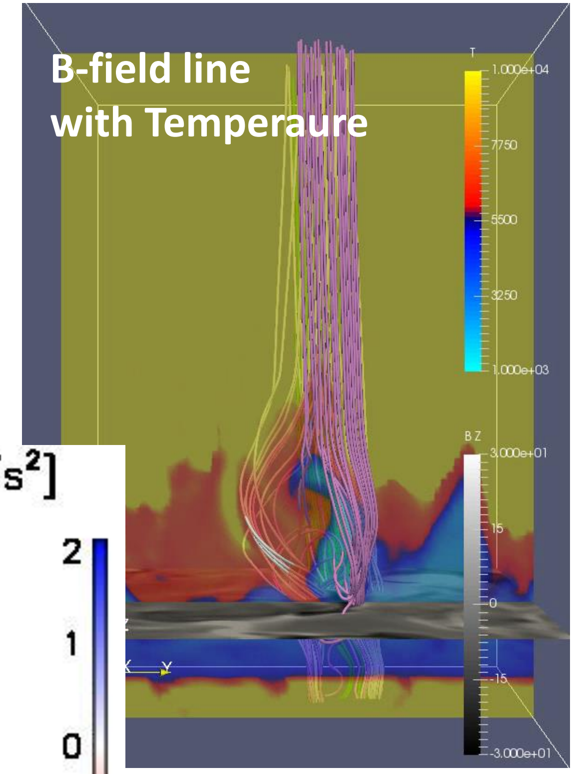
$$F_{\rm B} = -\frac{1}{\rho}\frac{\partial P}{\partial z} - g_0$$

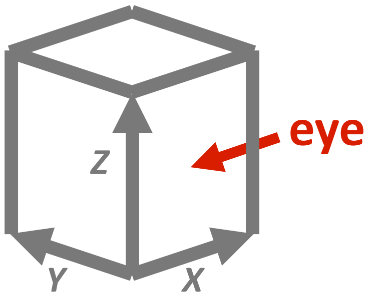
Lorentz force
=> strong, upward

$$F_{\rm L} = \frac{1}{\rho}\left(\boldsymbol{J} \times \boldsymbol{B}\right)_z$$







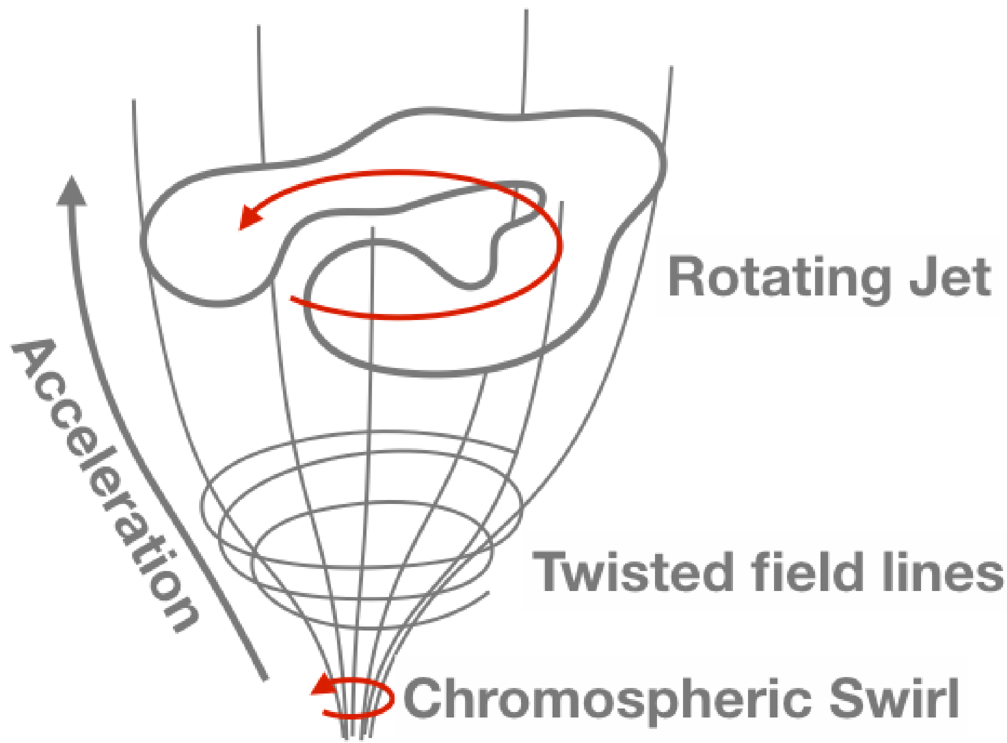


New generation mechanism of chromospheric jet

(1) Highly twisted magnetic field structure is generated by the strong vortex below.

(2) Rotating motion of twisted magnetic field lift up the dense chromospheric material to the upper layer.

(3) The top of the magnetically lifted plasma hits the transition region and elongates chromospheric plasma further upward.



