Connecting the Sun and the solar wind: the self-consistent transition of heating mechanisms

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Outline

• Importance of coronal heating in astrophysical context

• Heating & mass loss mechanisms of solar atmosphere

• Idealized flux tube model by 2.5D MHD simulation
Coronal Heating Problem

Temperature (K) vs. Height above the photosphere ($R_\odot$)

- Temperature scale ranges from $10^2$ to $10^8$ K.
- Height scale ranges from 0.0001 to 0.01 $R_\odot$.

Graph showing the temperature increase with height above the photosphere.
Mass Loss from the Sun

Optical Image (SOHO/LASCO)

\[ \dot{M} \sim 10^{-14} M_\odot/\text{yr} \]

Contribution to total mass loss

Fast Wind

Slow Wind

Ejection
• **Coronal heating & wind theory should answer**
  
  – Mass loss rate from the sun
  – Origin of Fast/Slow solar wind
  – Recent reduction of solar wind density
    (Janardhan+2011)
  – Faint young sun paradox
    (Suzuki+2013)
Application II : Cool Stars

• **Mass loss from cool stars impacts on**
  – stellar evolution
  – surrounding planetary systems
  – evolution of gas & dust in galaxies
  – atmospheric erosion of inner planets (Woods 2006)

• Wind could be driven from stars that have convection zone (later than F type)
Energy source for hot coronal wind

Thermal Energy

Mechanical Energy
Difficulty in energy dissipation

- Magnetic Reynolds number

\[ R_m = \frac{(\text{Alfven speed})(\text{System size})}{\text{Resistivity}} = \frac{\tau_D}{\tau_A} \]

\[ \tau_D \gg \tau_A \]

Dissipation Time Scale | Dynamical Time Scale
How to make small scale I

Shock waves

From T.K.Suzuki
How to make small scale II

Phase mixing  (Heyvaerts & Priest 1983)
How to make small scale III

Wave turbulence

- Wave interaction between upward/downward waves
- Drive turbulent cascade perp to magnetic field

Need reflection wave to drive turbulence
Energy dissipation path

- Magnetic energy
- Shock wave
- Phase mixing
- Wave Turbulence
- Thermal energy

...
Coronal model → Mass loss rate

- Coronal models predicts
  - temperature
  - density
  from the photospheric condition

- Combined with Parker theory
  - Mass loss rate
Purpose

• Find out the energy dissipation path of Alfven wave
• Derive mass loss rate from the photospheric boundary condition
• **Run numerical simulations**
  – Phosotphere to solar wind region
• **Observe numerical results**
• **Find heating mechanisms**
• **Check validity**
• **Extract basic process**
Numerical Set Up

- 2.5D Ideal MHD
- Thermal conduction
- Radiative cooling

Width [Mm]

Height [Mm]

2800 G

2.5 G

20 R\(_\odot\)
Energy injection (Boundary condition)

- White noise velocity perturbation
  - 1.1 km/s
  - 50-4,000 sec
Characters of our simulation

• **Advantages**
  – Waves/Heating : self-maintained (No heating function)
  – Large spatial domain (1 – 20 \( R_\odot \))

• **Disadvantages**
  – Single fluid MHD (No collisionless effects)
  – 2.5D approximation
    • Insufficient treatment for MHD turbulence
    • No vortex (torsional) motion. (De pontieu+2012)
Relation with nanoflare model

- Our model suppresses nanoflares
Dynamics of Transition Region

Log Density [g/cc]

Simulation

Ca II H

From Solar Optical Telescope
NAOJ/JAXA
Comparison with Observation

Red solid line: Simulation
Symbols: Observations
Interpretation of Result

• Hot corona & (fast) solar wind are reproduced as a natural outcome of the fluctuations of B-field at the photosphere

• **Important Results**
  – Dissipation of Alfven waves (discuss later)
  – Quasi steady transonic Wind
    • Thermal+Wave driven wind
  – Transition from $10^4$K to $10^6$K
Heating rate

- Total energy conservation w/o explicit dissipation
  \[
  \frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot \left[ (\mathcal{E} + P_T) \mathbf{V} - (\mathbf{V} \cdot \mathbf{B}) \mathbf{B} \right] = \rho g \cdot \mathbf{V} - Q_{\text{rad}} + Q_{\text{cnd}}
  \]

- Dissipation comes from
  - Shock dissipation
  - Numerical dissipation
Heating below the transition region - shock heating (Hollweg1982) -

\[ \frac{J^2}{\rho} \]

Heating rate per unit mass

Transition Region > 10 Mm

Alfvén wave front

Magnetic field lines
Coronal Heating

- Phase mixing? (Heyvaerts & Priest 1983) -

Horizontal Direction

Magnetic Heating

\[ J^2/\rho \]

Transition layer

Magnetic field lines

Current density

Time = 3079.59 min, n=0000
Summary

- Ab initio production of corona/wind
- Transition of heating mechanism
Future work (3D extension)

- **MHD turbulence and/or Nanoflare**
  (e.g. Van Ballegooijen+2011)
Future work (BP morphology)
Future work (star/planet)

- **Other stars or planets have different**
  - Radius
  - Gravity
  - Photospheric convection motion

- **Radiative process in cool stars/planets include molecule & dusts**