Structured Red Giant Winds with Magnetized Hot Bubbles and the Corona/Cool-Wind Dividing Line

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Introduction

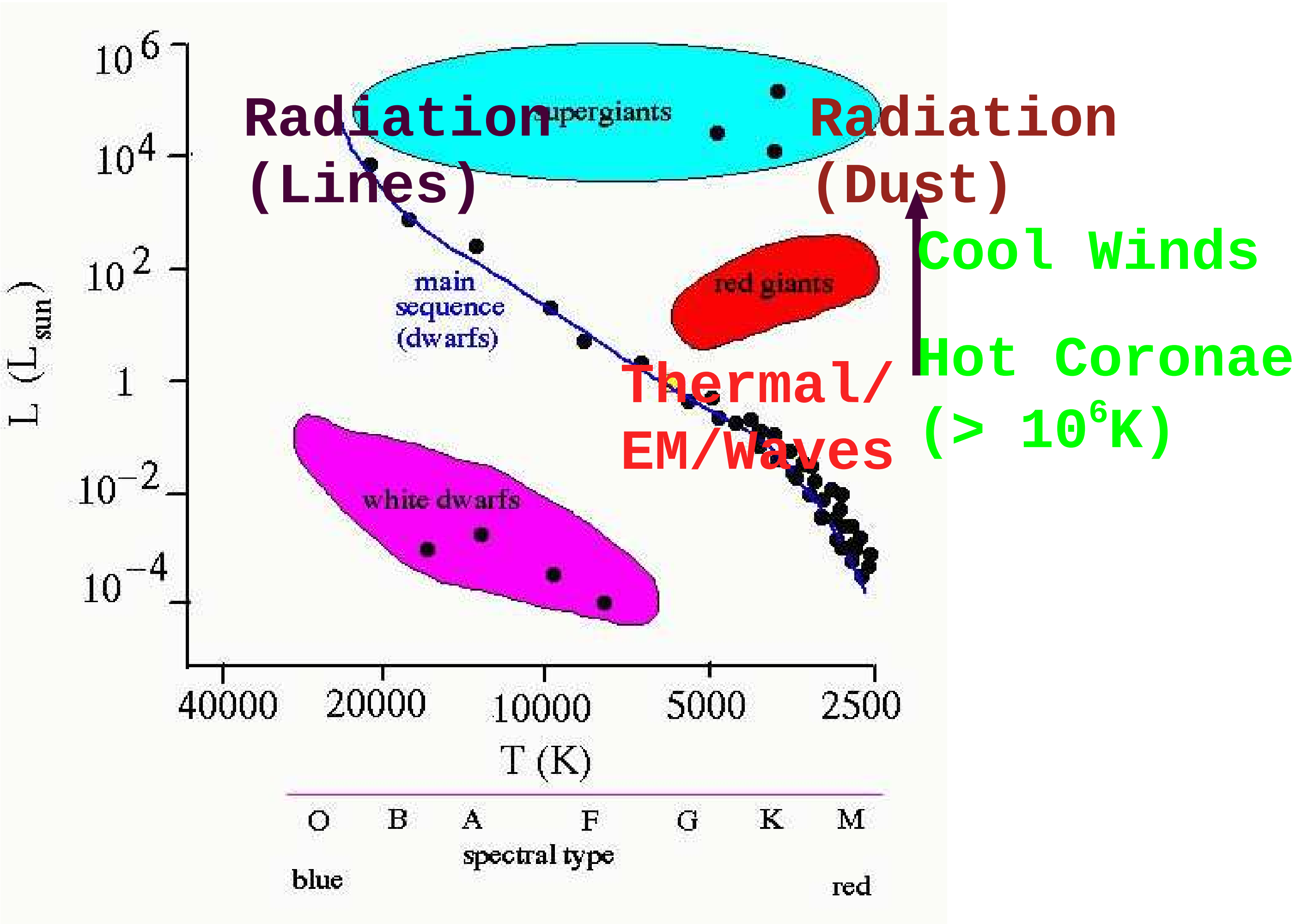
Why Mass Loss / Stellar Wind ?

- **All stars are losing their masses.**

- **Control Stellar Evolution at Later Epochs**
  - **~ Half of initial mass lost before Planetary Nebulae/Supernovae**
  - **Low- Intermediate Stars : Evolution to ‘‘Unusual’’ Stars**
    (Blue Horizontal Branch Stars; Yi et al. 1997)

- **Winds Affect Environments**
  - **Sun => Earth; Space Weather**
  - **Proto-Star Winds => Planetary Formation**

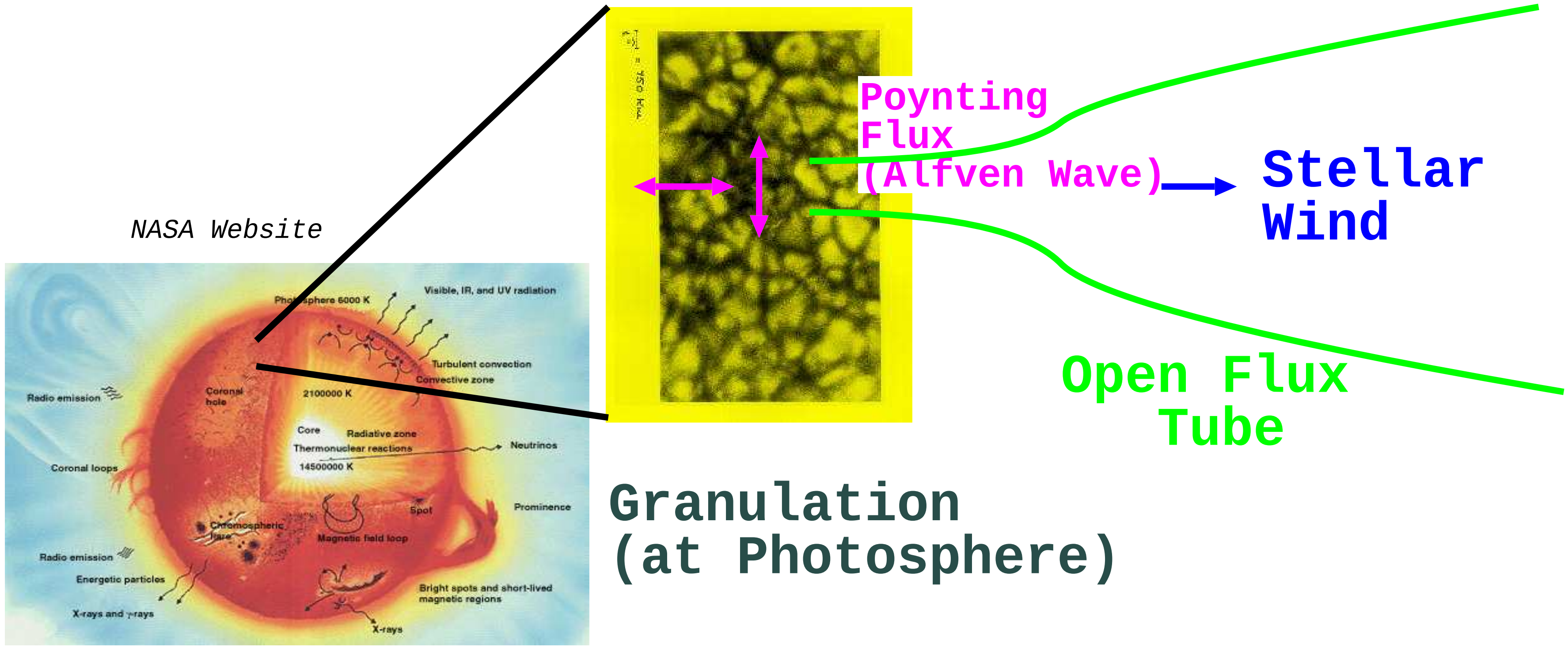
Stellar Winds in HR diagram



Today's talk : Main Sequence & Red Giant Stars with Low & Intermediate Mass

- **Turbulent/Wave Driven Winds**

Global Energy Transfer

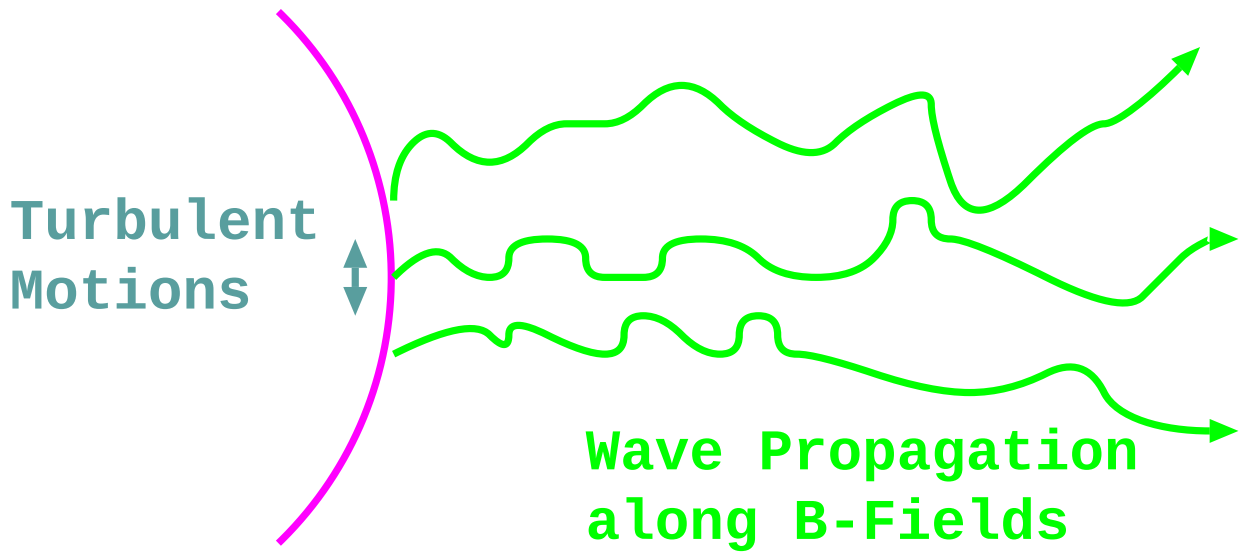


Nuclear Reaction at the Center

- **=> Radiation & Neutrino**
- **=> Surface Convection => Stellar Wind**

Alfven Waves in Open Field Regions

Wave-Driven Winds



- Turbulent motions excite various modes of MHD (precisely plasma) waves
- Alfven Wave is most appropriate
  - (Almost) No steepening => less dissipative => propagate a longer distance
  - (Compressive waves dissipate too quickly)
- Dissipation of Alfven waves

