Stellar winds and coronae from solar-type stars with different metallicities

Takeru K. Suzuki

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Outline

- Solar Wind and Corona by Alfvénic waves
    - Importance & Roles of Density Perturbations
- Active & Inactive Solar Winds
- Stellar wind from low/zero-metallicity solar-type stars
- Solar wind velocity and Magnetic flux tubes

Surface ⇔ Atmosphere

Surface Fluctuation

HINODE-SOT

Solar Wind/Coronal Mass Ejection

SOHO-LASCO

- Energy Source: Fusion reaction at the center
- Surface Convection
- Hot Corona ($T \gtrsim 2 \times 10^6$K) & Solar Wind

Fluctuation at the Photosphere

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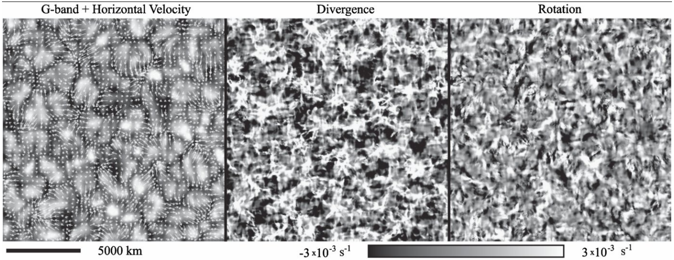
- $\delta v_\perp$ in QSs by local correlation tracking



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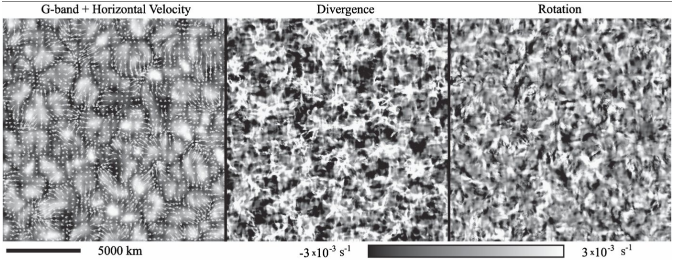
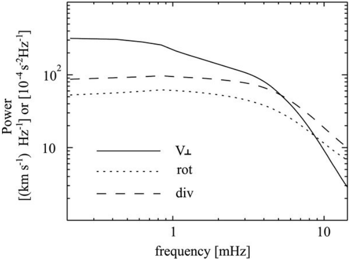




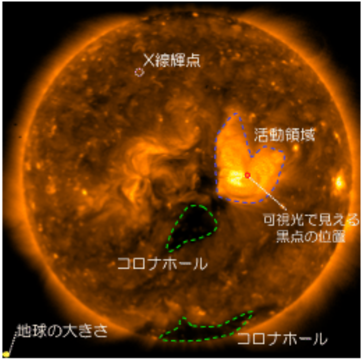
Matsumoto & Kitai 2010

$$\langle \delta v_\perp \rangle = 1.1 \text{km/s}$$

$$F = 10^8 (\text{erg/cm}^2\text{s}) \left(\frac{\rho}{10^{-7}\text{g/cm}^3} \right) \left(\frac{\delta v}{1\text{km/s}} \right)^3$$

see also Tarbell+ 1990

Energetics



Energetics

Classification of Regions

Withbroe & Noyes (1977)

Region	CH	QS	AR
Loss(erg/cm^{2}s)	8×10^5	3×10^5	10^7
Type	Wind	Cond. & Rad.	Rad.

