Self-Consistent MHD Modeling of Solar Wind

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Outline

- (Brief) Introduction
- Our Works
  - Simulations of Solar Wind Driven by Nonlinear Low-freq. Alfven Waves

Suzuki & Inutsuka 2005, ApJL, 632, L49

First Dynamical Simulation which connects photospheric B-field
and Interplanetary Region (Solar Wind)

  - Disappearance of Solar Winds (= Failed SW)
  - Fast/Slow Solar Winds

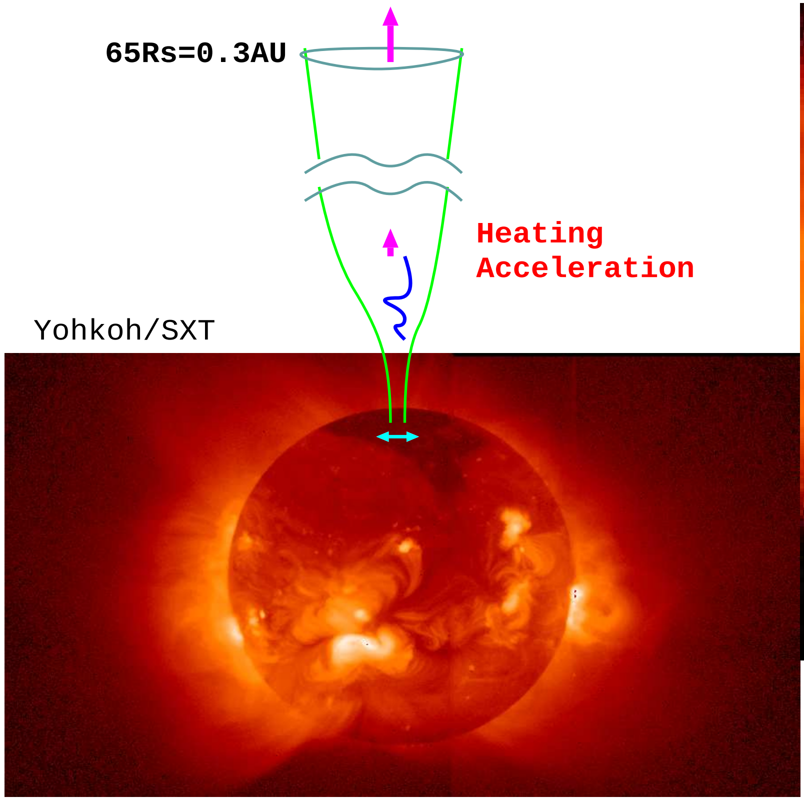
Suzuki & Inutsuka 2005, submitted to JGR (astro-ph/0511006)

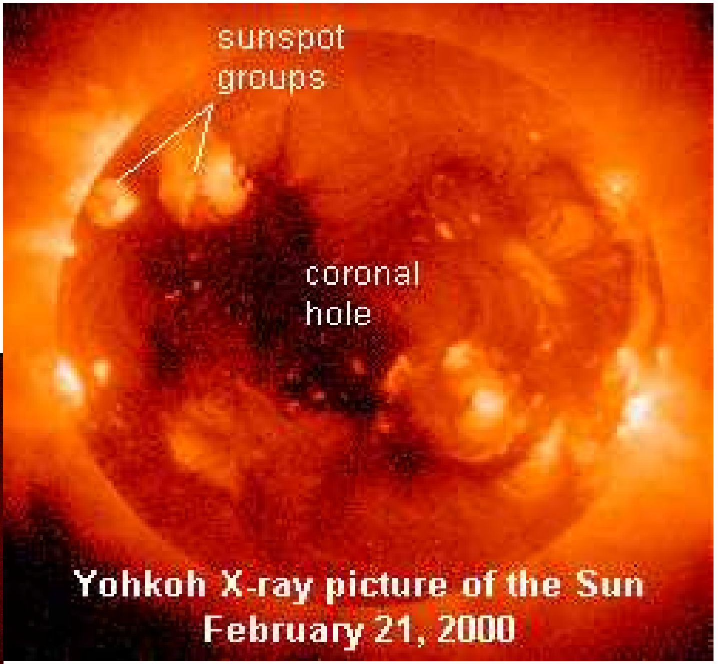
- Observational Test by Solar-B
  - Grab an evidence of the nonlinear dissipation of Alfven Waves

Photospheric dv, B <=> Coronal Density and Temperature / SW Speed

SOT <=> EIS/XRT

SW from Coronal Holes





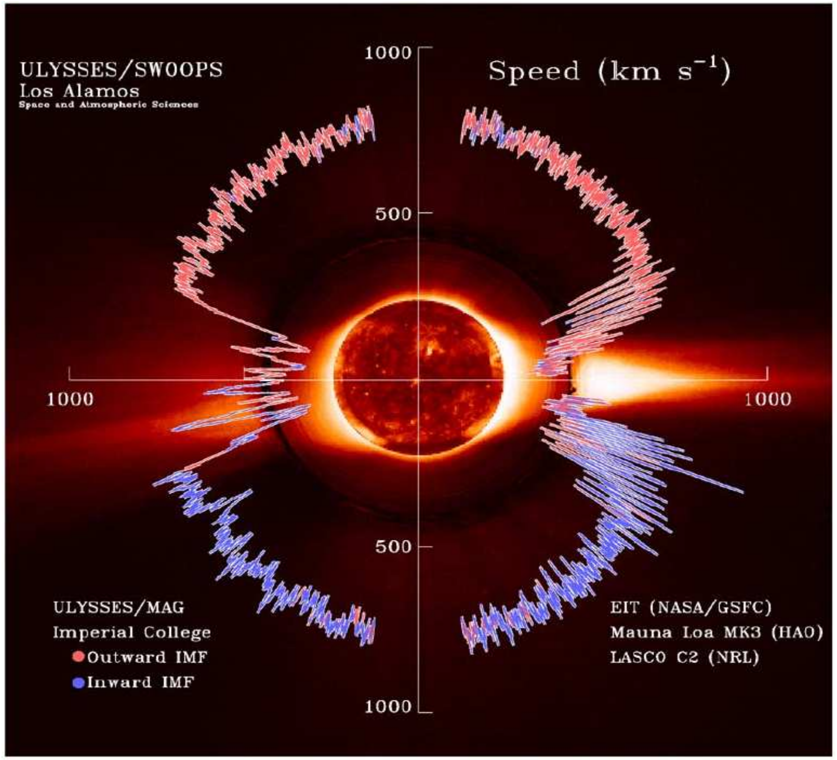
We mainly focus on Solar Winds from coronal holes

- **Polar Coronal Holes**
- **Mid- to Low-Latitude Coronal Holes**

Just after the launch (Solar Minimum) of Solar-B, the surface is largely covered by Coronal Holes

Fast/Slow Solar Wind

During Solar Minimum



Property (1 AU)	Slow Wind	Fast Wind
Flow Speed	~400km/s	~750km/s
Density	~7 cm-3	~3 cm-3
Origin	Low-Lat.Holes(??)	Polar Holes

What is the Problem

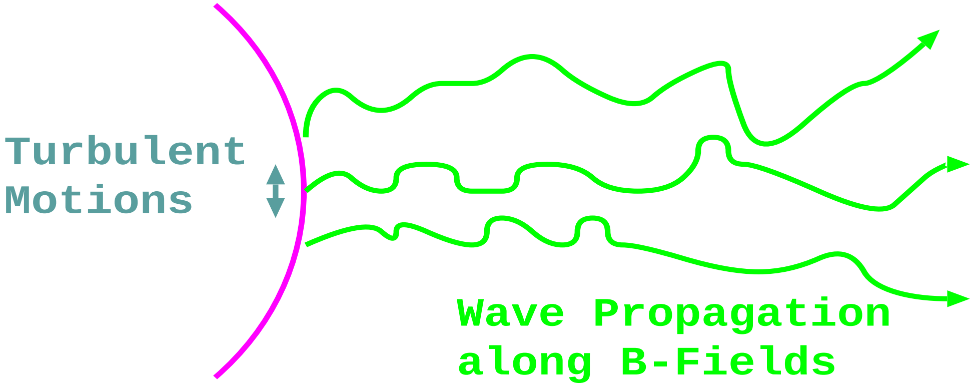
How does the Solar atmosphere react to injection of the (Poynting) energy from the surface in the open coronal holes?

- **Corona formed ?**
- **Transonic High-Speed Wind Accelerated ?**

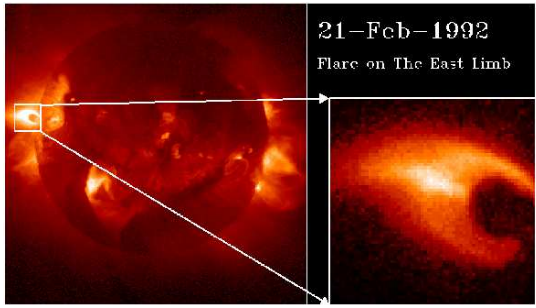
by dissipation of (Poynting) energy.