  => Heat and accelerate atmosphere

Outline

1D MHD simulations of Alfven wave-driven stellar winds

- **Solar Corona/Wind**
  - **The sun is a ''reference'' to various stars**

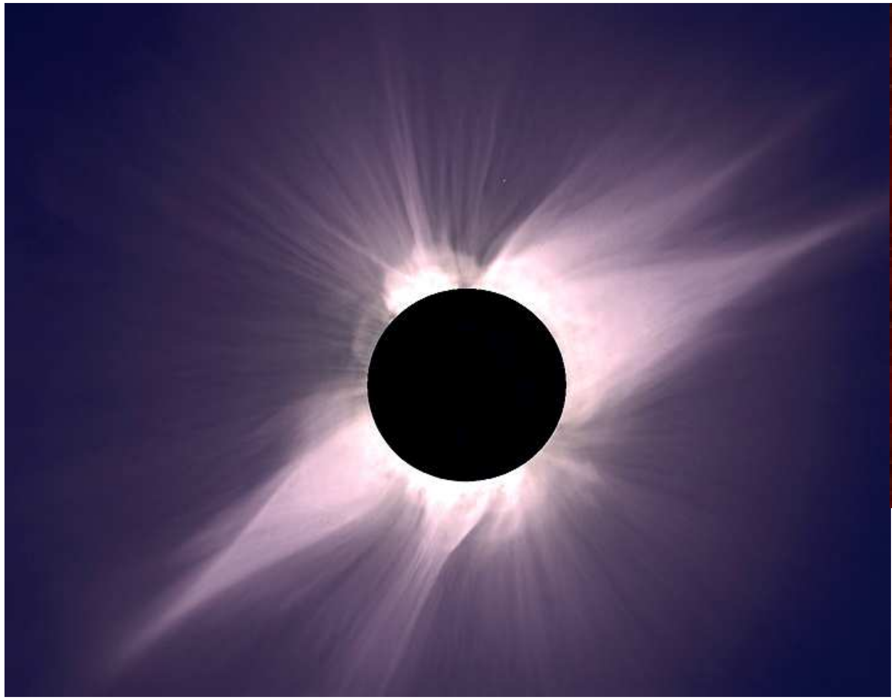
    Suzuki & Inutsuka 2005, ApJ, 632, L49; 2006 J. Geophys. Res. 111, A06101;
    Suzuki 2006, ApJ, 640, L75

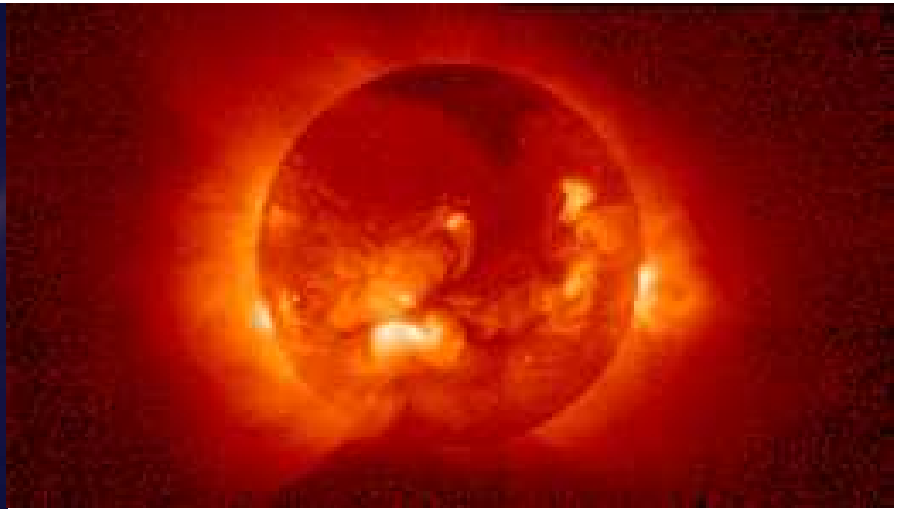
- **Red Giant Winds**
  - **Evolution of stellar winds from Main Sequence to Red Giant**
  - **Disappearance of Steady Corona and Onset of Massive Cool Wind**

    Suzuki 2006, ApJ, submitted (astro-ph/0608195)

Solar Corona & Wind

Jul.11th, 1991 Full Eclipse in Hawaii(NASA & ESA); YOHKOH





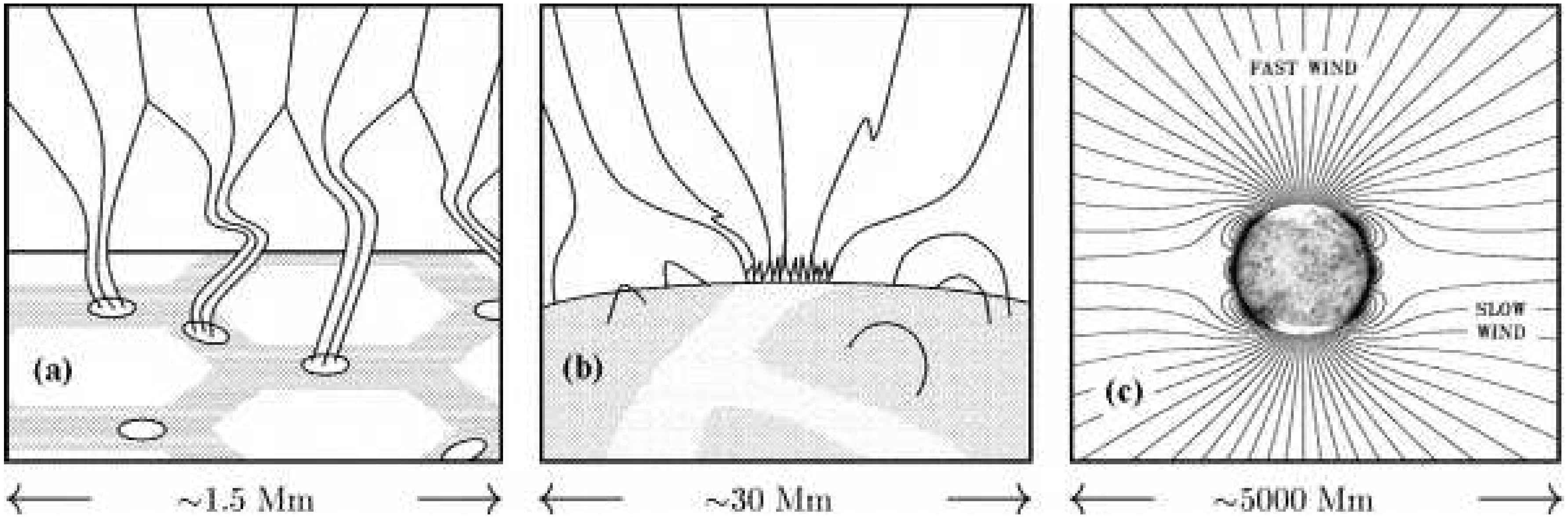
- Photosphere(Surface) : 6000K
- Corona : 1M(10^6)K

  How to Heat up ?
- Hot plasma streams out from the corona (Solar Wind).

Energetics

Turbulence => B-field Fluctuations => Upgoing Waves
=> Heating & Acceleration (bulk flow)

Cranmer & van Ballegooijen 2005

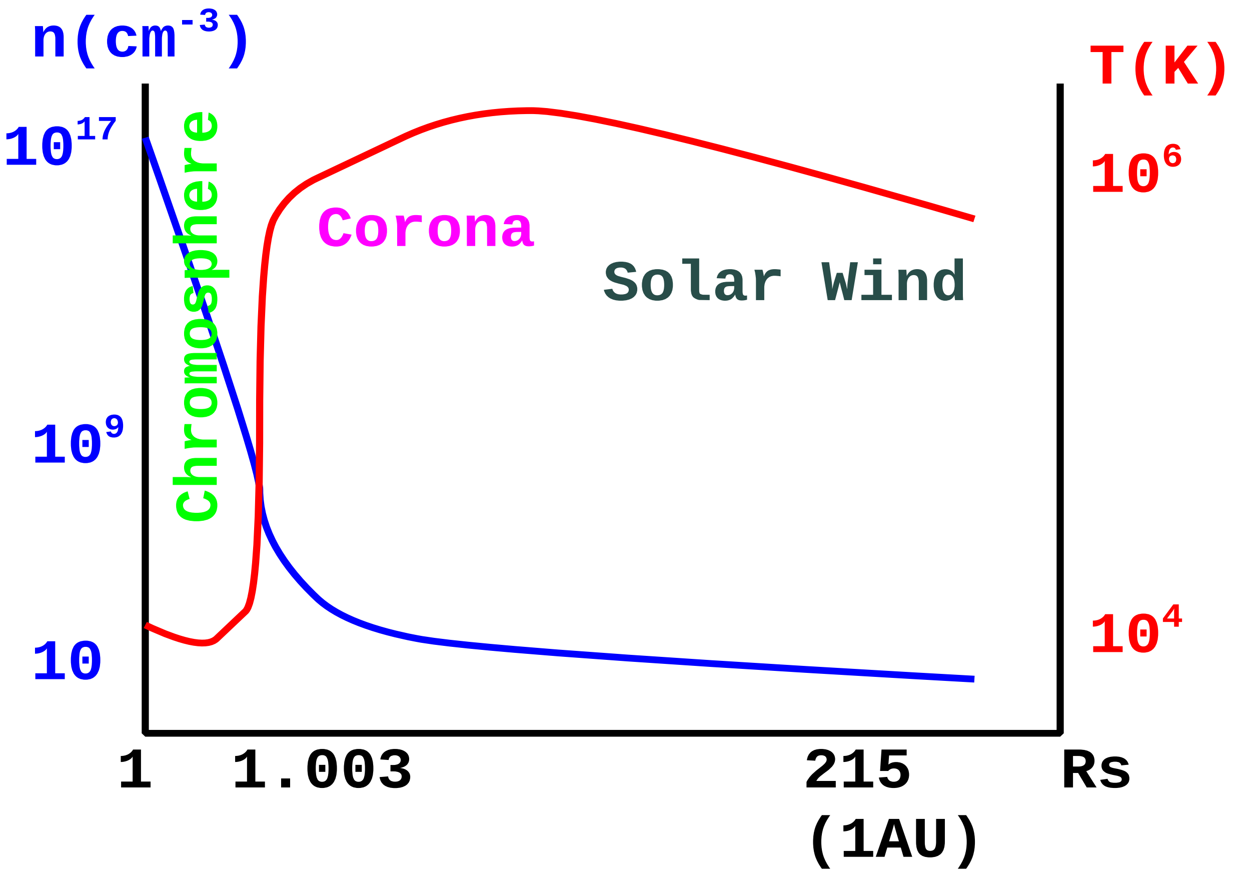


Turbulent Energy Flux :

$$\sim 10^8 \mathbf{erg\ cm^{-2} s^{-1}} \left(\frac{\rho}{10^{-7}\mathrm{gcm^{-3}}}\right)\left(\frac{\delta v}{1\mathrm{km/s}}\right)^3 \gtrsim 100 \textbf{ times of required}$$