CH=Coronal Holes; QS=Quiet Regions;

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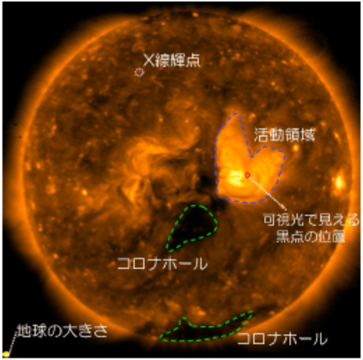

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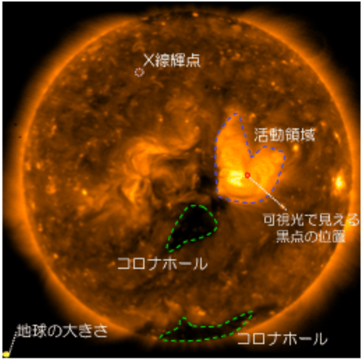

The surface convection has sufficient energy.

Coronal Heating / Solar Wind Acceleration

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Energy/Momentum/Mass transfer
in the atmosphere

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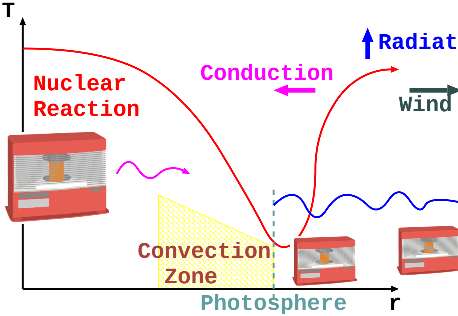

In Situ Heating
in the Corona & Wind

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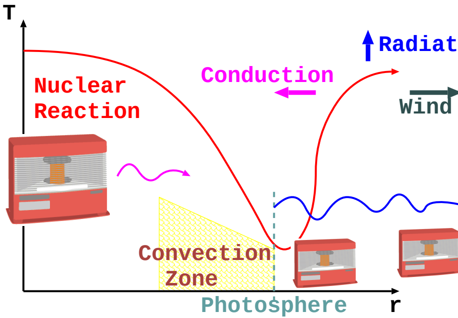

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Keys:

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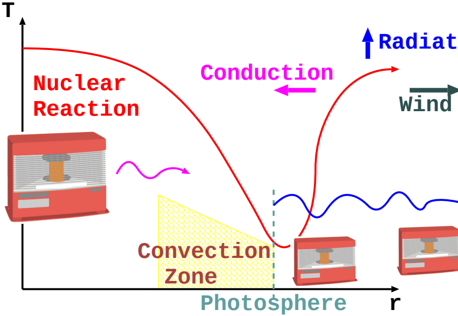

In Situ Heating
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Keys:

- Propagation / Reflection / Dissipation of waves

Stratified Atmosphere

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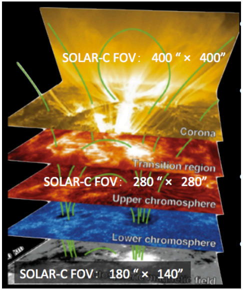
Layers in Atmosphere



Hinode web

- Corona(≳100MK)
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- Chromosphere (≲10kK)
- Photosphere (5800K)

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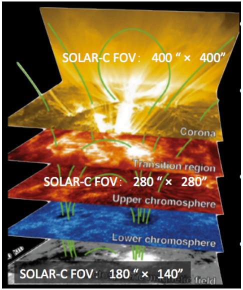

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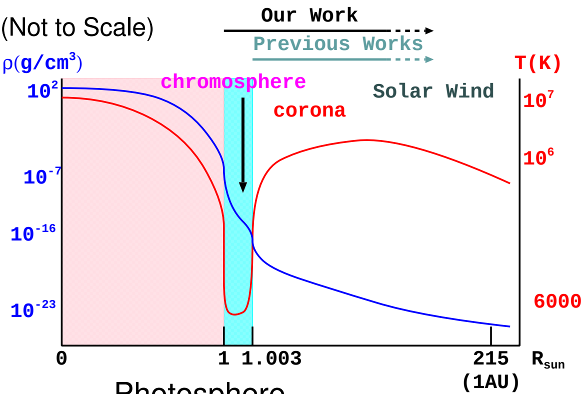
Interior ⇔ Interplanetary Space

(Not to Scale)



