A Driving Mechanism of Temperature Dependent Plasma Up-Flows in the Solar Corona

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Abstract

1. We propose a very simple mechanism to drive temperature depending plasma up-flows in the solar corona
2. The new mechanism is based on the fact that
    a. Thermal plasma in magnetic field have diamagnetic moment.
    b. Diamagnetic moments are pushed upwards where magnetic field is weak.
    c. As the diamagnetic moment is proportional to the temperature, magnetic force acting on higher temperature plasma exceeds the gravity force

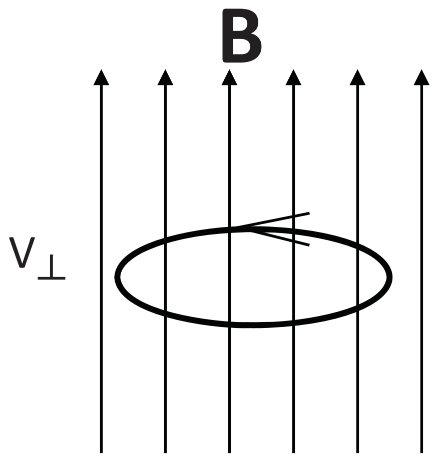
Summary

- We can explain by a very simple mechanism (diamagnetic force) the observational evidences that hot plasmas are pushed upwards and cool plasmas fall down
- Temperature which divide up- or down- flows is determined only by magnetic scale length

$$H_0 > L_B$$ Hydrostatic scale length > magnetic scale length

$$T_6 > L_B / 100'' \sim (L_B / 60\,Mm)$$

Magnetic moment of moving charged particles in magnetic field



$\boldsymbol{\mu} = -\,(1/2)\, mV_{\perp}^{2}\ \mathbf{B}/B^2$

: charged particles feel **B** not **H**

For thermal plasma with isotropic T:

$\boldsymbol{\mu} = -\, k_B T\, (\mathbf{B}/B^2)$

$\mathbf{M} = 2\, n\, \boldsymbol{\mu}$ (electron+ proton)

$= -\, 2\, n\, k_B T\, (\mathbf{B}/B^2)$

n: electron/proton number density

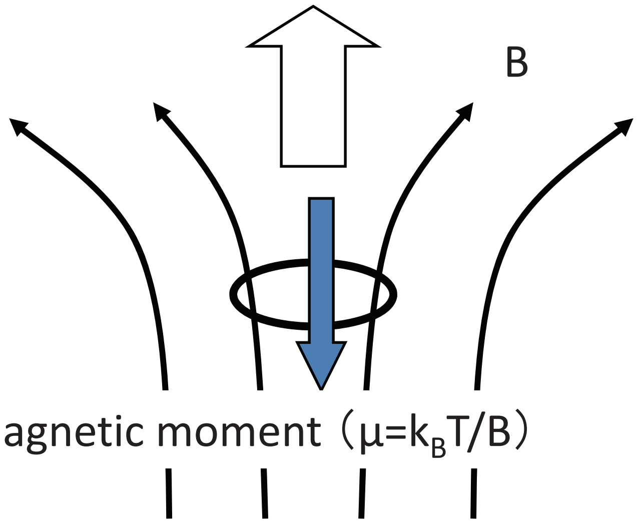
Plasma is nonlinear diamagnetic medium

$(M \propto -\, 1/B)$

Diamagnetic Force

In the presence of gradient of magnetic flux density (B), dia-magnet is pushed toward weak B region.