Wave Heating in Open Regions

- **Waves : Alfven Wave is promising**
  - **travel long distance to heat outer (SW) as well as inner (Corona) regions**



- **Reconnections : Probably Important in Closed Region**



Tsuneta et al.1992

  - **may Generate Waves at Higher Altitude**

Alfven Waves

2 Types

- High-freq (ion-cyclotron; 10^4Hz) waves

  Heating of Heavy Ions (Large m/q) Kohl et al.1998; Cranmer et al.1999

  Difficult to heat P & e
  - No sufficient Power
  - Heavy ions (lower-resonant freq.) absorb energy before protons

    Cranmer 2000

- Low-Freq waves(<0.1Hz) (This work)

  Mathaeus et al.1999; Oughton et al.2001; Ofman 2004
  - Probably, More Power (e.g. 5 min. Oscillation)

Waves in Solar atmosphere

- Key : Nonlinearity

  Upward propagation with preserving energy flux

$$\rho\,\delta v_{\perp}^{2} v_{\mathrm{A}} = \mathrm{const.} \Rightarrow \delta v_{\perp} \Uparrow \Rightarrow \delta v_{\perp}/v_{\mathrm{A}} > 1 \text{ (Non-Linear)}$$

(Note) Wave action, instead of energy flux, is an adiabatic constant in moving media

Previous Works

To Study various non-linear wave processes,

Time-dependent Simulation : Straightforward

- **Analytic/Steady-state Modeling sometimes needs too much Simplification**

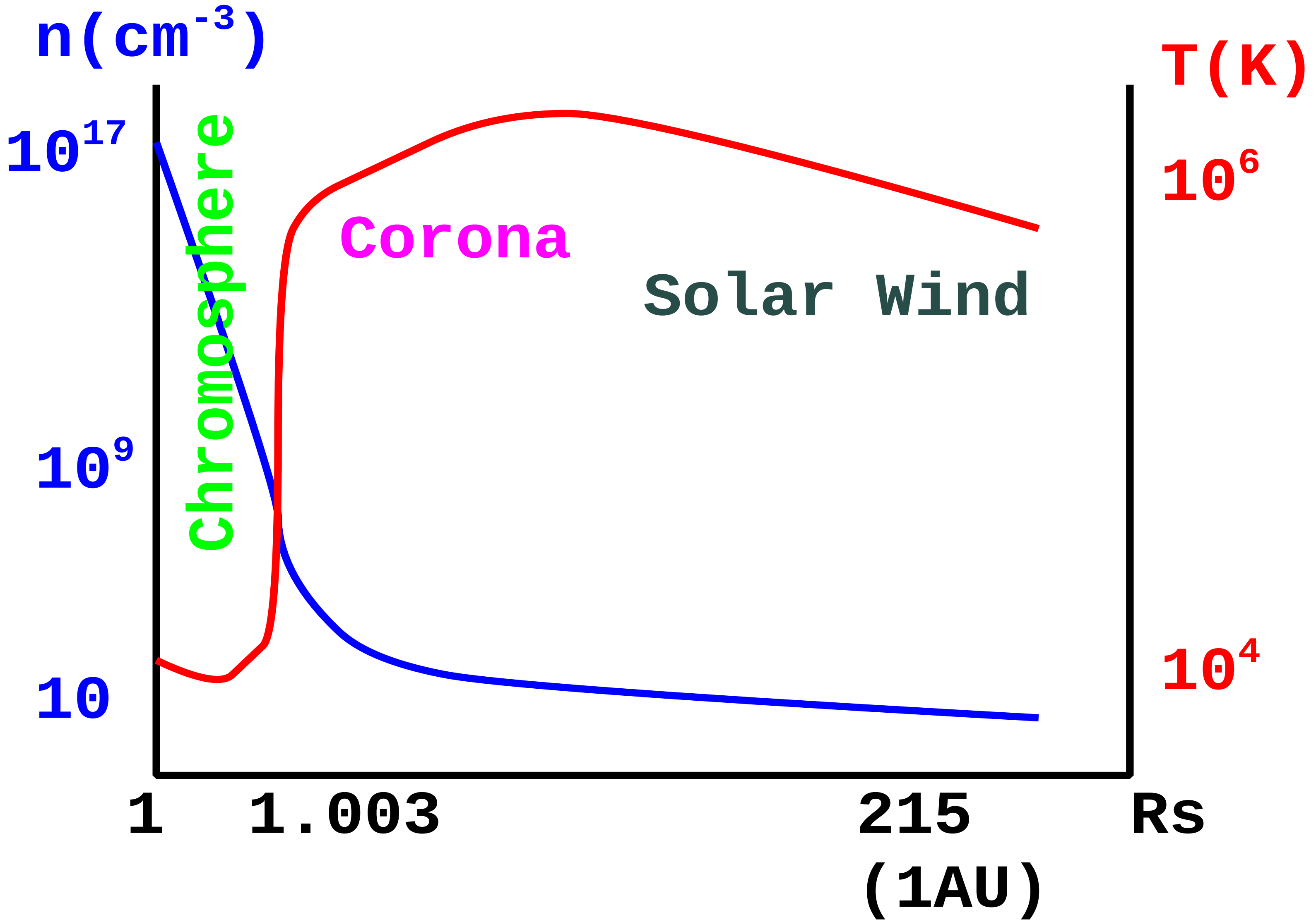
However, a lot of Difficulties even in simulations

- **Huge Density Contrast : > 15 orders of mag.**
  - **Previous simulations : Separate Regions**
- **Outgoing boundary condition at Outer Boundary**

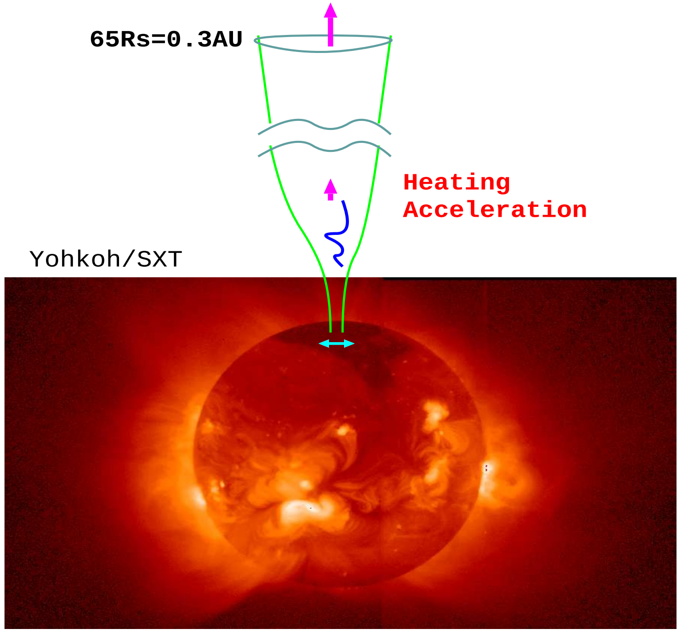
Model	Chromos.	Corona	Dynamical	Dim.	Multi-fluid	Heating
Cranmer & van Ballegooijen (2005)	Yes	Yes	No	(2D)	No	Wave(Model)
Ofman(2004)	No	Yes	Yes	2.5D	Yes	Function/Wave
Lie-Svendsen et al.(2001)	Yes/No	Yes	Yes	1D	Yes	Function
Bogdan et al.(2003)	Yes	No	Yes	2D	No Need	Wave(Auto)
This Work	Yes	Yes	Yes	1D	No	Wave(Auto)

No one has successfully done dynamical wave simulation from photosphere to >a few Rsun even in 1D

Chromosphere/Corona/SW



Simulation



- Region : Photosphere ~ 64 Rsun (0.3AU)
- Transverse(Alfven) fluctuations from the Photosphere
  - Appropriate dv (~1km/s), spectrum(1/f; 20sec - 30min)
  - (How about wave generation at higher altitude ?)
- Outgoing Boundary Condition
- 1D ; SuperRadial expansion of Flux tube (mimic dipole B)
- Ideal MHD with radiative cooling & thermal conduction

Characters of our Simulation

Advantage

- **Broadest Region with respect to density contrast**
- **Waves/Heating/Cooling : Automatic(Waves of P>20s)**
  - **No Heating Function**
- **Minimal Parameters**
  - **Photospheric Perturbation**
  - **Super-radial flux tube (mimic dipole B-field)**