Photosphere

Earth orbit

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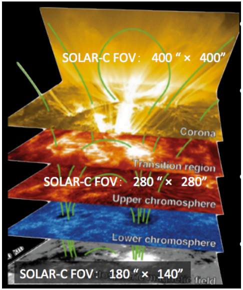

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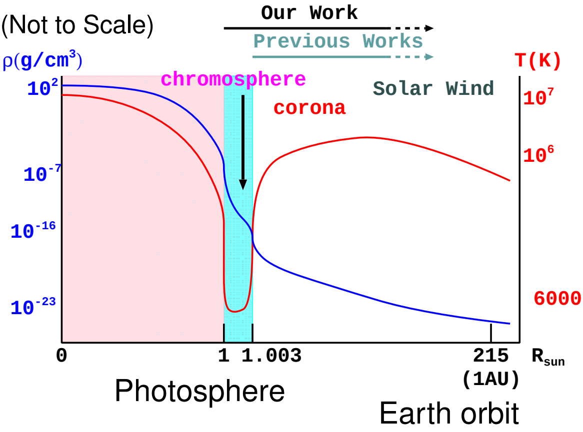

- Huge Density Contrast
(16 orders of mag.
from Photosphere to 1au)

Models/Simulations for "Solar Wind"

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2. Beyond MHD
   - Ioncyclotron resonance ? Axford & McKenzie 1997; Kohl+ 1998
   - Other kinetic effects

Our Simulation

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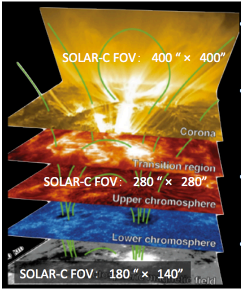
Layers in Atmosphere



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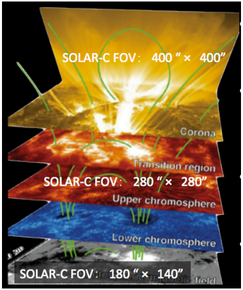

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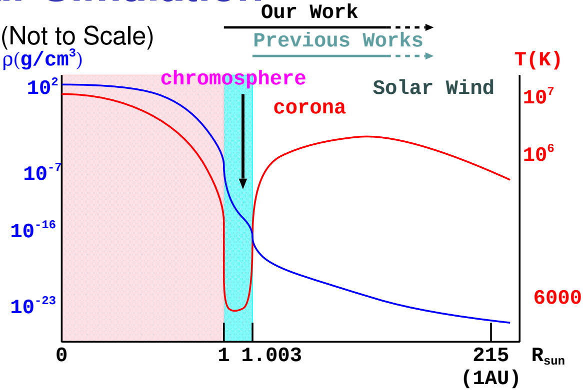

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- MHD + rad.cooling + conduction

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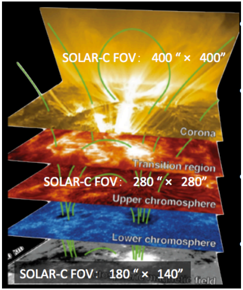

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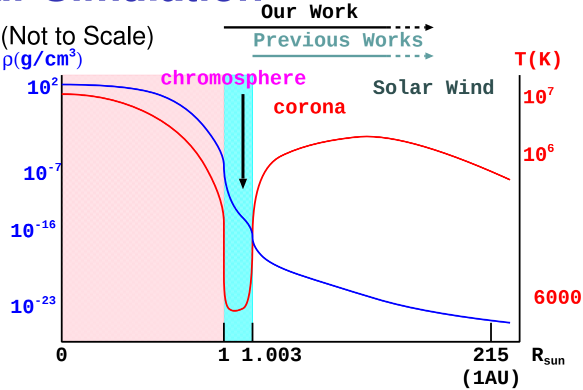

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Forward-type simulations from Photosphere ⇒ $\dot{M}$.