- **Energetics : Non-problematic**
- **Main difficulty : How to lift-up the energy and let it dissipate at appropriate location in the stratified atmosphere**

Huge Density Gap



Gravity (Stratified Atmosphere) plays an essential role.

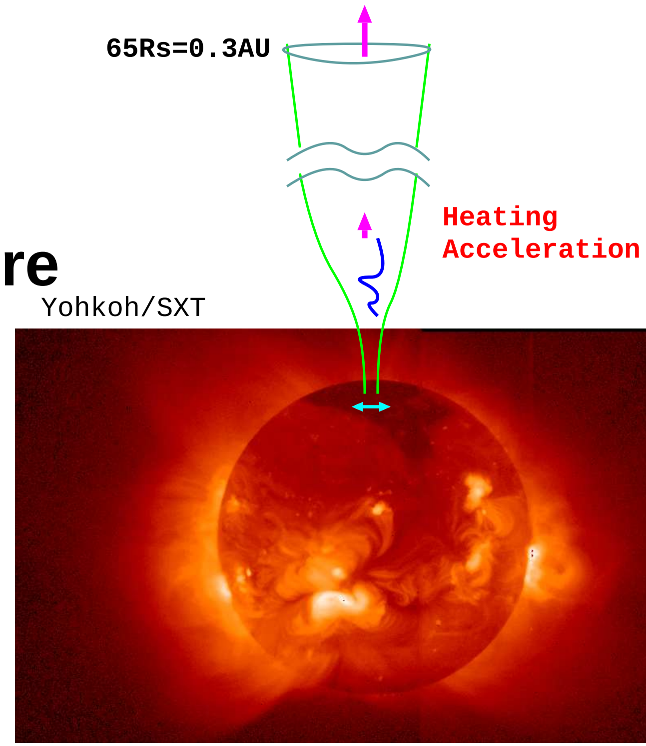
- **Alfven Waves (~5 min) : Nonlinear & Non-WKB**
  - **Amplification of amplitude** $(\textbf{If } \rho\delta v^2 v_{\rm A} \textbf{ conserves} \Rightarrow \delta v \Uparrow \textbf{ for } \rho \Downarrow)$
  - **deformation of shape** $(\lambda > v_{\rm A}(dv_{\rm A}/dr)^{-1})$

No work treats the entire region even in 1D

Simulation of Solar Wind

Solve Global Energy Transfer as self-consistent as possible

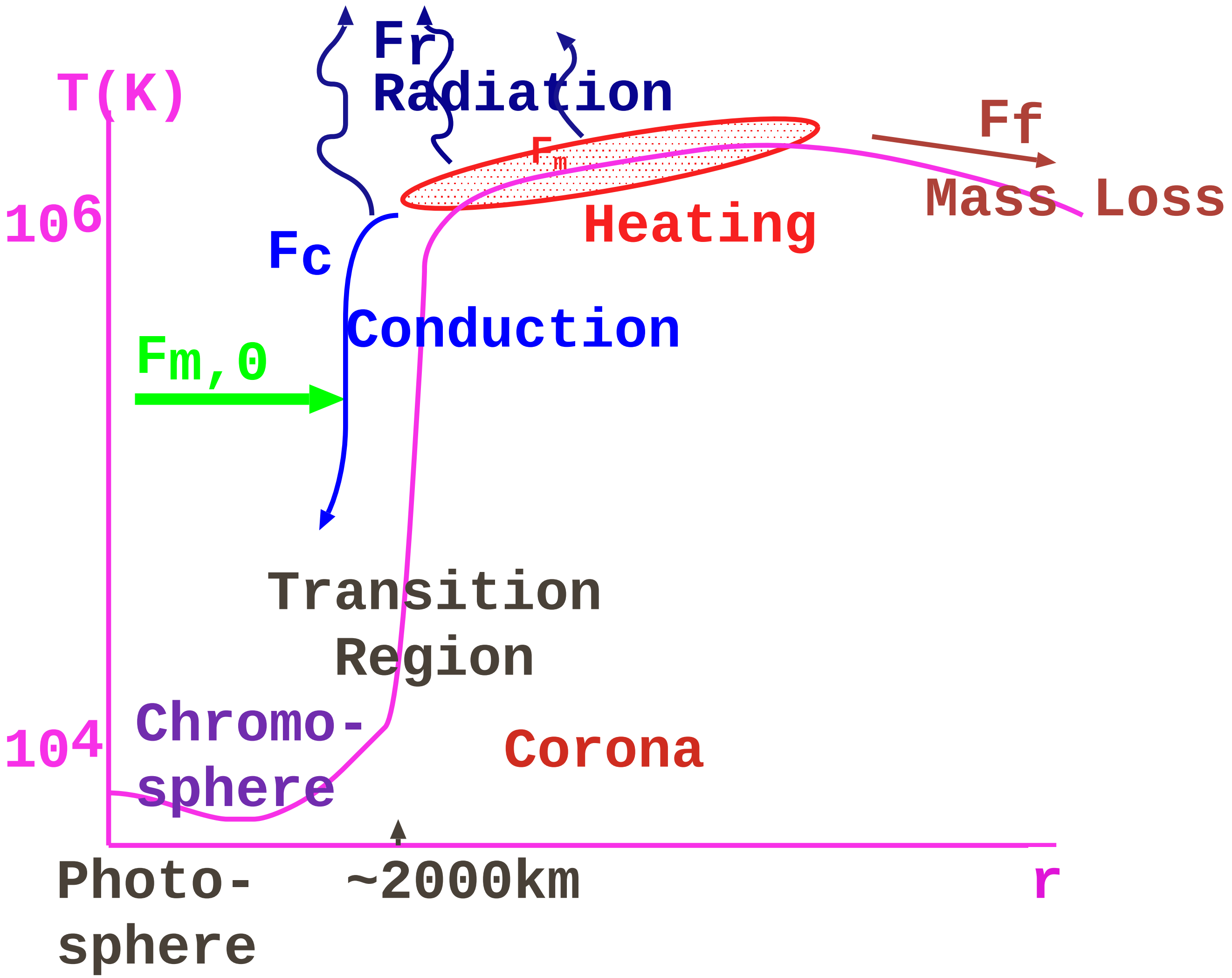
- **Calculation Region : Photosphere - 0.3AU**
  - 15 orders of mag. density difference
  - Super-radial expansion of flux tube
  - Outgoing Boundary Condition
- **Inject Fluctuations with 1km/s from Photosphere**
  - Spectrum : 1/f around 5 min.
- **Time-dependent MHD with Radiative Cooling and Conduction**
  - Realistic Chromosphere/Transition Region/Low Corona
  - For Nonlinear and Non-WKB waves



But, Need Compromise

- **1D & 1 Fluid**
  - 2D/3D or kinetic treatments are impossible (CPU/Memory resources)
- **Only Low-Freq. (<0.1Hz) Alfven Waves by ~minutes Oscillation**
  - NO transverse cascade and Ioncyclotron waves