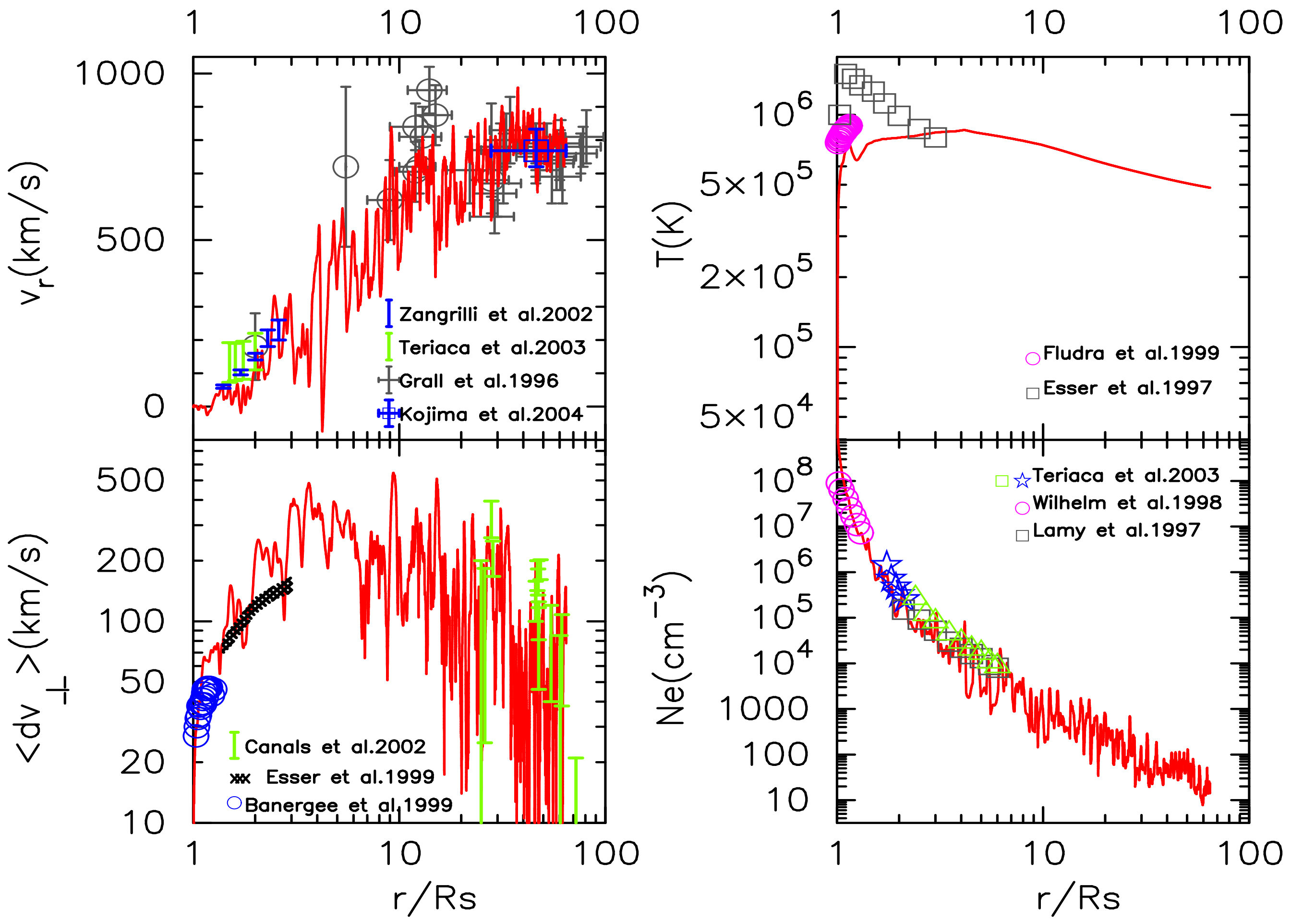
Disadvantage

- **1-fluid ideal MHD**
  - **Plasma Heating : only by MHD shock; No Collisionless processes**
  - **Actually, observed ion/electron T are different.**
- **1D**
  - **Wave Propagation : Restricted to B-direction(B//k)**

(In spite of 1D 1-fluid MHD)

First Simulation which directly connects Photos. & SW

Result of Fast Wind (Fiducial Case)



Observations

- (r<6Rsun) : SoHO(CDS/UVCS/SUMER/LASCO)
- (r>8Rsun) : Inter-Planetary Scintillation (Nagoya-STE;EISCAT)

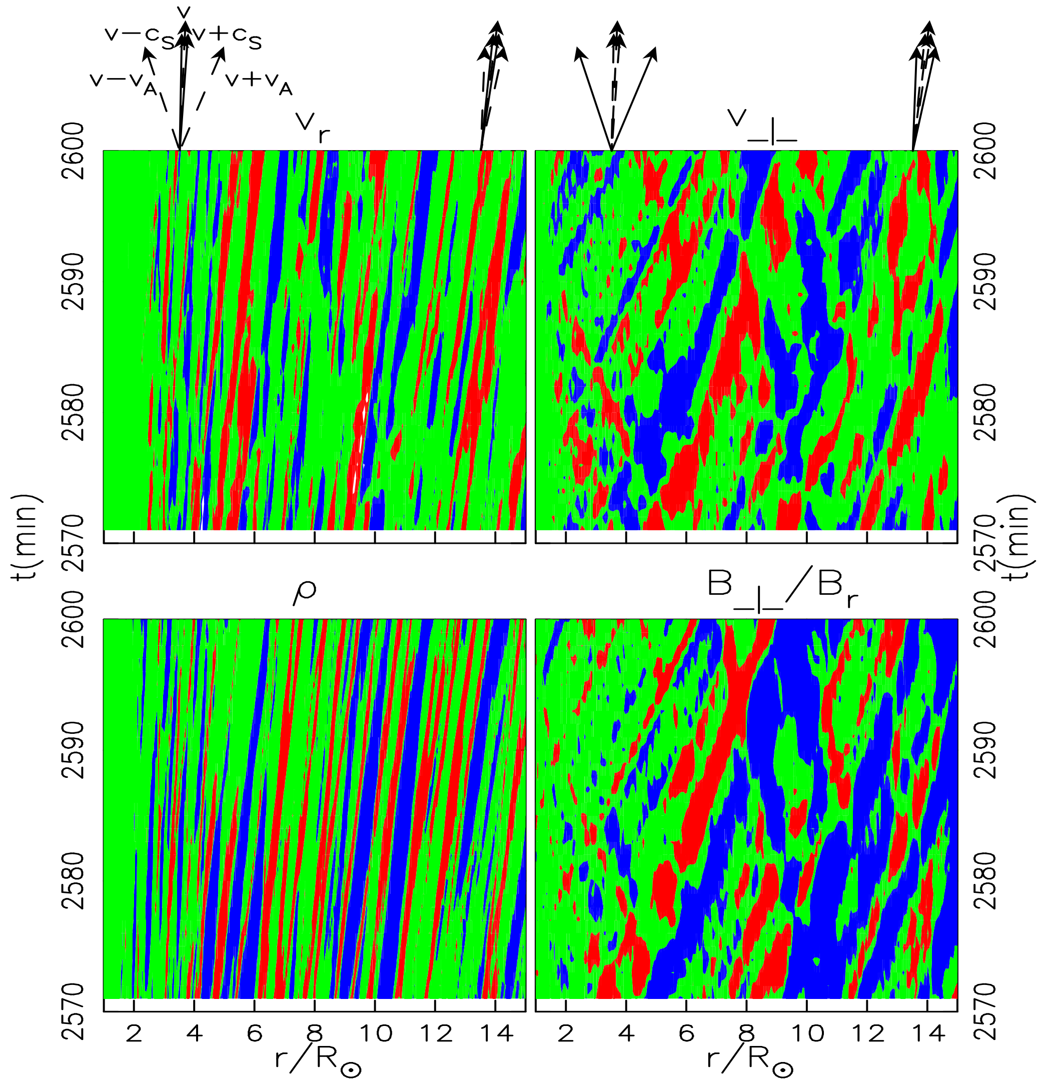
Interpretation of Result

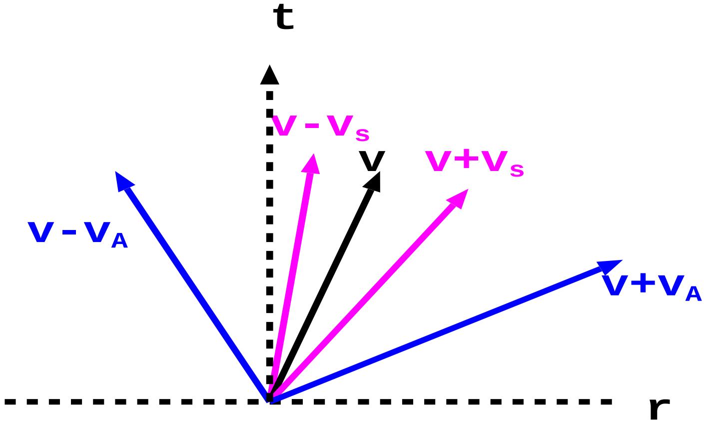
Forward Simulation shows that corona and (fast) solar wind is Natural Outcome of the fluctuations of B-fields at the photosphere.

Important Results

- (Nonlinear) Dissipation of Alfven Waves (discuss later)
- Transonic Wind : Stable
- Not Thermal-driven but Wave-driven Wind
  - Wave-Pressure > Gas-Pressure
- Chromosphere(10^4K)<= Sharp TR =>Corona(10^6K)
  - Thermal Instability(Rad.Cooling) & Stabilization by Conduction
- Outflow Velocity
  - 1.014Rsun(z=10Mm) : up to 10km/s (mixed with waves)
  - 1.14Rsun(z=100Mm) : 50-100km/s (c.f. Tu et al.2005)
  - 2.5Rsun (~ Sonic Point) : ~150km/s(No difficulty at sonic point.)
  - 10Rsun : 500-800km/s (Acceleration : r<10Rsun)

Time-Distance diagram (contour)