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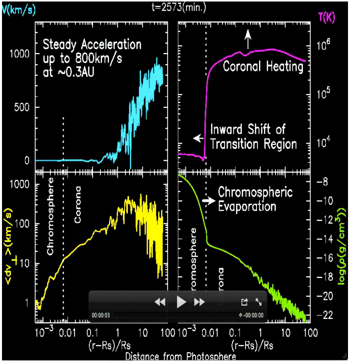
1D (1.5D)

Suzuki & Inutsuka (2005), ApJ, 632,L49



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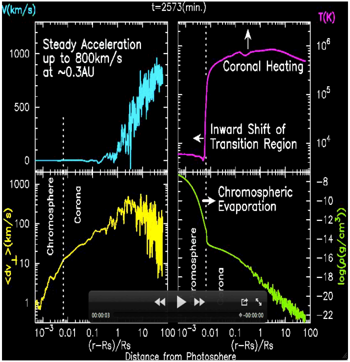

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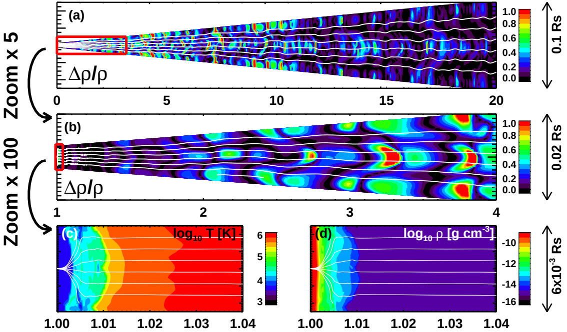
(1D)

2D (2.5D)

Matsumoto & Suzuki 2012, ApJ, 749, 8



mesh#: 8,000× 32

Simulation by Matsumoto

Observation & Simulation

Based on Matsumoto & Suzuki (2014)

HINODE/SOT

Comparison with Observations

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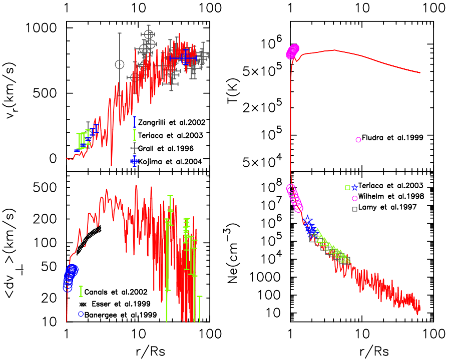
(1.5D) Suzuki & Inutsuka 2005 ApJ, 632, L49 ⇓



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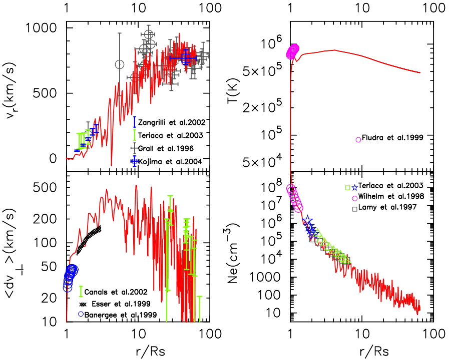

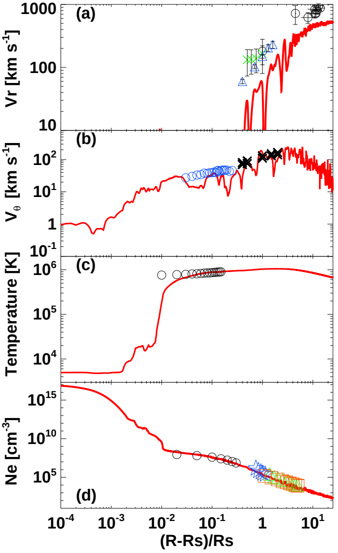

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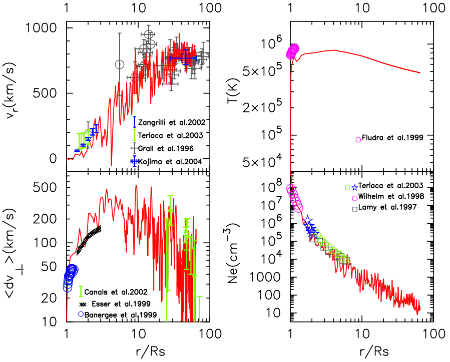