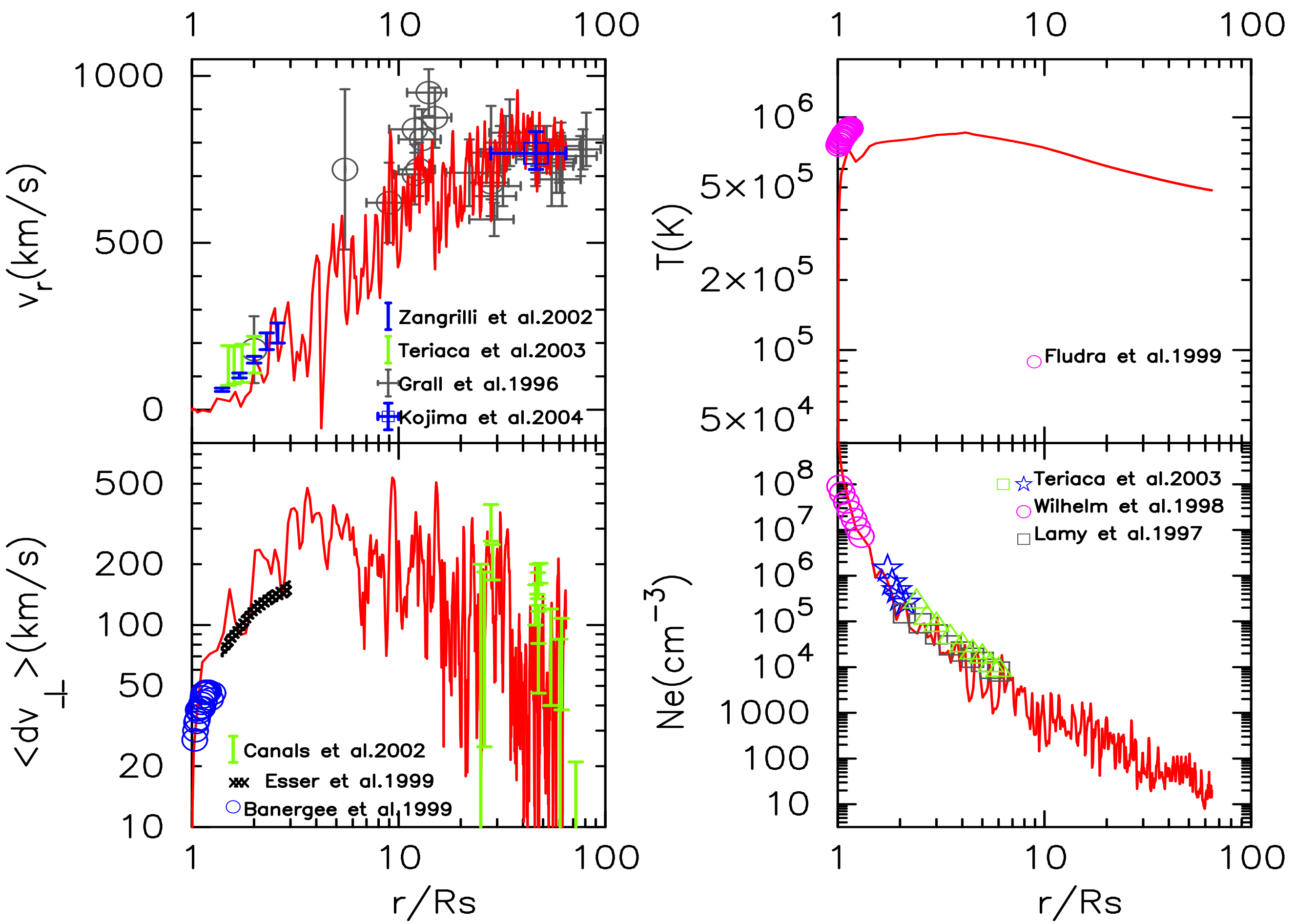
Chromosphere/Transition Region/Corona



We use Spitzer Conduction : $F = \kappa_0 T^{5/2} \frac{dT}{dr}$ (erg cm^{-2}s^{-1})

Comparison with Observations

Suzuki & Inutsuka 2005, ApJ, 632, L49



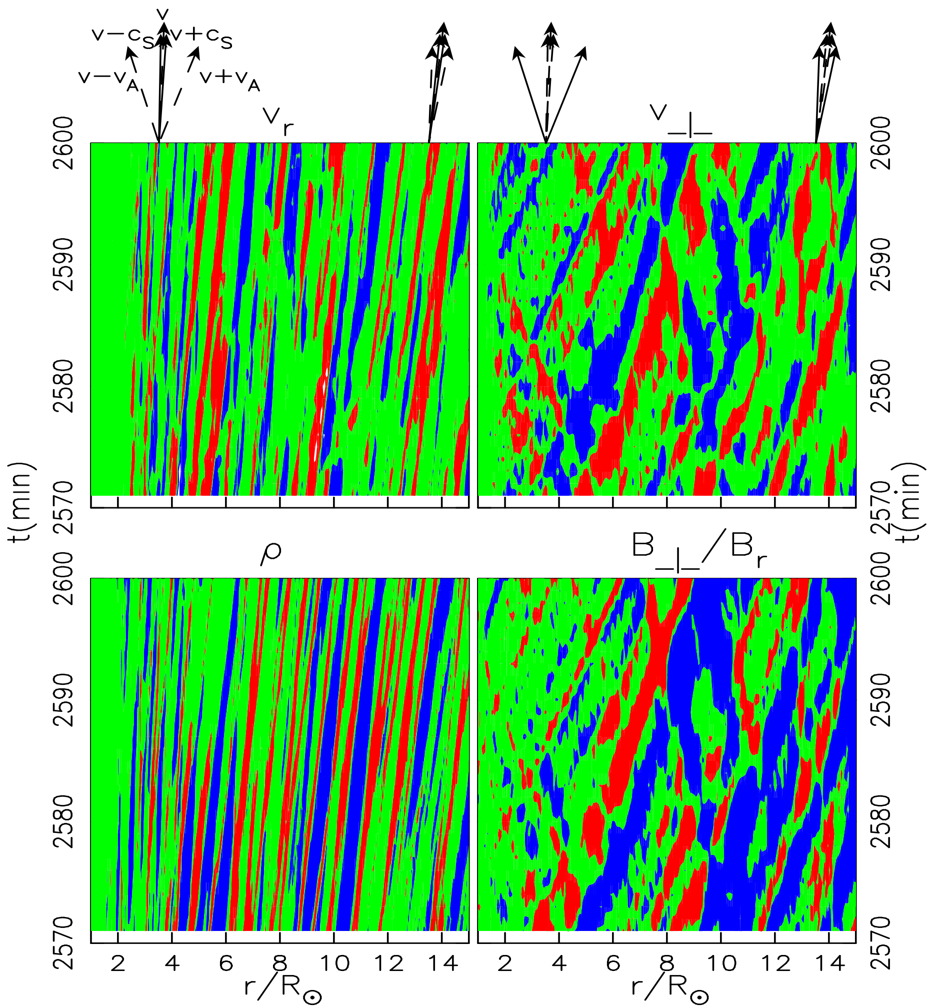
Observations

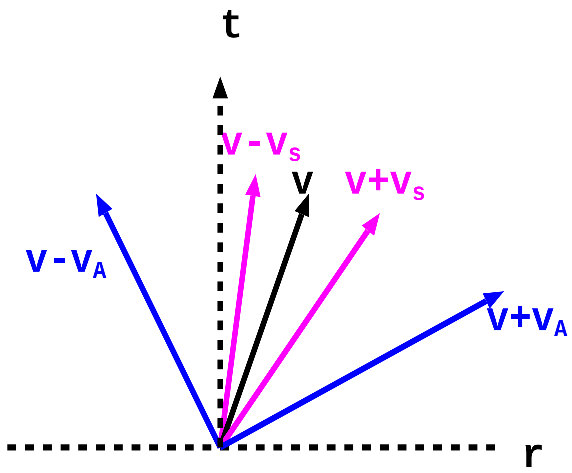
- (r<6Rsun) : SoHO(CDS/UVCS/SUMER/LASCO)
- (r>8Rsun) : Inter-Planetary Scintillation (Nagoya-STE;EISCAT)

"Forward Simulation" naturally explains obs. corona/SW.

Time-Distance Diagram (contour)

Suzuki & Inutsuka 2006, J. Geophys. Res., 111, A06101





(Alfven)*2+(Slow)*2+(Entropy)

(Fast & Alfven degenerate)

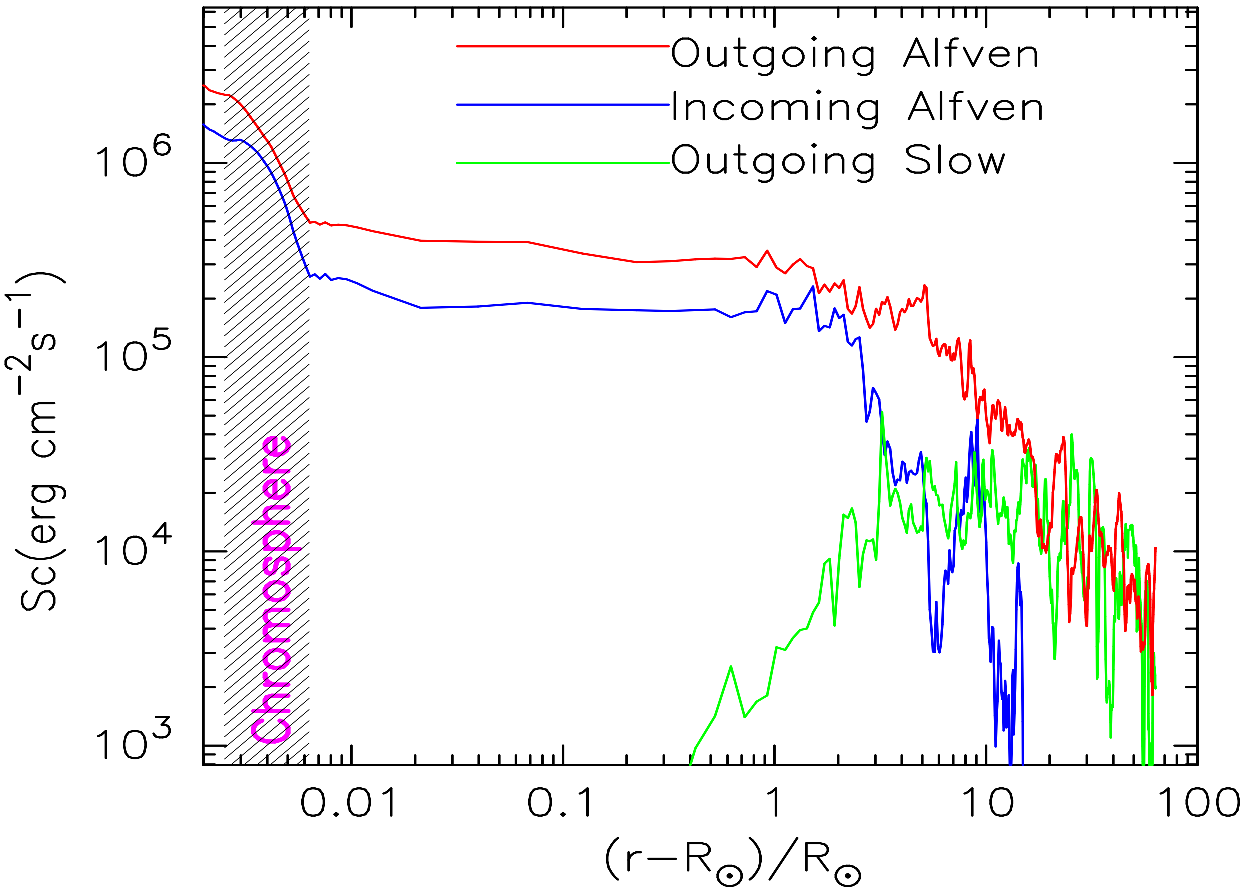
(see Cho & Lazarian 2002; 2003 for more general cases)