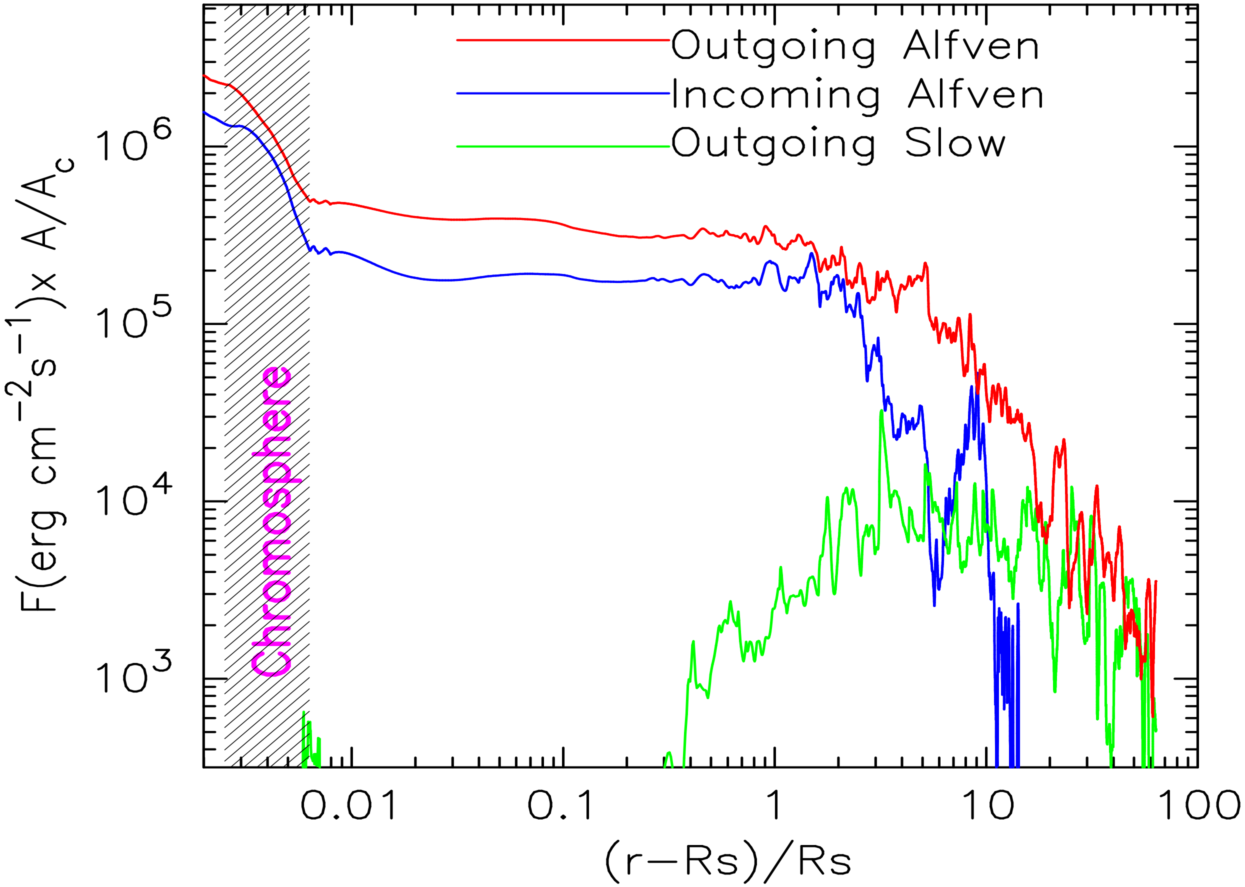




- **Both Outgoing & Incoming Alfven (=Fast) Waves in B_perp & v_perp**
- **Outgoing Slow (sound) Waves in rho & v_r**

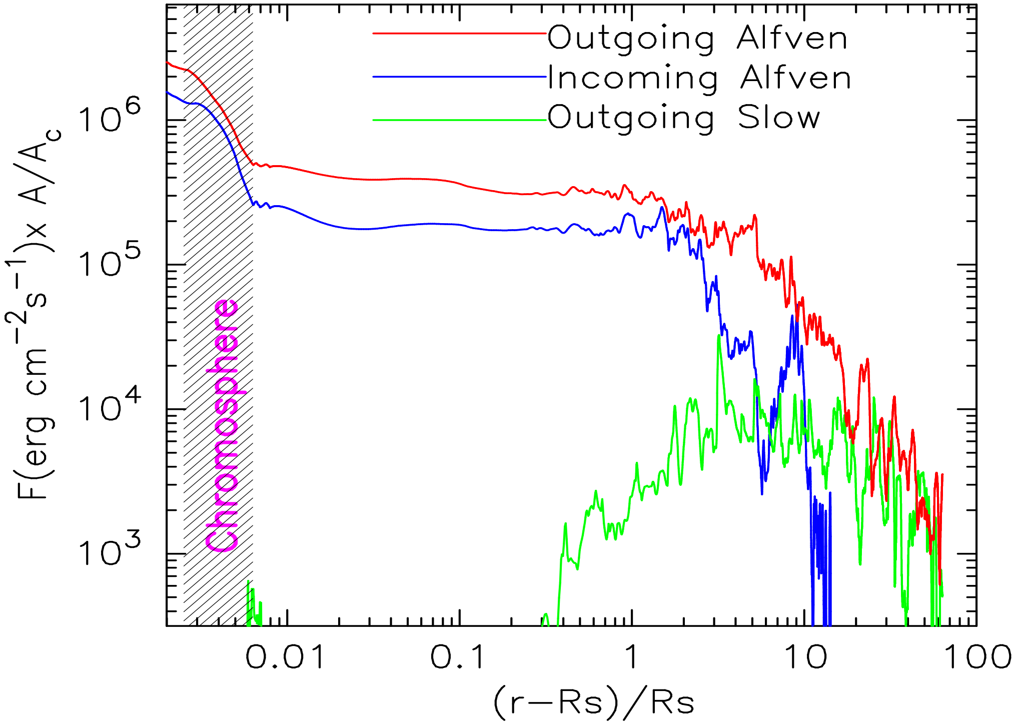
Wave Dissipation

(Normalized at 1.02Rs for Superradial Expansion of Flux Tube)



- Only <0.1% of the initial Energy Flux of Outgoing Alfven Waves Remains at 0.3AU

In Chromosphere & TR



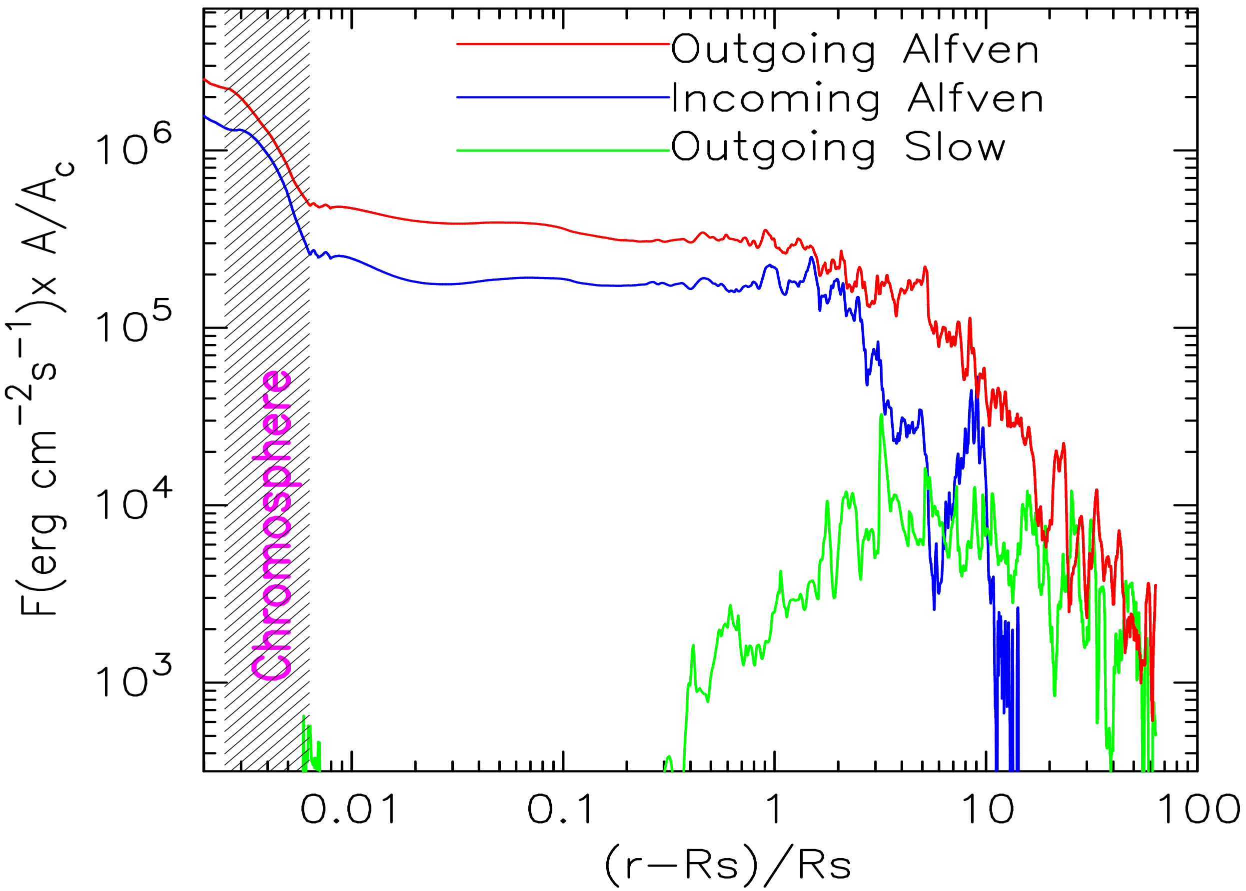
- 🟩 **Outgoing Alfven : reflected downward by rapid variation of Alfven speed. (due to stratification)** **Moore 1991**
- 🟩 **~15% of initial energy transmits into corona.**

c.f. Bogdan et al.2003; Cranmer & van Ballegooijen 2005

- 🟩 **But the transmitted flux (5x10^5 erg/cm^2/s) is sufficient for the coronal hole heating.**