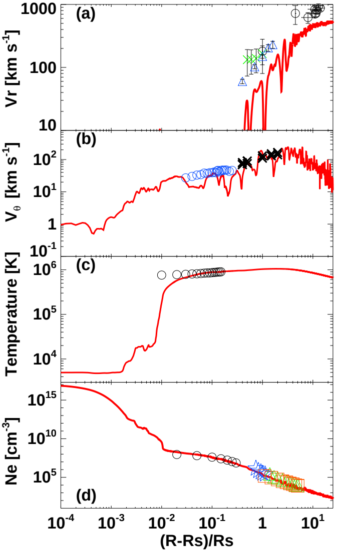

- cool chromosphere / sharp TR / 1MK corona

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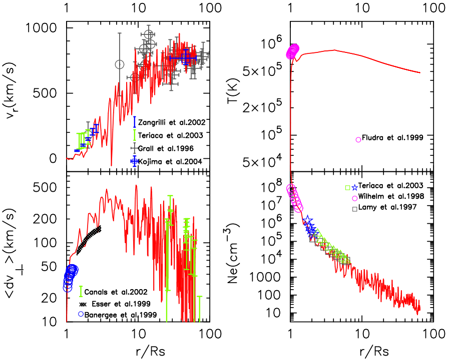

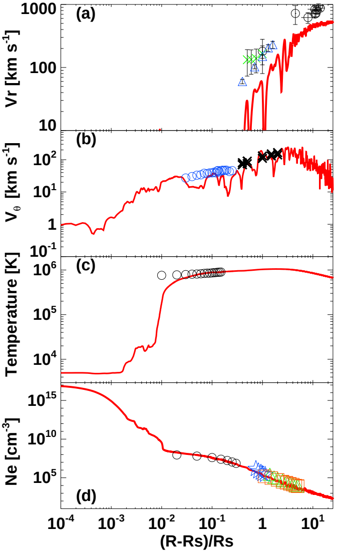

- cool chromosphere / sharp TR / 1MK corona
- drive SW with 700-800 km/s

Heating in 1D simulation; $t - r$ diagrams

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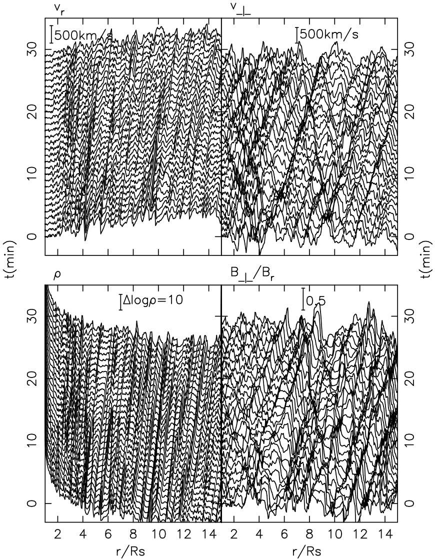

Suzuki & Inutsuka 2006, JGR, A06101

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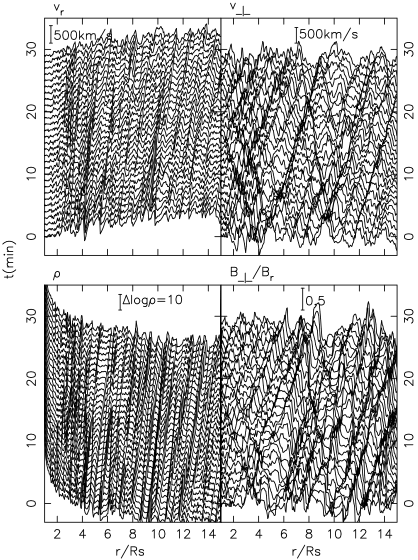