- **In B_perp & v_perp, Not only outgoing but incoming Alfven waves**
- **In rho & v_r, slow MHD (~sound) waves**

Dissipation of Waves

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

Suzuki & Inutsuka 2005, ApJ, 632, L49



- **Only ~ 0.1% of the initial energy remains at 0.3AU**
- **85% is reflected back before reaching corona.**
- **15% => Coronal Heating & SW acceleration**

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.**

Kudoh & Shibata 1999; Moriyasu et al.2004

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)

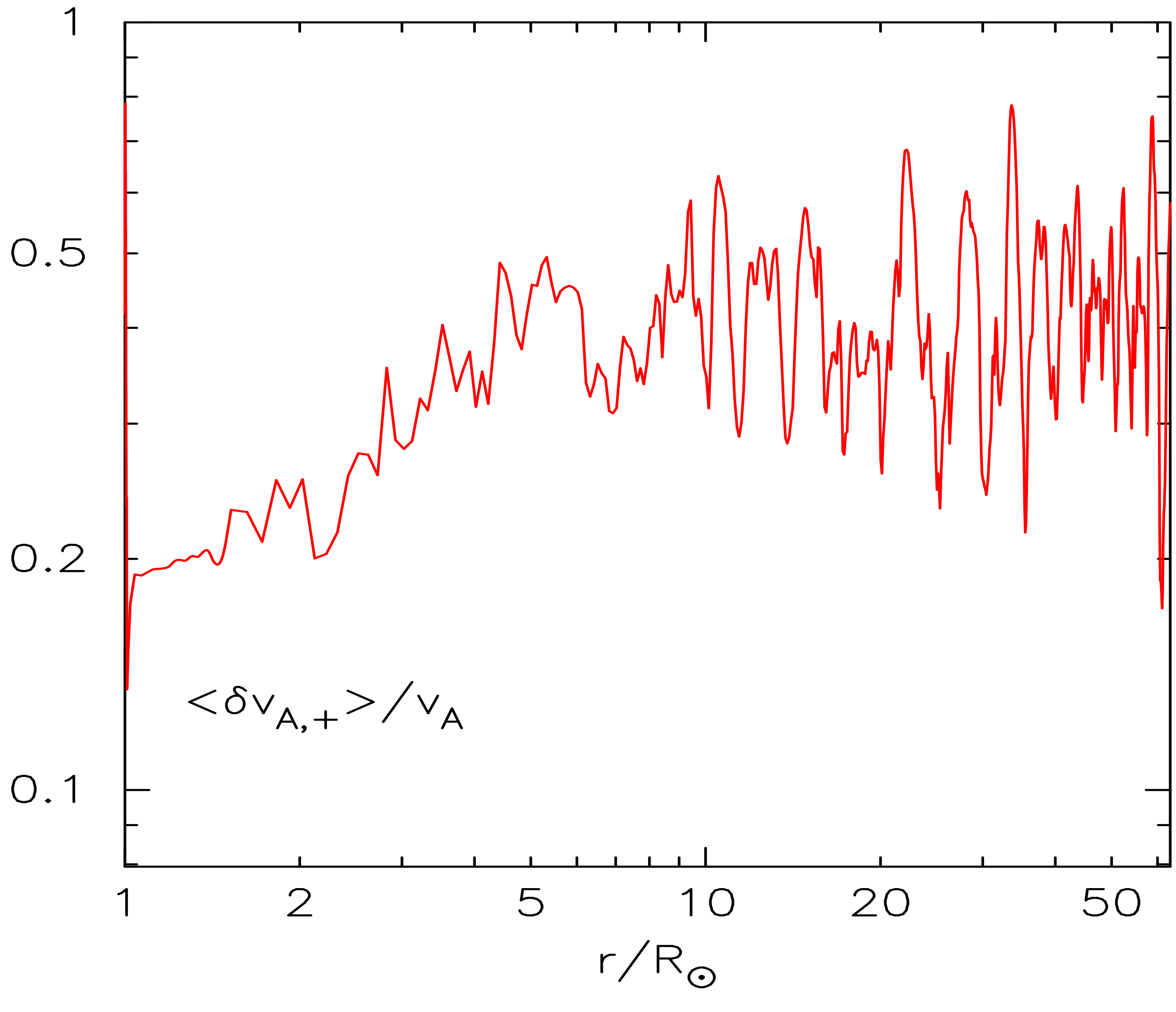
- **Density fluctuations(slow-mode) become Mirrors to reflect Alfven waves.**

Decay Instability by three-wave interaction

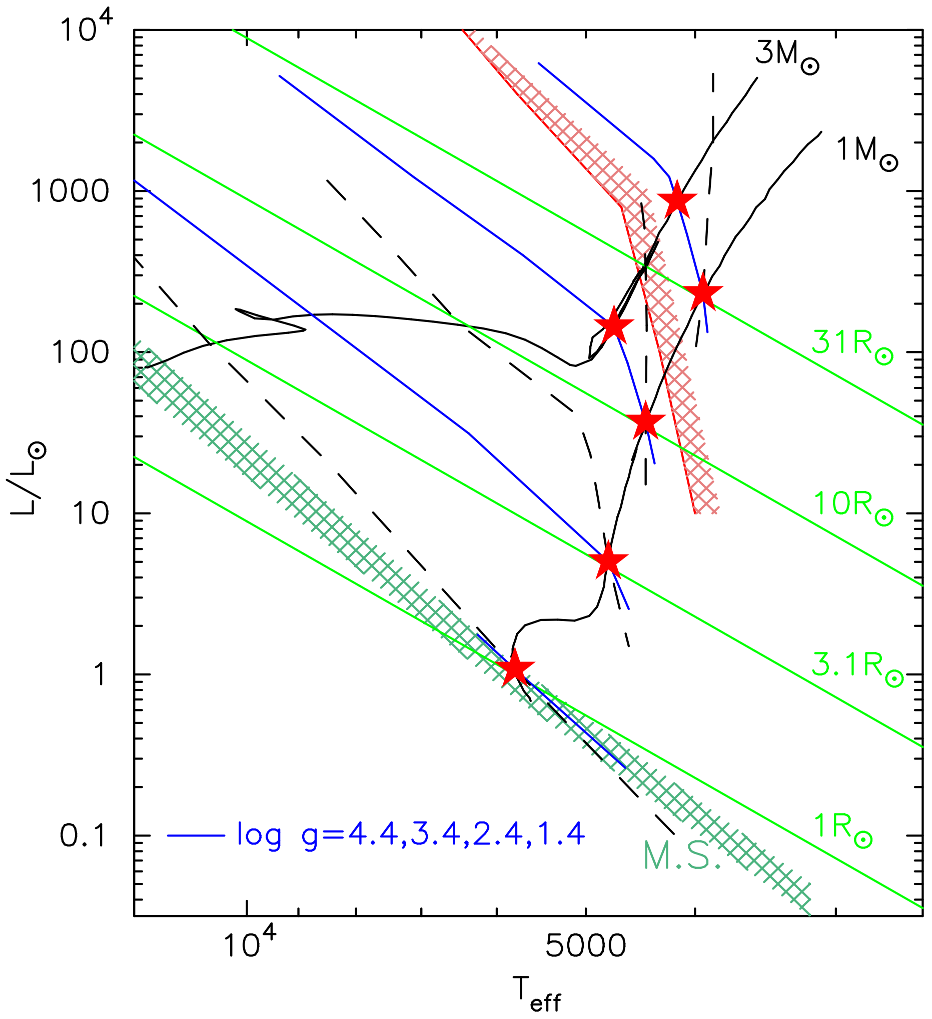
  - **(outgoing Alfven => incoming Alfven + outgoing slow MHD)**

Goldstein 1978; Terasawa et al. 1986

Nonlinearity



Red Giant Winds



From Main Sequence to Red Giant

- **Disappearance of Steady Corona & Onset of Massive Winds**
- **Wind becomes highly time-dependent**

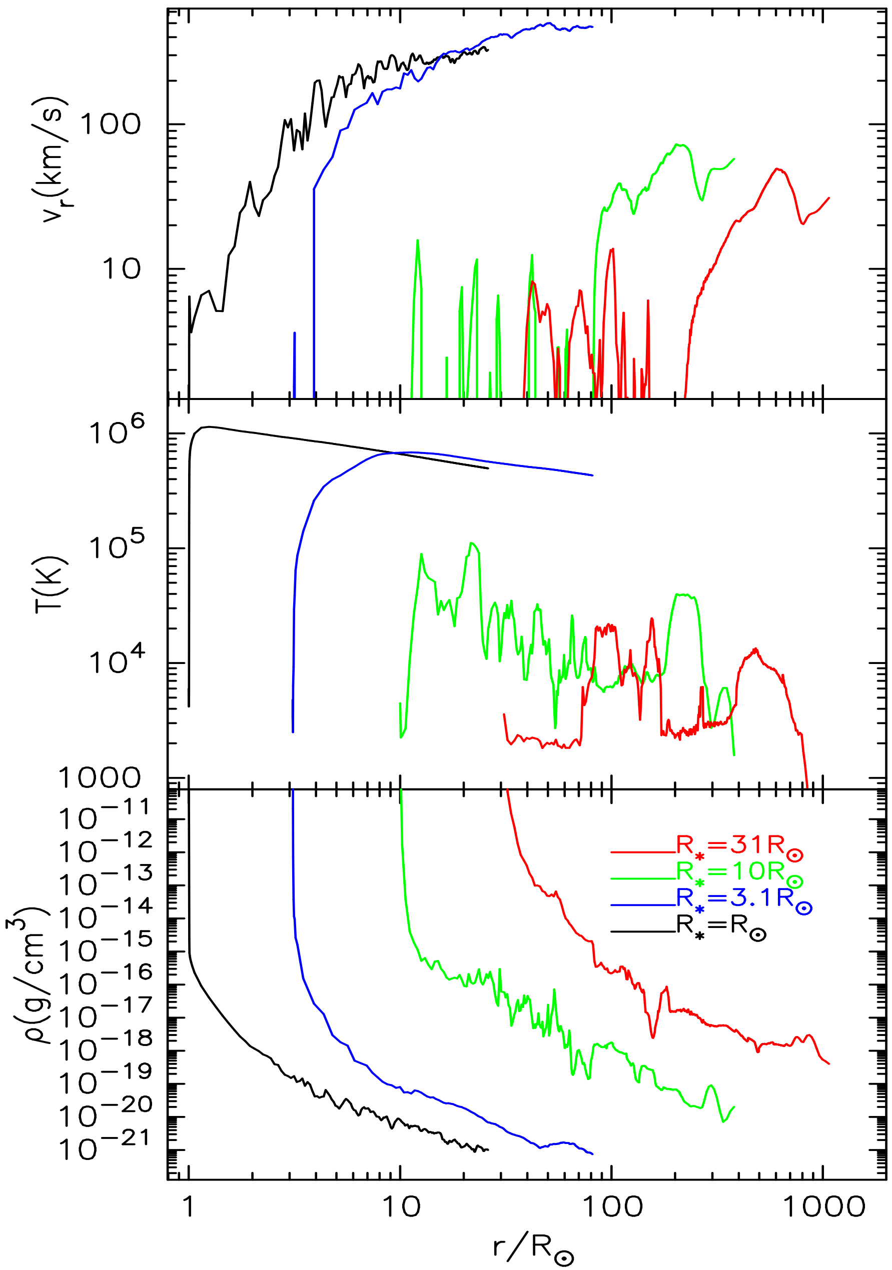
Probably across the X-ray Dividing Line (Linsky & Haisch 1979)