Example (Wave Reflection)

In Corona & Solar Wind



- **A key process in dissipation of Alfven waves is excitation of MHD slow waves.**

(Kudoh & Shibata'99; Moriyasu et al.'04)

Coronal Heating / Wind Acceleration

Most Dominant Process in Dissipation of Outgoing Alfven Waves

- **Generation of MHD Slow (Sound) Waves**
  - **Variation of magnetic pressure, dB_perp, of Alfvenic fluctuations excite longitudinal motions.**

Slow Waves => (Steepen) => Slow Shocks

  - **Slow shock converts both magnetic and kinetic energy to heat.**

Energy & Momentum of Outgoing Alfven Wave

=> Slow Waves => Slow Shocks => Plasma

(Coronal Heating & Solar Wind Acceleration)

  - **Slow Waves are observed (Ofman, Nakariakov & Deforest 1999; Sakurai et al.2002)**
- **Density fluctuations(slow-mode) become Mirrors to reflect Alfven waves. (3-wave interaction; Goldstein 1978);**

Another dissipation mechanism (less dominant)

- **Fast Shock by steepening of Alfven Wave (linear pol.)**

Exmp.(Compressive Mode Generation)

Limitations of Our Simulations

Treatments of Chromosphere : Simplified

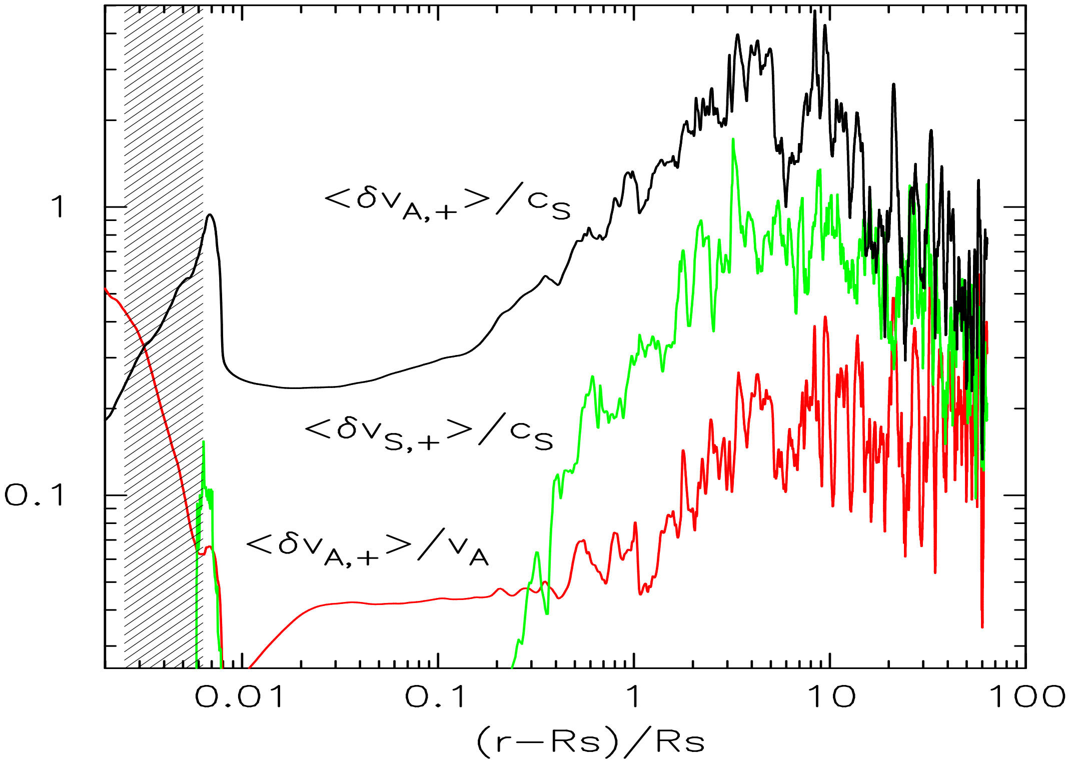
- Empirical radiative loss (No rad. transfer) c.f. Carlsson & Stein(2002)

1D & MHD Approximation?

- 🟩 **Multi-dimensional effects**
  - Turbulent cascade : Transverse Direction
    Goldreich & Sridhar 1995; Matthaeus et al 1999; Oughton et al.2001
  - Phase Mixing Heyvaerts & Priest 1983; Nakariakov et al.1998
  - Refraction (angle of B & k changes) : Fast mode
    Bogdan et al.2003
  - Interactions between field lines => Nano-Flares (Katsukawa & Tsuneta 2001);
    Wave Generation in the corona
    Axford & Mckenzie 1997; Miyagoshi et al.2005
- 🟩 **Kinetic/Collisionless effects**
  - Collisionless (Landau & Transit-Time) damping for fast/slow modes?
  - Ioncyclotron Resonance (left-handed Alfven)?
  - Conductive flux in collisionless plasma ?
  - Electron/Ion T's are different

We need to study these issues via Local Simulations

Amplitude



- **Alfvén Wave Nonlinearity,** $\frac{\langle \delta v_{\mathrm{A},+}\rangle}{v_{\mathrm{A}}} \lesssim 0.3$

More or Less Constant in Corona/SW

Constancy of the nonlinearly must be more or less robust even if other nonlinear processes operate.

Summary of Fiducial Case

Results:

- **’Forward’ simulation of nonlinear Alfven Waves naturally explains the observed corona and fast wind.**
- **Dissipation of Outgoing Alfven waves via Nonlinear Processes**
  - **=> Slow waves => Slow shocks**
  - **=> Incoming Alfven => wave-wave interaction**
  - **Nonlinearity dv/V_A < 0.3 (more or less constant)**
  - **(Caution)Our simulation has several limitations.**

From Next Page:

- **Photosphere <=> Corona/SW connection in various coronal hole properties**
- **Test Nonlinear Alfven wave scenario by SOT<=>EIS/XRT observation**

Variety & Observational Test

Obs of Alfven waves is difficult, so we need ideas.

Photosphere - Corona/SW connection ?

Input Parameters in Our Simulations

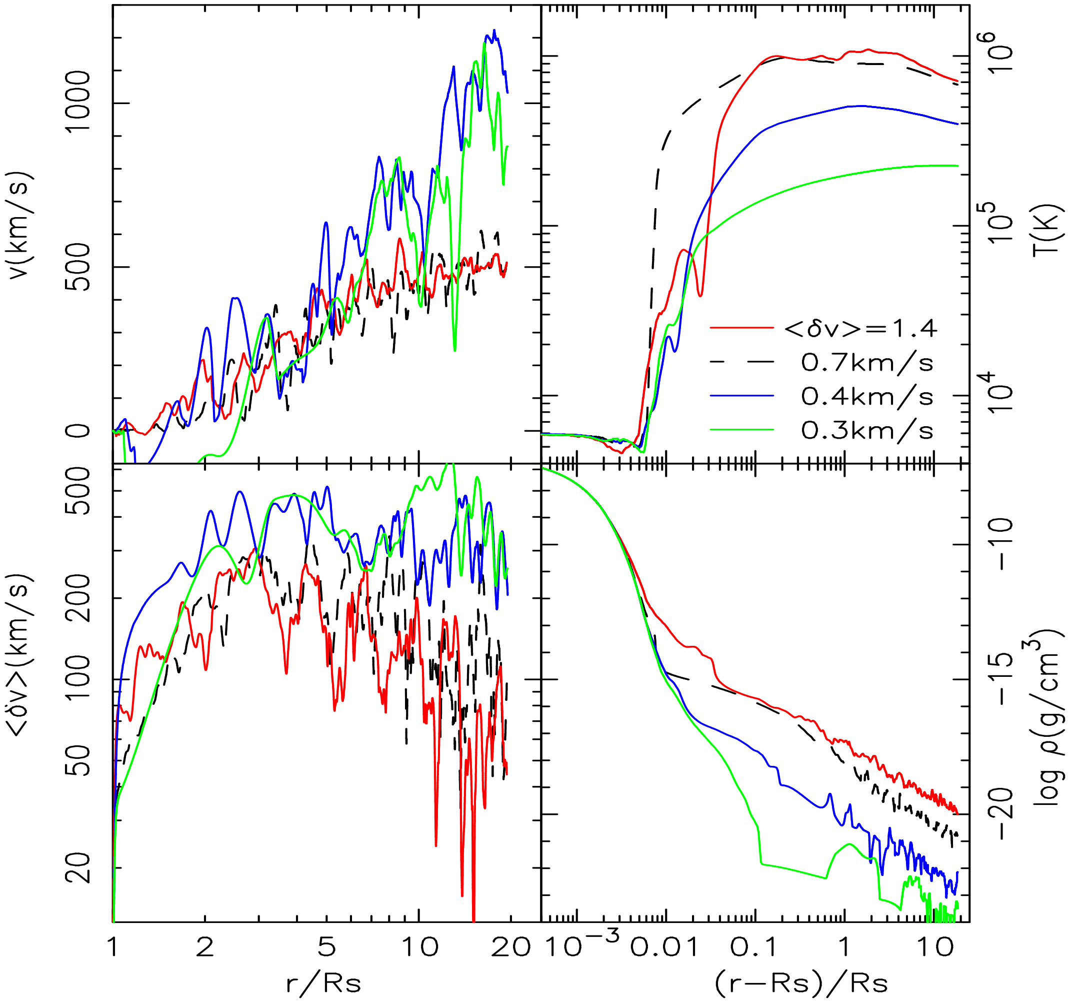
- **dv (photospheric fluctuations) <= SOT**
  - **Amplitude**
  - **(Spectrum & Polarization : weak dependence)**
- **B (photospheric strength) <= SOT**
- **f (flux tube expansion) <= 3D simulation**