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- longitudinal waves in ρ, v_r (slow MHD≈ sound waves)
  - $\delta B^2 \Rightarrow \delta\rho$ (Ponderomotive force)
    Hollweg 1982; Kudoh & Shibata 1999
  - Parametric Decay (Goldstein 1978) in inhomogeneous background
    Shoda+ 2018 & Shoda's Talk

⇒ steepening

⇒ shock dissipation

▸ Compressible waves

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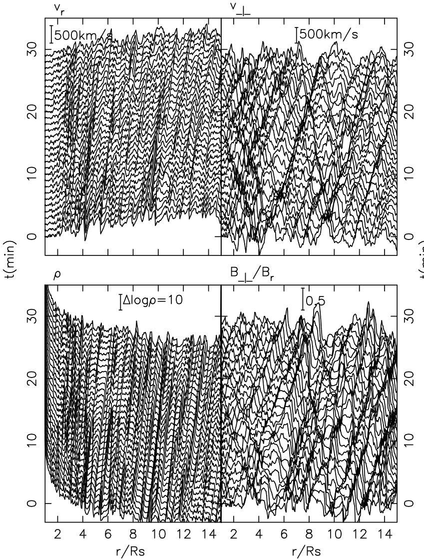

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See Nariyuki-san's works (Nariyuki & Hada 2007; Nariyuki+ 2008; 2009; 2014) for kinetic/multi-fluid effects on parametric decay

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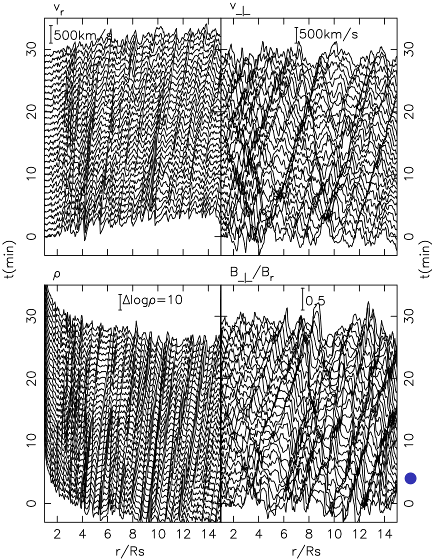

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  - Parametric Decay (Goldstein 1978) in inhomogeneous background

    Shoda+ 2018 & Shoda's Talk

$\Rightarrow$ steepening

$\Rightarrow$ shock dissipation

▸ Compressible waves

See Nariyuki-san's works (Nariyuki & Hada 2007; Nariyuki+ 2008; 2009; 2014) for kinetic/multi-fluid effects on parametric decay

- transverse waves in $v_\perp, B_\perp$ (Alfvén waves)

Reflection everywhere ▸ Reflection test

Observation of $\delta\rho$ by AKATSUKI

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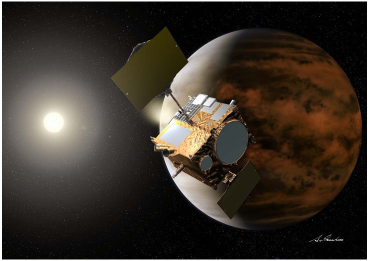
AKATSUKI (JAXA): planned as Venus Climate Orbiter



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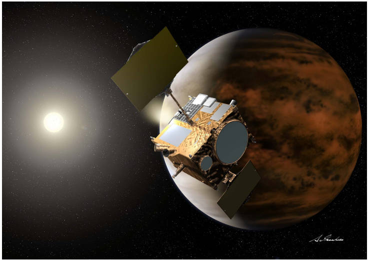