Diamagnetic force: μ(dB/dR) (mirror force)



$$L_B = \left(\frac{1}{B} \frac{dB}{dR} \right)^{-1}$$

Magnetic scale length

$F = \mu(dB/dR) = k_B T / B \, dB/dR = k_B T / L_B$

Forces acting on a plasma particle

- Upward force: Diamagnetic force
  - $F_u = 2\frac{k_B T}{B}\frac{dB}{dR} = \frac{2k_B T}{L_B}$; electron + proton
- Downward force : gravity (near surface)
  - $F_d = m_p g_0$

Condition for upflows

- Upward force exceeds downward force

$$F_u / F_d = \frac{2k_B T}{m_p g_0 L_B} = H_0 / L_B > 1 \qquad H_0 = \frac{2k_B T}{m_p g_0}$$

- In the solar corona

$$H_0 \sim 60 Mm \times T_6 \sim (100'' \times T_6) > L_B$$

$$T_6 > L_B / 100'' \sim (L_B / 60 Mm)$$

Temperature dependent plasma upflow

SoHO/SUMER observation

- Peter & Judge
  ApJ 522, 1999
  - SoHO roll to determine zero velocity（cos(θ))
  - AR(closed)/CH(open) observation
  - Upflow: T> 0.5 MK (both in closed & open field region)
- First report in 1977
  - Sandlin et al.   ApJ, 214

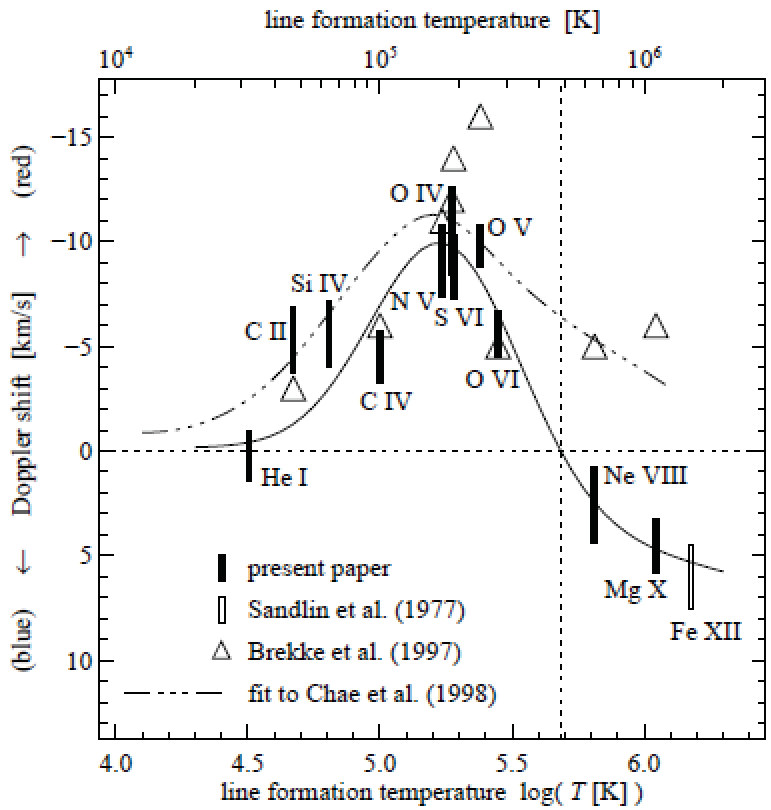


FIG. 6.—Variation of the Doppler shift at disk center with formation temperature of the line. Error bars for the data of Brekke et al. (1997) were typically 2 km s^{-1} (not shown). The solid line is a by-eye fit to the Doppler shifts in the present study.

Hinode Observation Ⅰ

- Imada et al.