Heating by Nonlinear Alfven Waves expects :

- **Larger Coronal Density <= Larger dv, Smaller B**
- **Larger Coronal Temperature <= Larger dv, Larger f**
- **Larger dv in SW <= Smaller dv, Larger B/f**
- **Faster Wind speed <= Larger B/f**

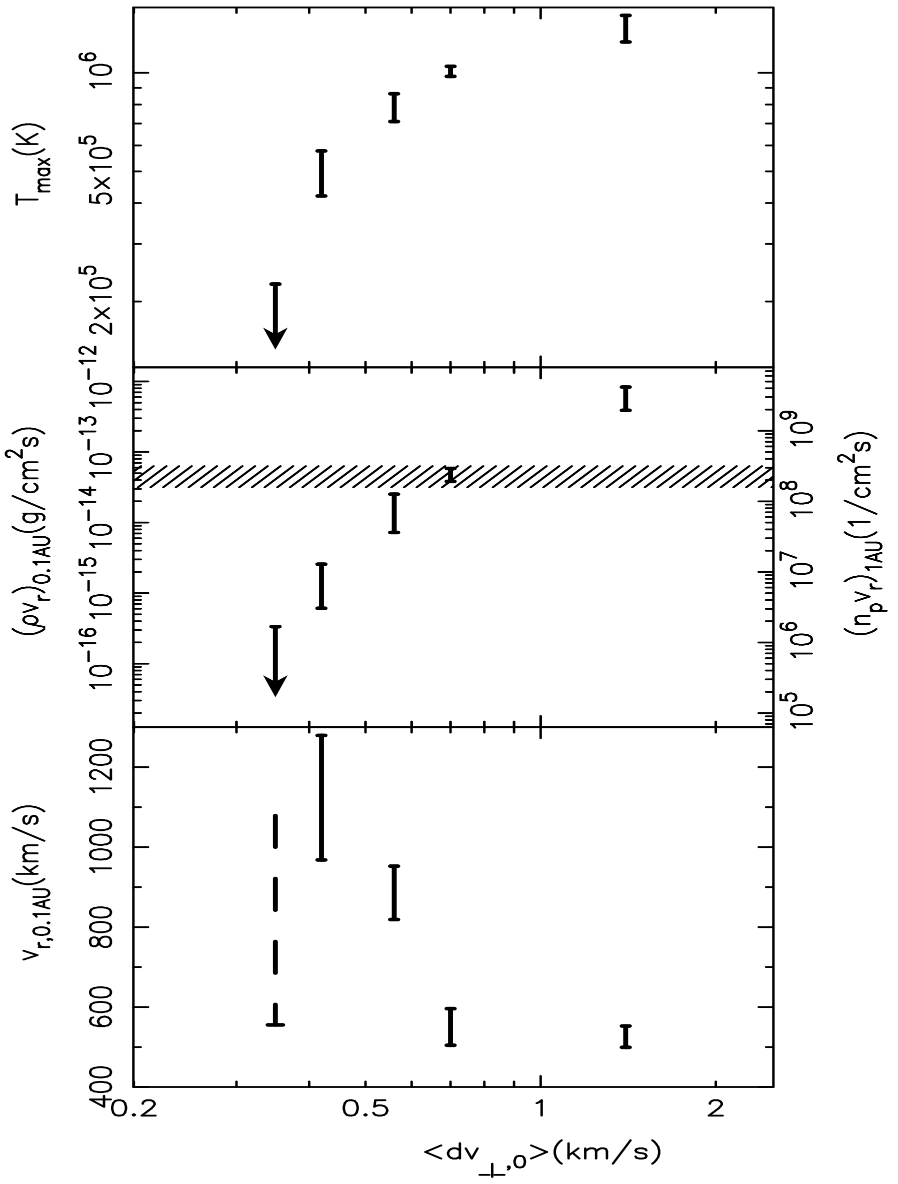
(LHS by EIS & XRT and RHS by SOT)

Dependence on dv



- **larger dv_surface => hotter & denser corona**
  => smaller dv_corona

Sensitive Dependence on dv



Interpretation of dv Dependence

- Coronal density, accordingly mass flux of SW, shows steep positive dependence on <dv>, because of an unstable behavior related to the Nonlinearity

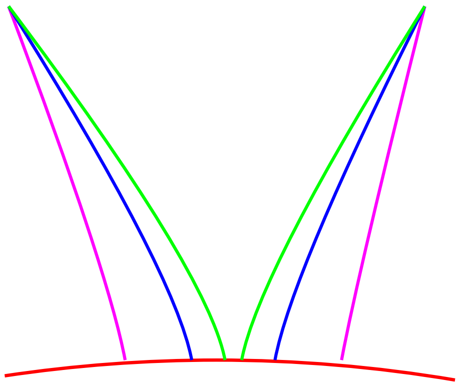
$$\textbf{Heating} \Downarrow \Rightarrow T \Downarrow \Rightarrow \textbf{Chromospheric Evaporation} \Downarrow \Rightarrow \rho \Downarrow$$
$$\Rightarrow v_{\rm A}(= B/\sqrt{4\pi\rho}) \Uparrow \Rightarrow \delta v/v_{\rm A}\textbf{(Nonlinearity)} \Downarrow \Rightarrow \textbf{Dissipation}\Downarrow$$
$$\Rightarrow \textbf{Heating} \Downarrow \ : \text{Catastrophe } \textbf{(Suzuki \& Inutsuka 2005b)}$$

  - If <dv> = 0.7km/s => 0.4km/s, Density => 1/100

    Disappearance of Solar Wind!!
  - On May 11, 1999, the observed solar wind density becomes < 0.1(/cm^3), in contrast to the usual value, 5(/cm^3)
  - (Note!) Observed wind speed is inconsistent with our result; stream interaction is important for this event. (Usmanov et al.2000)

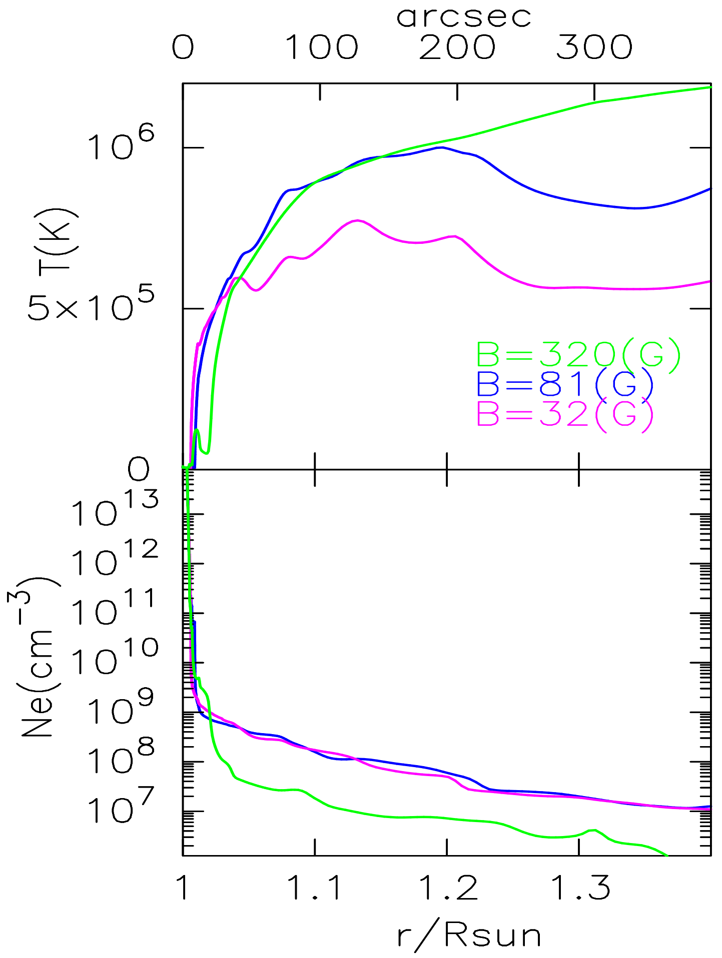
- Larger dv at Surface => Faster Dissipation
  => Smaller dv in Corona & SW
- Dependence of T on <dv> is gradual due to Conduction