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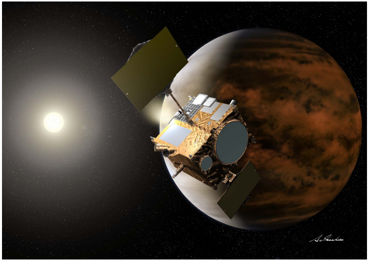

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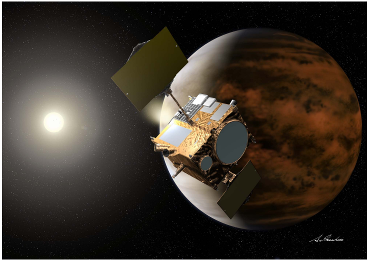

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Observe the Sun in June–July, 2011

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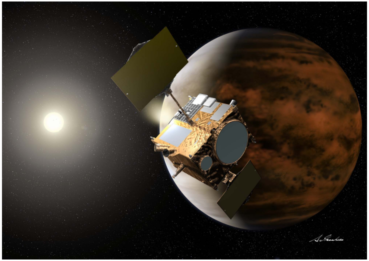

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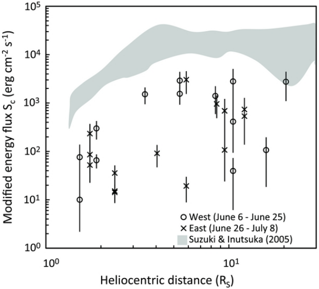

Miyamoto, Imamura et al.2014

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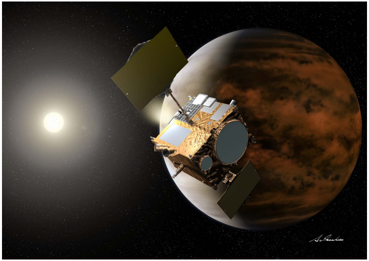

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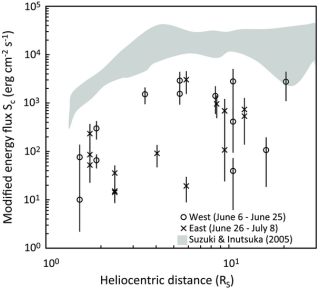

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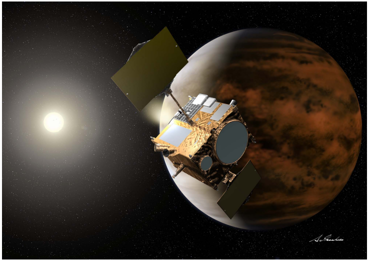

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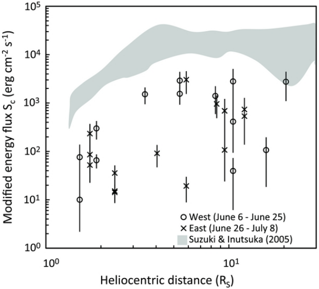

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$\delta\rho$: a good target for Parker Solar Probe

The second orbital injection was successful on Dec.7, 2015

Dissipation of Alfvén waves ⇒ Heating

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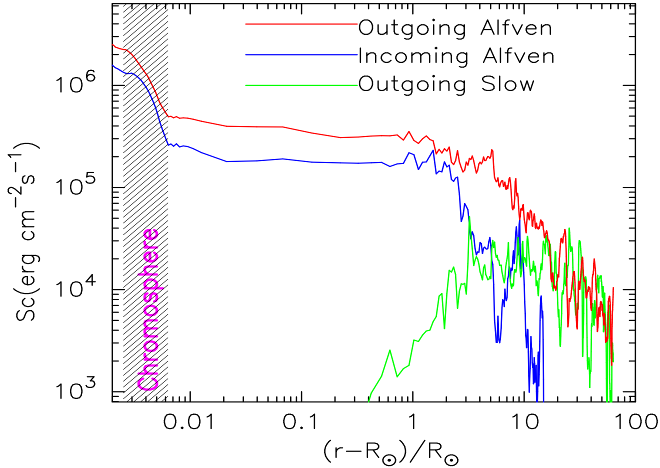
Suzuki & Inutsuka 2005