Set-up

Replace the Sun with Red Giants
How the wind properties evolve with the stellar evolution ?

- **Calculation Region : Photosphere ~ 20-30 stellar radii**
  - **1D Super-Radially Open Flux Tube**
- **Fluctuations from Photospheres**
  - **dv <= Convective flux (negative dependence on gravity)**
    (Renzini et al.1977; Stein et al.2004; Shibahashi 2005)
  - **Spectra (period) <=> pressure scale height ~T/g**
  - **Transverse => Alfven Waves**
  - **Longitudinal (Sound waves) : ineffective due to rapid damping**

Evolution of Winds



Suzuki 2006, ApJ, submitted (astro-ph/0608195)

(<=time averaged structures)

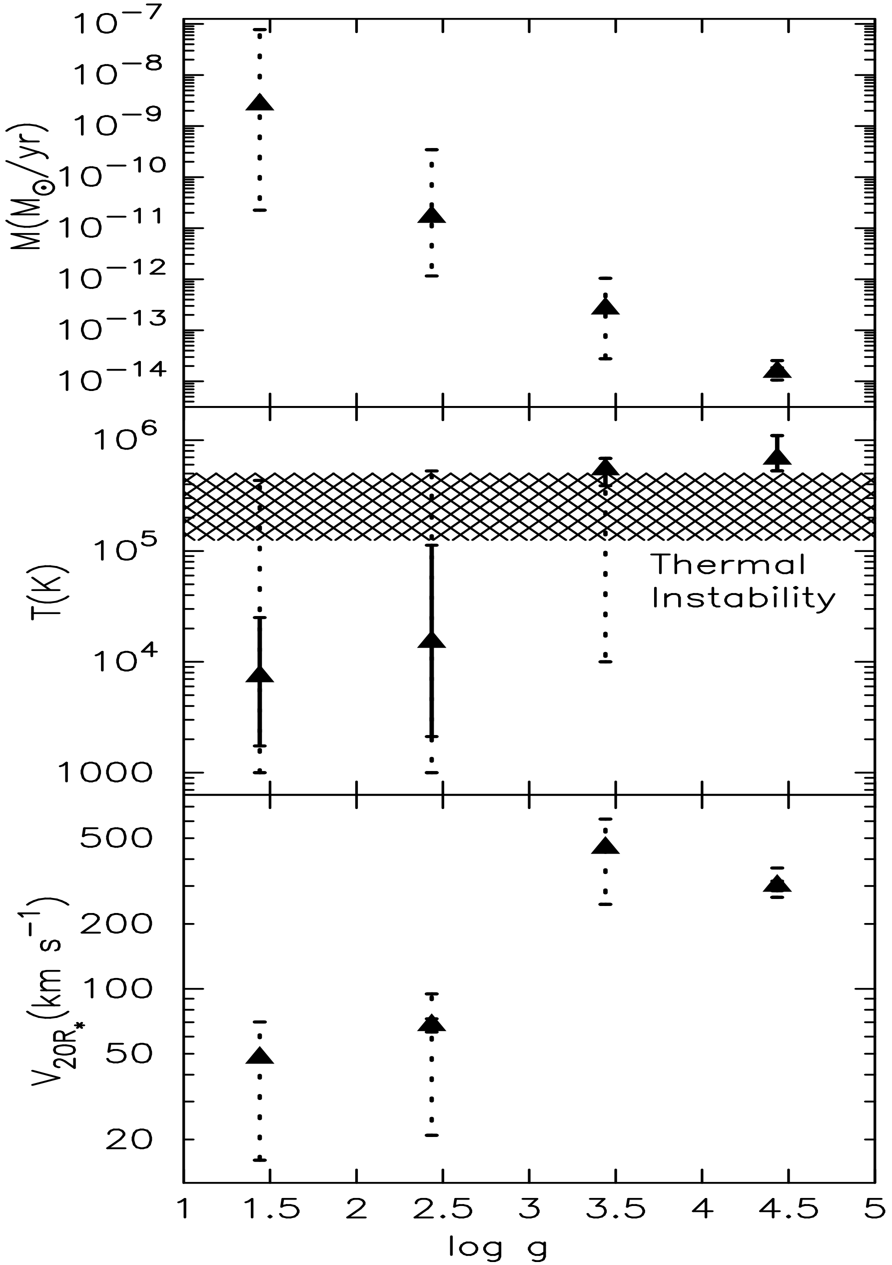
As a star evolves

- **Disappearance of Steady Corona**
- **Onset of Cool Dense Wind**

Why dense ?

- **Gravity confinement is ineffective**

Typical Wind Properties



Suzuki 2006, ApJ, submitted (astro-ph/0608195)

(left : evolved)

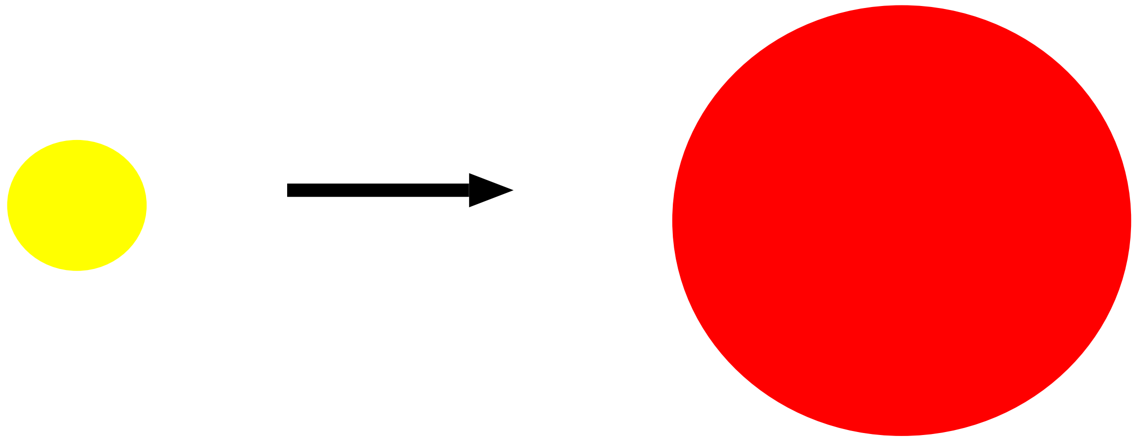
As a star evolves

- **Mass loss rate raises rapidly**
- **Temperature drops drastically**
- **Speed also drops**

The gap at log g~3 ?

- **Thermal Instability**

Escape Velocity



Main Sequence		**Red Giant**
Small	$R_\star$	**Large**
Large	$v_{\rm esc}(=\sqrt{2GM_\star/R_\star})$	**Small**

$$R_\star \gtrsim 10R_\odot \Rightarrow v_{\rm esc} \lesssim c_{\rm S}(T=10^6{\rm K})$$