  PASJ, 59, 2007

  - EIS observation
  - Declining phase of a X-class flare
  - Unipolar Plage region
  - Strong Upflow T > 1 MK

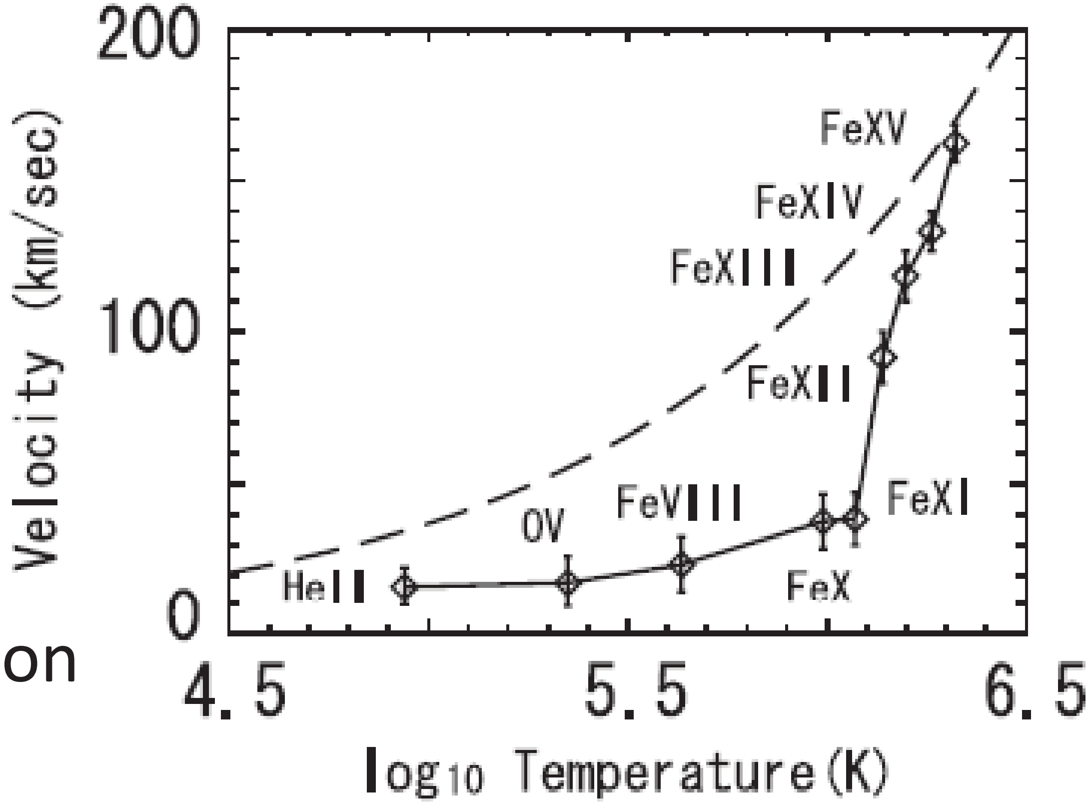


Fig. 6. Upflow velocity as a function of the temperature. The dashed line shows the sound speed. Around 1 (MK), the trend of the temperature dependence is significantly changed. The upward velocity is almost the sound speed in Fe XV.