Summary

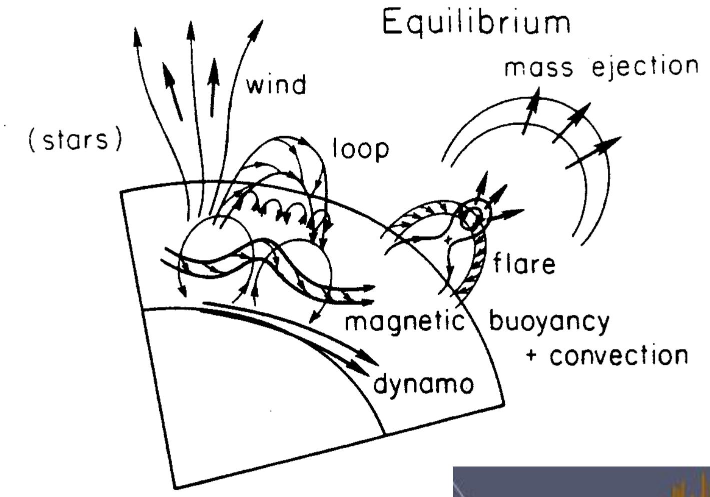
We presented a three-dimensional simulation that successfully reproduces tall chromospheric jets above the strong photospheric magnetic field.

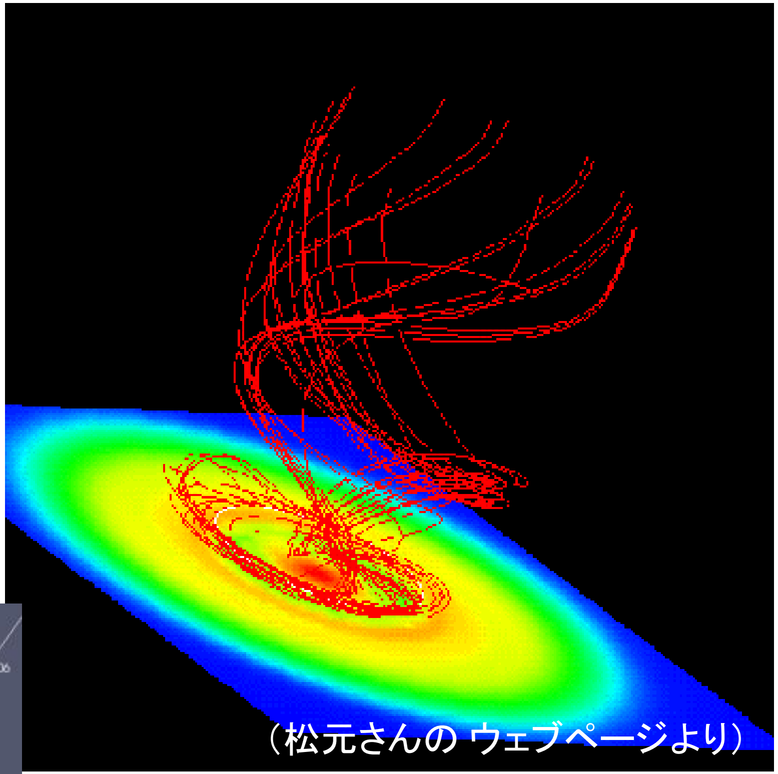
We find that these jets are driven magnetically, relating to the highly twisted chromospheric magnetic field lines.

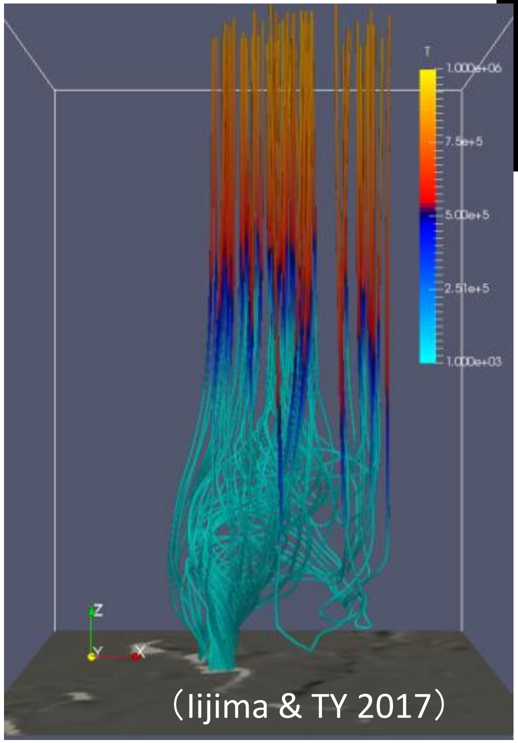
The produced jets form a cluster with the diameter of several Mm with finer strands, which is consistent with the multi-threaded nature of spicules.

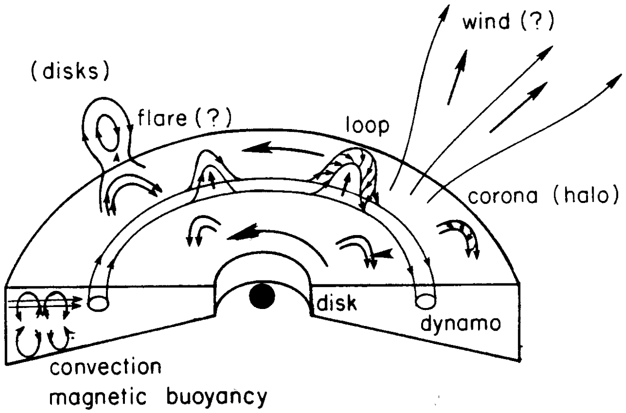
Torsional motion is an important candidate as a driver of chromospheric jets!

最後に


Equilibrium
mass ejection
wind
(stars)
loop
flare
magnetic buoyancy
+ convection
dynamo


（松元さんの ウェブページより）


T
1.000e+06
7.5e+5
5.00e+5
2.51e+5
1.000e+03
（Iijima & TY 2017）


wind (?)
(disks)
flare (?)
loop
corona (halo)
disk
dynamo
convection
magnetic buoyancy

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