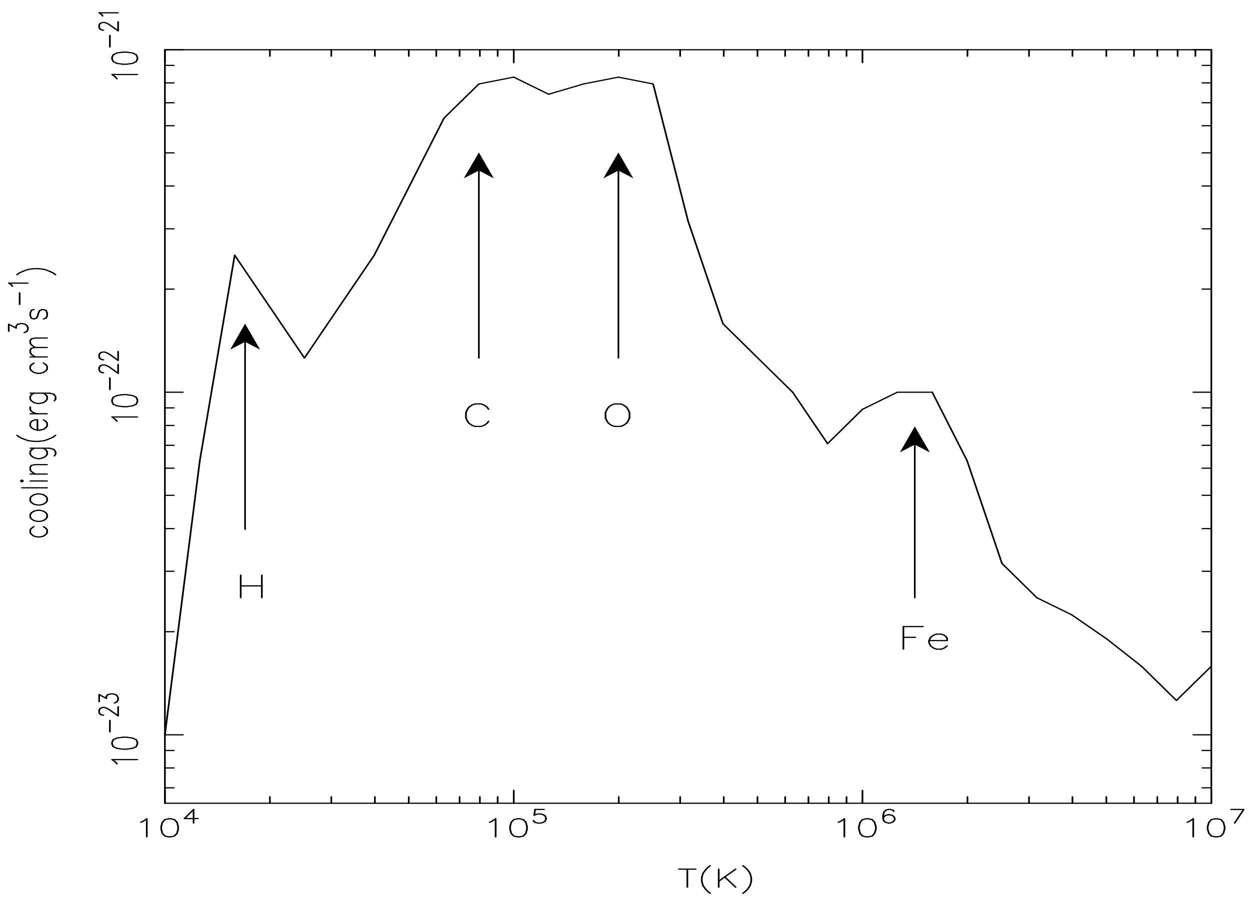
Gas streams out

before heated up to stable coronal temperature.

Thermal Instability

Cooling Function

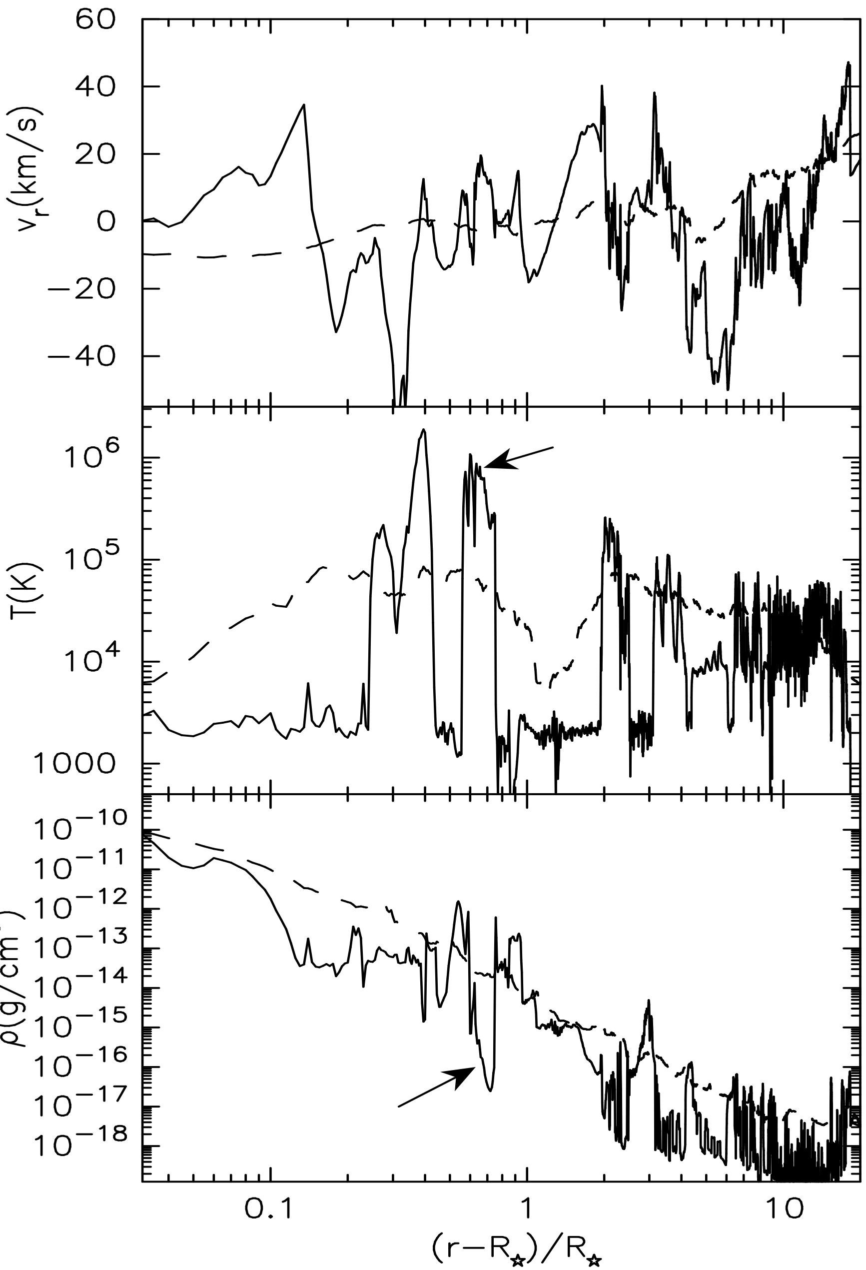
Landini & Monsignori-Fossi 1990



- **>~0.1MK : Thermally Unstable**
- **>1MK : Stabilization by Conduction**

=> ~10^4K or >~ 1MK

Structured Red Giant Winds



Suzuki 2006, ApJ, submitted (astro-ph/0608195)