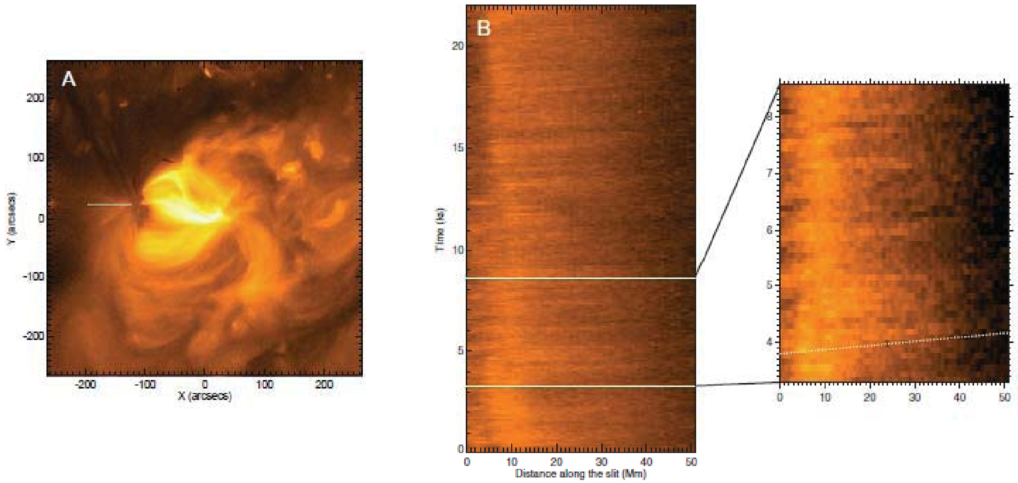
Hinode Observation Ⅱ

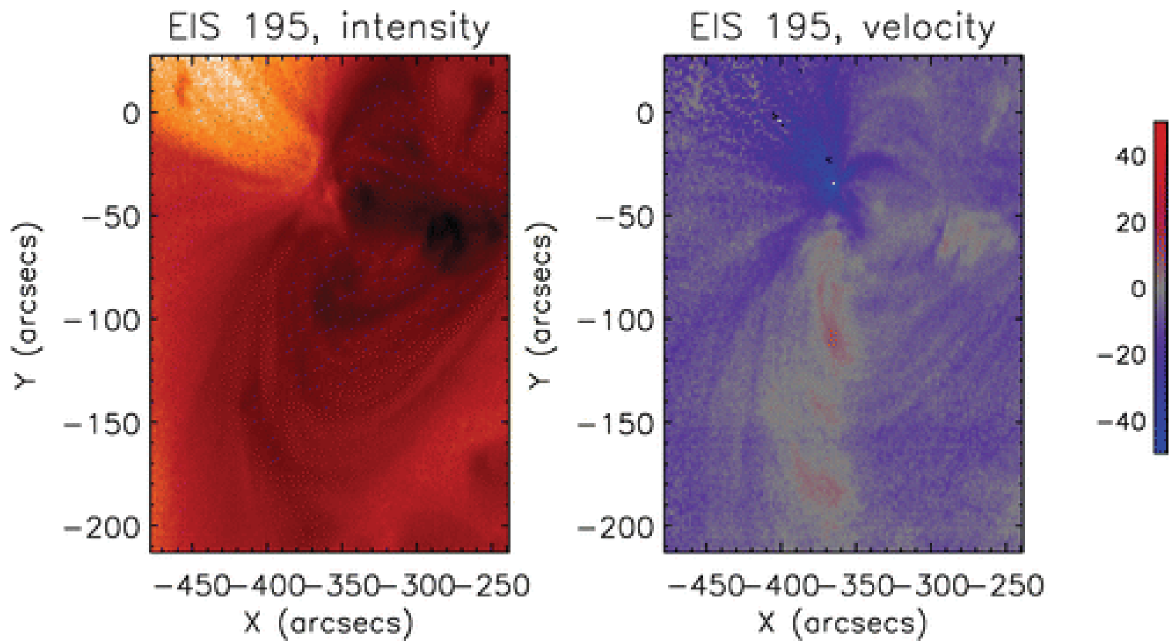
- Sakao et al.

  Science 318, 2007
  - XRT
  - Open field region
  - 140 km/s
- Harra et al.

  ApJL 676, 2008
  - EIS
  - ~100 km/s

    along B





Existing explanations

- Solar wind acceleration
  - Applicable only to open field region
- Lifted as spicule and falls back after cooling
  - Not applicable to explain upflows of hot plasma
- Siphon flow
  - Applicable only to closed loop
  - Cannot explain temperature dependence
- Nanoflare driven waves
  - To explain Doppler shift as the result of non-linearly developed waves
  - Foot points of open flow regions are not hot

Discussion

- We proposed a temperature dependent up-flow mechanism. Heating mechanisms are not discussed. (Coronal heating problem is out of our scope.)
- Absolute values of velocities are not discussed.
- Observations of acceleration / deceleration is needed for further confirmation.
- We should expect cooling as the plasma goes up under collisionless condition.