Dependence on B



B(G)/f=32/15
B(G)/f=81/37.5
B(G)/f=320/150

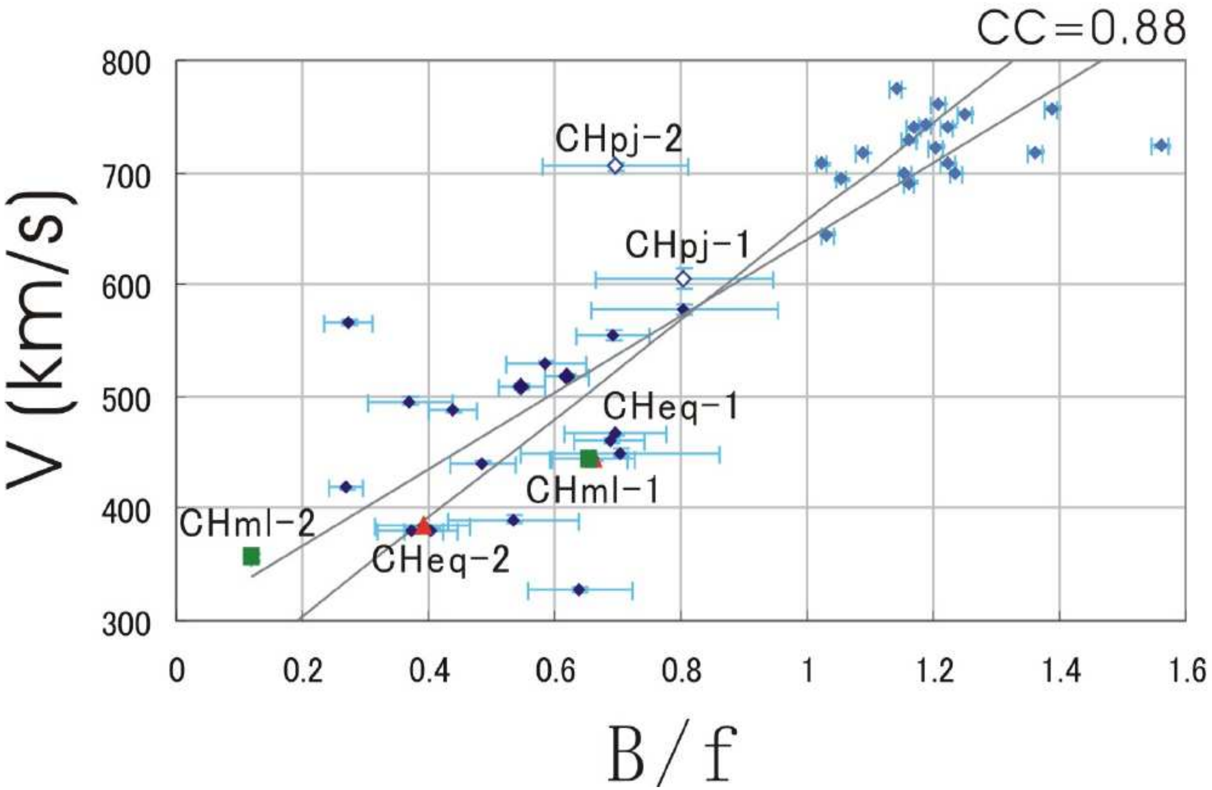
(B/f & dv = const.)

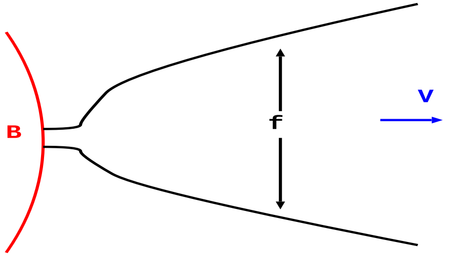


- **Smaller B => Larger dB/B => Heating in Inner Region**
  => Denser Corona (Coronal Base at Lower Altitude)
  - **Anticorrelation of B (by SOT) and DEM (by EIS)**

Wind Speed <=> B/f

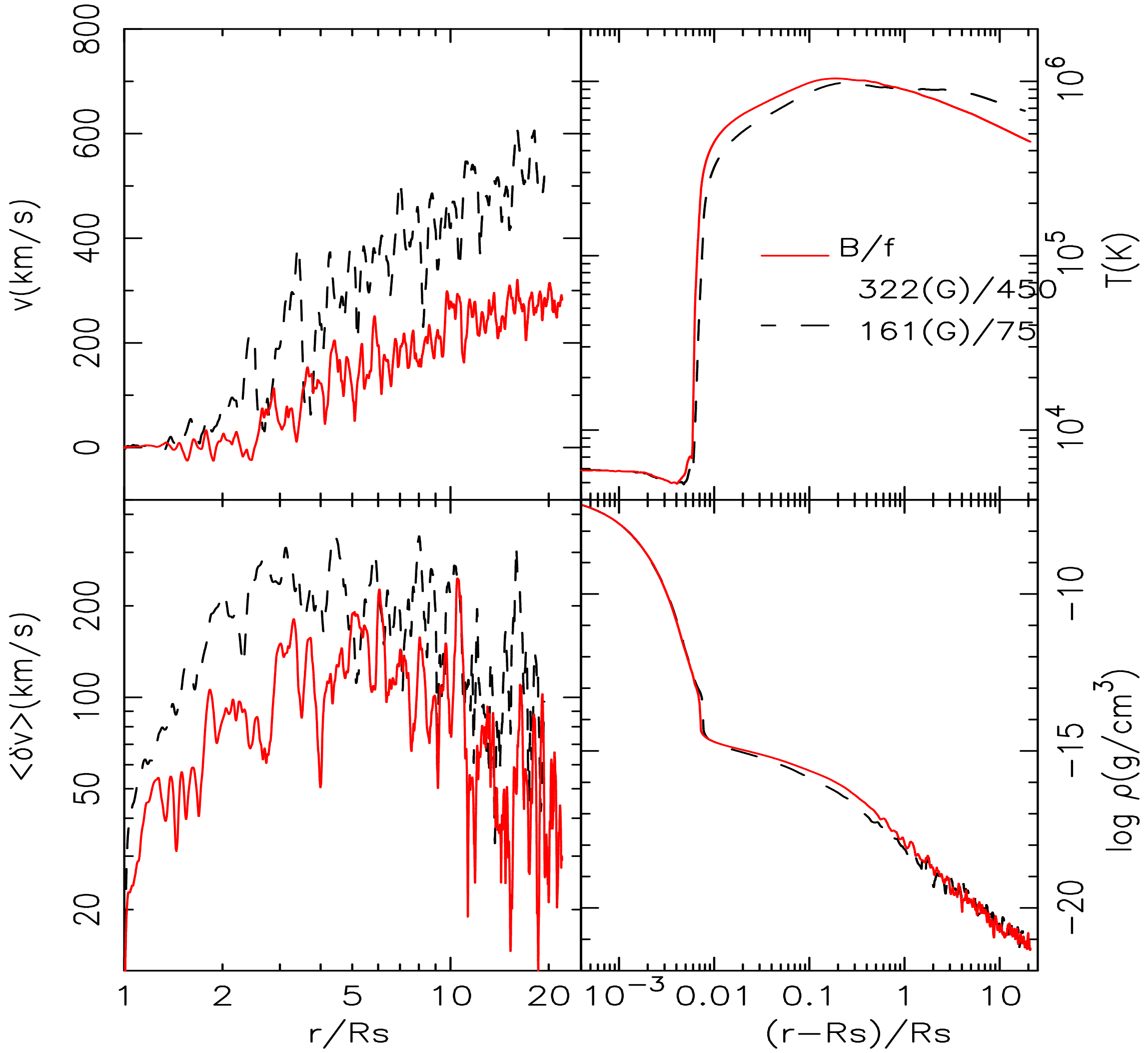
Hirano et al.2004; (Kojima et al.2005; Hakamada et al.(2005))





B/f : Best Control Parameter of Solar Wind Speed

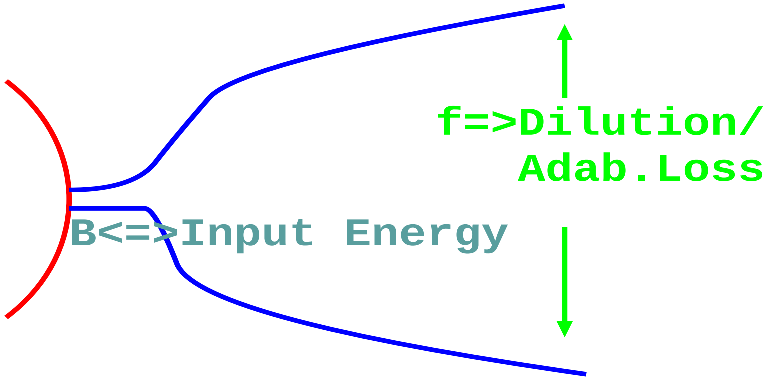
Dependence on B/f



- 🟩 **Larger B/f => Larger dv_corona & Faster Wind**

Interpretation of B/f Dependence

Simulation also gives V-B/f : Reasonable



With Respect to Dissipation Location

- Small B/f => Small B_corona => Large dB/B_corona
  - => Rapid Dissipation in subsonic region
  - => Slower Wind & Smaller dv in Corona

Wave => Thermal => Solar Wind (Thermal-driven Wind)

- Large B/f => Large B_corona => Small dB/B_corona
  - => Slow Dissipation in supersonic region
  - => Faster Wind & Larger dv in Corona

Wave => Solar Wind (Wave-Driven Wind)

Fast/Slow Winds

Dependence on B/f is closely related to Difference of Fast & Slow Winds.