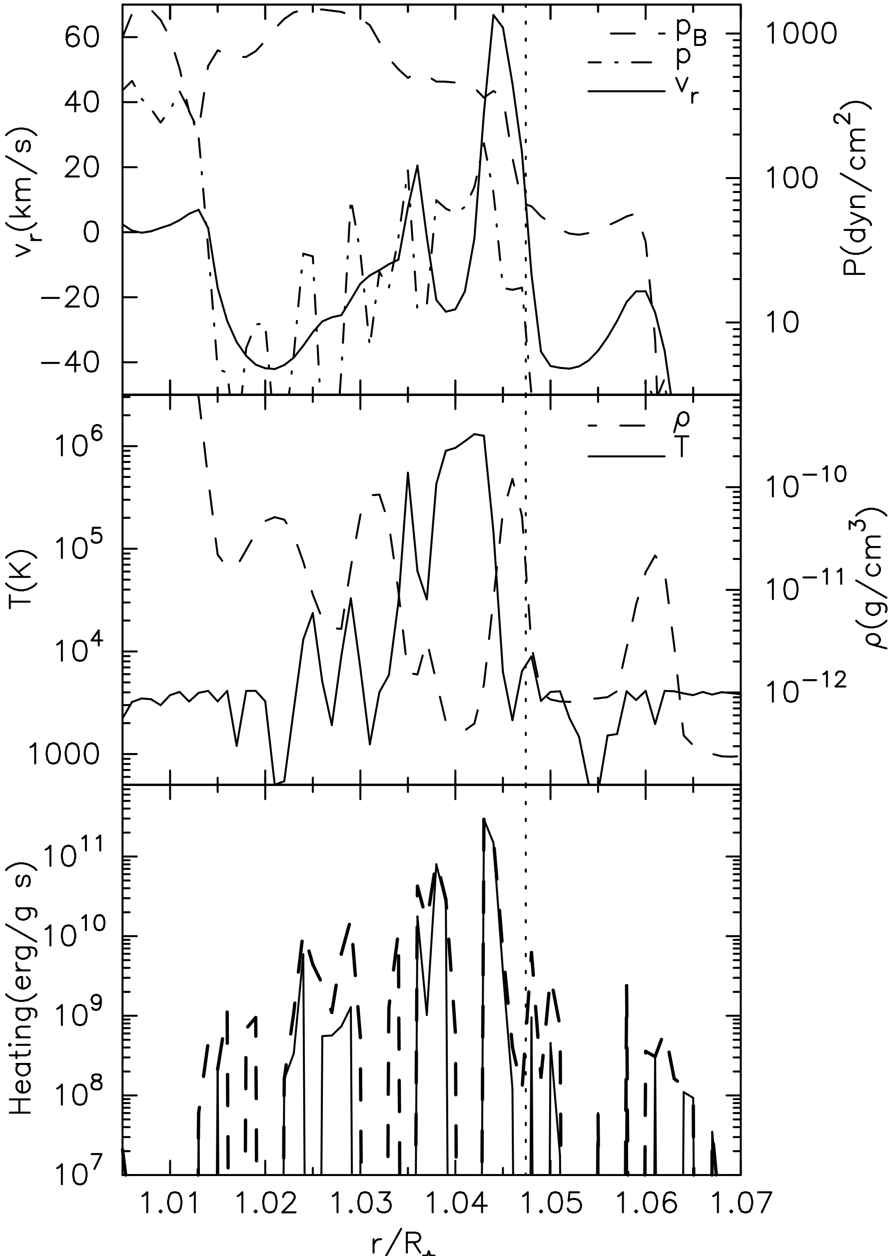
Solid:Snap-shot
dashed:time-averaged

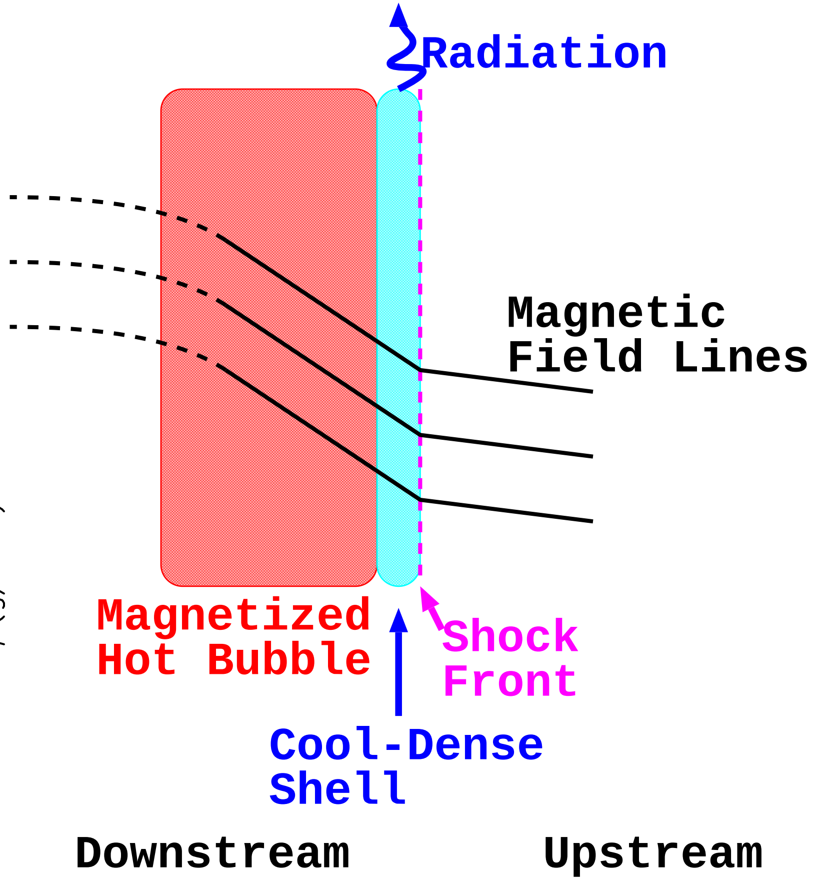
- Magnetized hot bubbles, embedded in
- Cool dense chromospheric winds

Thermal instability drives time-dependent winds

Magnetized Hot Bubble

Creation of Bubble

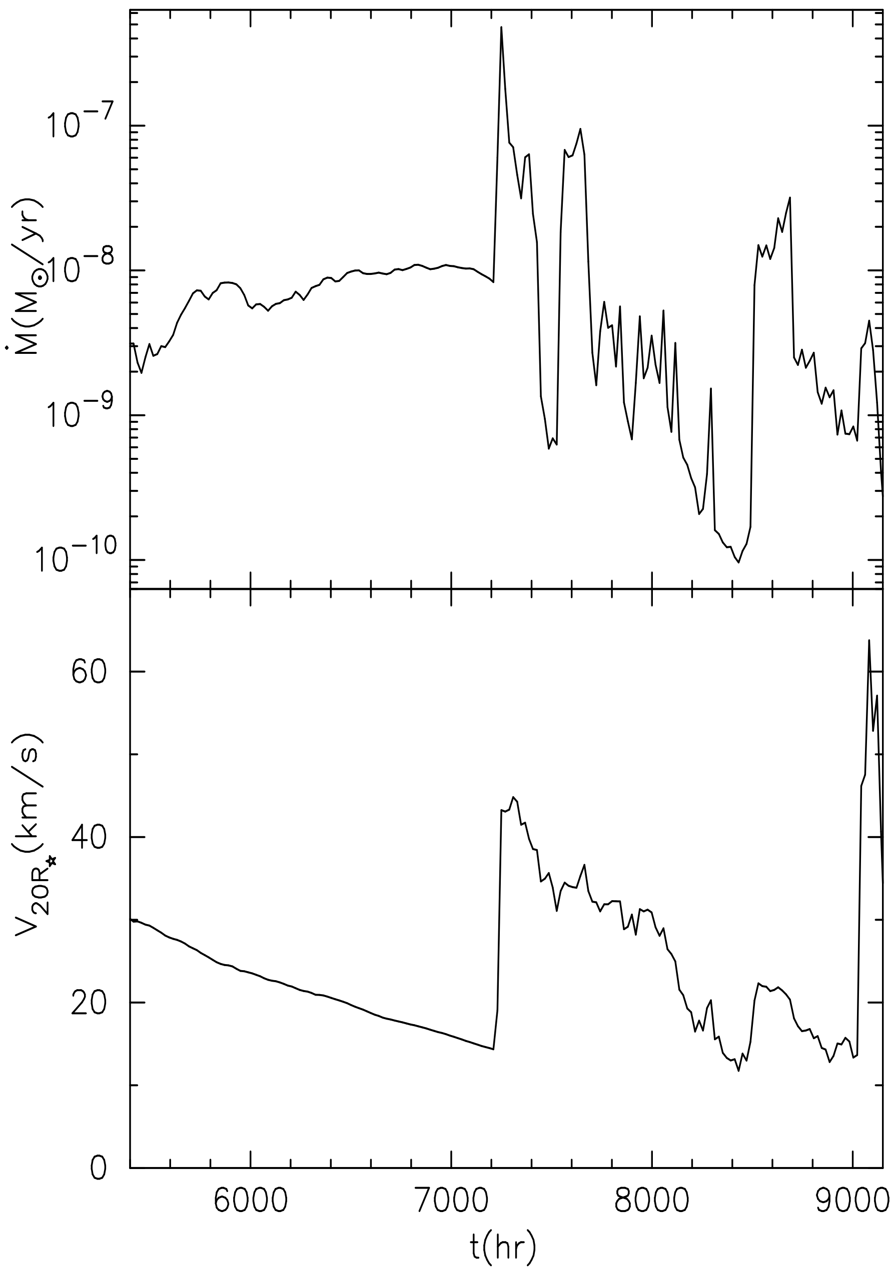




Hot bubble is supported by B-field

- **Density kept low => Avoid cooling**
  - **Cool-dense shell <= Kim & Ryu 2005**

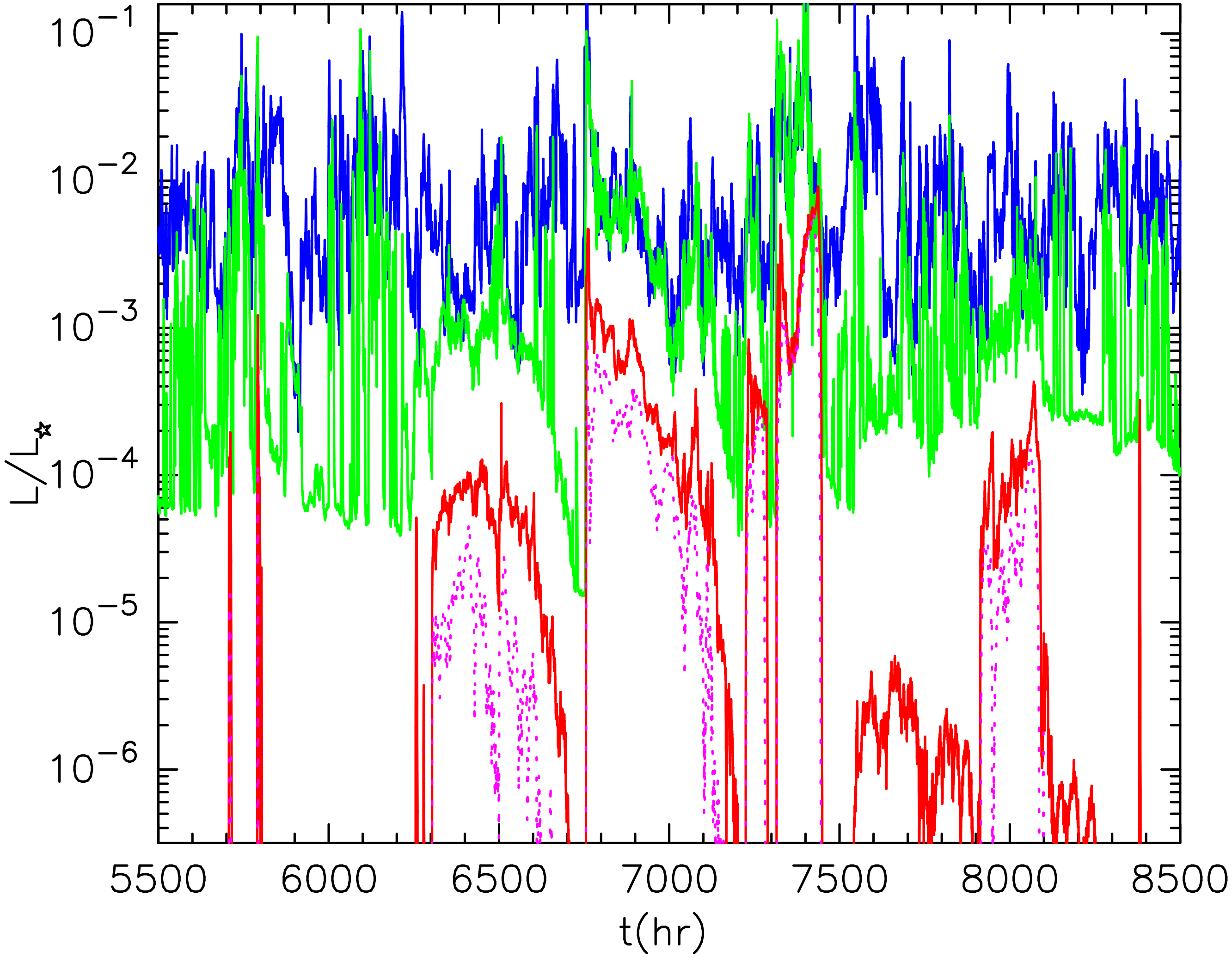
Time-dependent Winds



Mass loss rate varies a factor of ~5000

- **Steady-state calculations (most previous works) are not good to study acceleration mechanism. (O.K. to derive average mass loss rate)**

Intermittent X-ray



T<2x10^4 K; 2x10^4 K < T < 5x10^5 K; 5x10^5 K < T (10^6 K < T)

- **Observed X-ray from Hybrid Stars can be explained by magnetized hot bubbles?**
  - **But, need to take into account absorption by outer material**

Summary

We performed 1D MHD simulations of Alfven wave-driven solar and stellar winds.

- **Coronal heating and solar wind acceleration are natural consequence of the surface convection.**
  - **Nonlinear dissipation of low-freq.(MHD) Alfven waves seems plausible**

- **Wind properties change with stellar evolution;**
  Importance of gravity effect and thermal instability (cooling)
  - **Disappearance of steady corona**
  - **Highly time-dependent & structured red giant winds**