Based on Parameter Study,

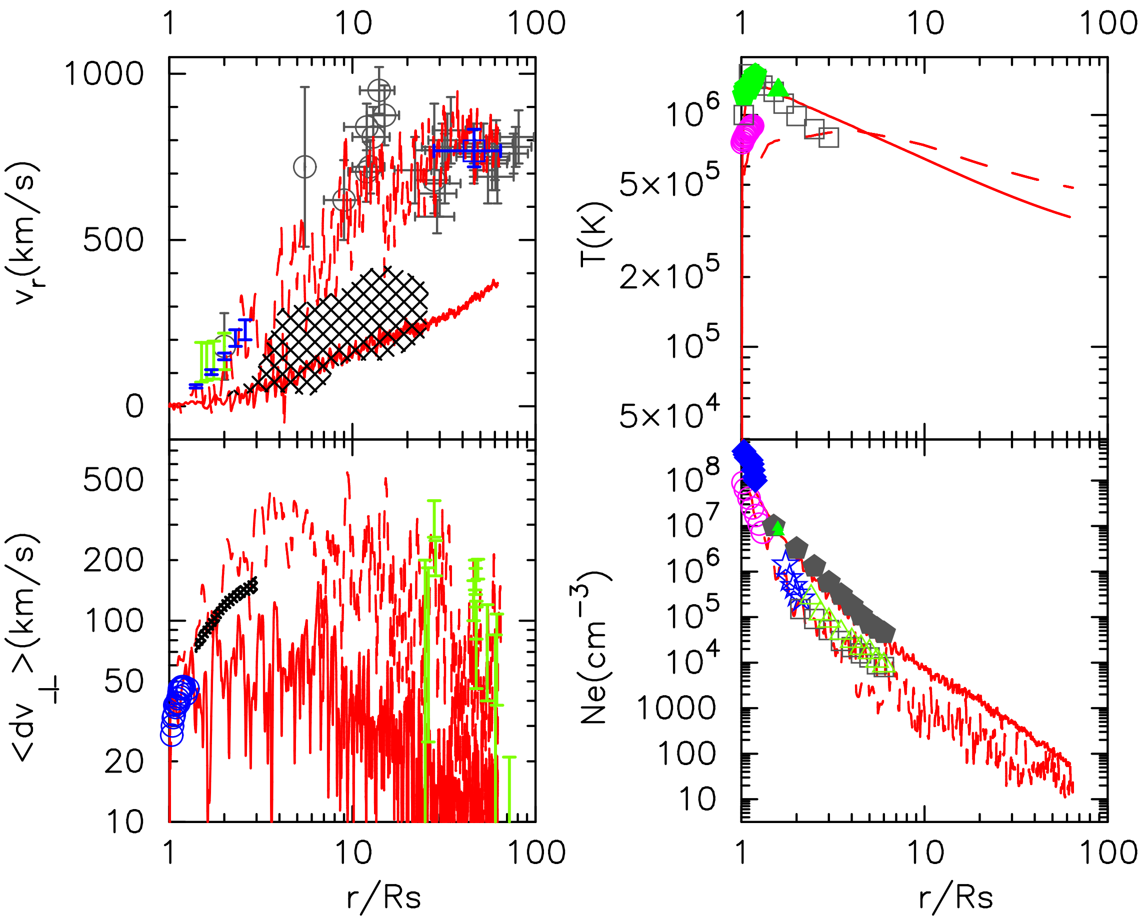
	dv	B/f
Fast Wind	small	large
Slow Wind	large	small

For Example,

- Fast Wind : dv=0.7km/s, B/f=161(G)/75 =2.1
- Slow Wind : dv=1km/s, B/f=322(G)/450 = 0.7

(Note!) We consider Slow Winds from (mid- to low-latitude) coronal holes. A different approach is necessary for slow winds from closed structure (e.g. Helmet Streamer).

Fast/Slow Winds



(Slow Wind Data : Sheeley et al.1997; Parenti et al.2000; Hayes et al.2001)

- **Anti-Correlation of Coronal T and Wind Speed**

  (Geiss et al.1995; Schwadron & McComas 2003; McIntosh & Leamon 2005)

- **Larger Alfvenic Amplitude in Fast Wind** **(e.g.Tsurutani et al.2005)**

Photosphere-Corona/SW connection and Solar-B Obs.

- Coronal Density <=> photospheric dv(positive),
  photospheric B(negative)
  - Interplume/Plume
  - Larger B : Interplume / Smaller B : Plume

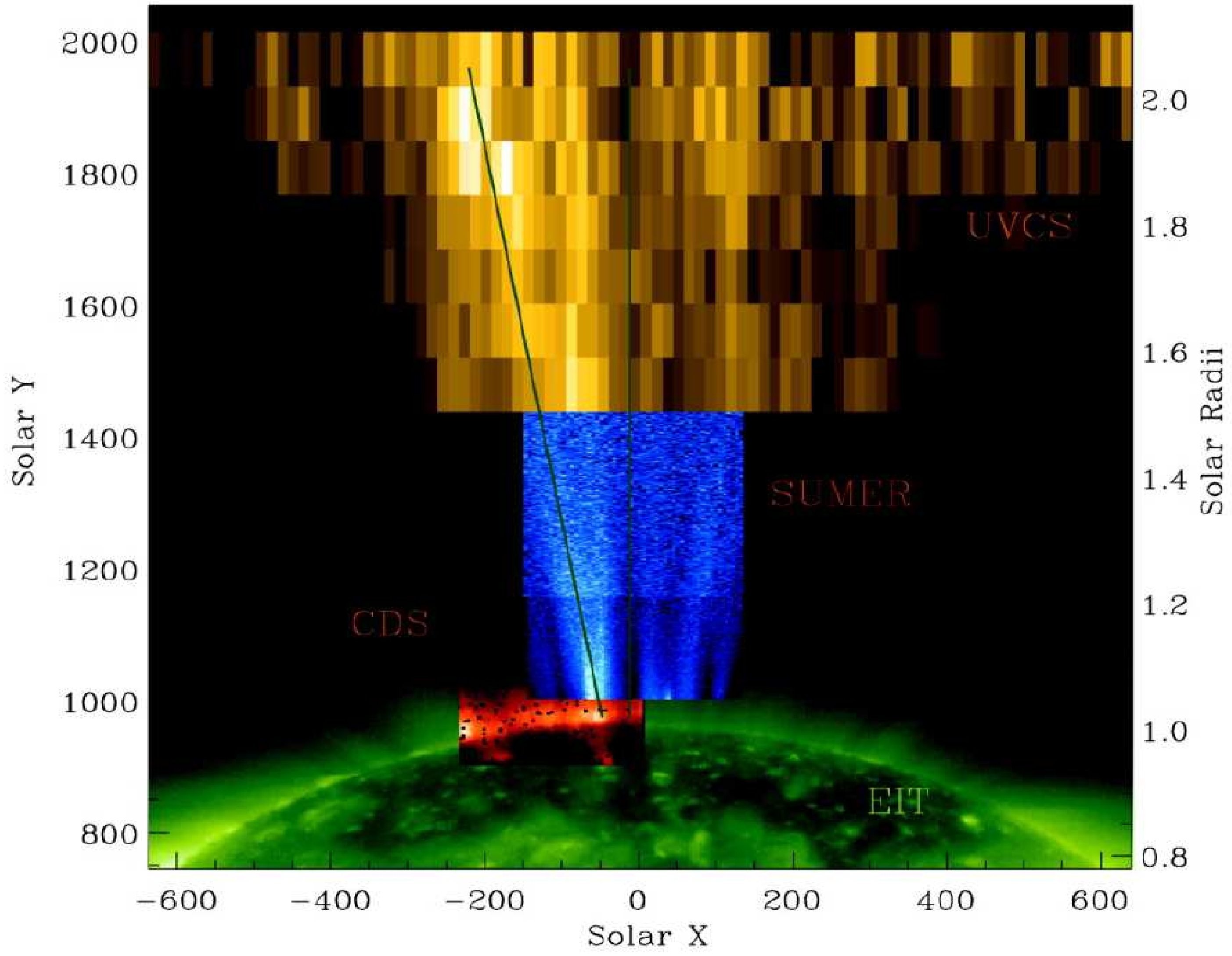
Teriaca et al.(2003); Gabriel et al.(2003)

- Coronal Temeprature <=> photospheric dv(positive)

- dv in Corona/SW <=> photospheric dv(negative),
  B/f(positive)
  - Photospheric B,dv in various regions
    <=> dv (nonthermal broad.) in Corona/SW
  - Nonthermal broadening may be observed from grand (e.g.Norikura)

- SW speed <=> B/f(positive)
  - Photospheric B <=> Wind speed by Interplanetary Scintillation / Satellites

Plume/Interplume



Teriaca et al.2003

Discussions

We have assumed injection of fluctuations with constant dv from the photosphere in flux tubes with fixed B & f.

But they change in time.

- **Change of dv**
  - **Transition Region moves (dynamically) by condensation/evaporation**
  - **New steady state after a few times of Alfven time**
- **Change of B (and accordingly, f)**
  - **Need Multi-Dim. Treatment**
- **Waves generated at higher altitude by e.g. Reconnection Events**
  - **Avoid attenuation through chromospheric propagation**
  - **Effect : increase of dv in our simulation**

Summary

Our 1D MHD simulations covering from photosphere to 0.3AU show :

- **Corona and transonic solar wind are natural consequence of the photospheric fluctuations of B-field, provided <dv>~>0.5km/s.**
  - **Dissipation of nonlinear low-frequency Alfven waves is important**
- **If <dv> becomes half, the solar wind disappears.**

Heating by Nonlinear Alfven Waves expects :

(Some Relations are Unique for Nonlinear Alfven Waves)

- **Larger Coronal Density <= Larger dv, Smaller B**
- **Larger Coronal Temperature <= Larger dv, Larger f**
- **Larger dv in SW <= Smaller dv, Larger B/f**
- **Faster Wind speed <= Larger B/f**

(LHS by EIS & XRT and RHS by SOT)