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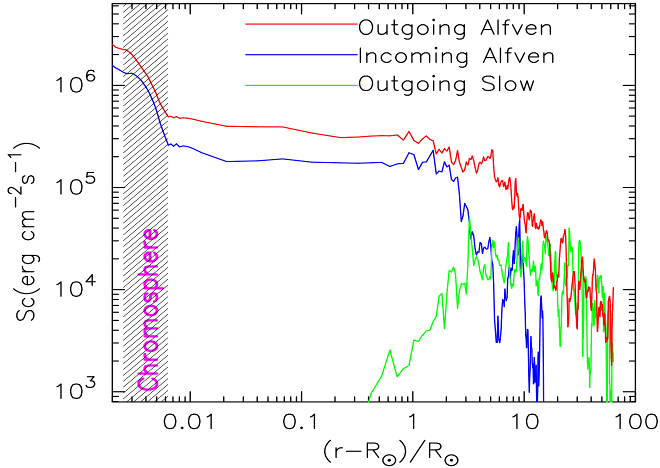

- ~ 90% of the initial Poynting flux reflected back before reaching the corona.

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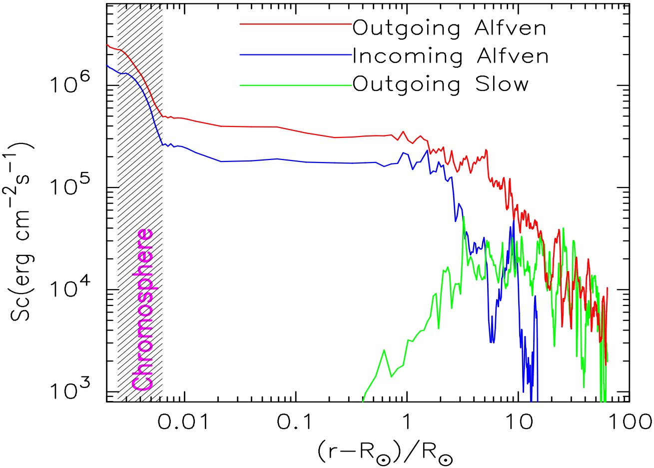

- ~ 90% of the initial Poynting flux reflected back before reaching the corona.
- The transmitted energy is enough.

Sun in Time –Solar-type stars–

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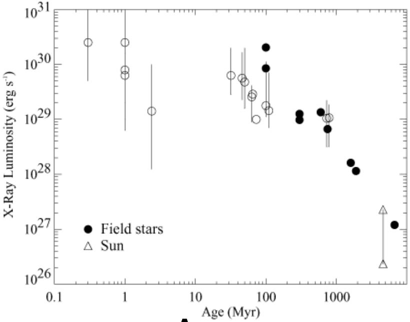
L_X (Güdel 2007)



Age

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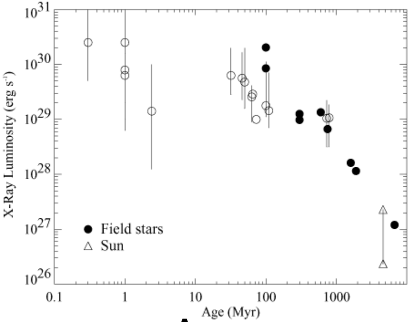

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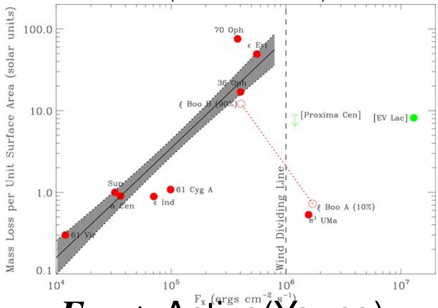
$\dot{M}$ (Wood et al.2014)



$F_X \Rightarrow$ Active(Young)

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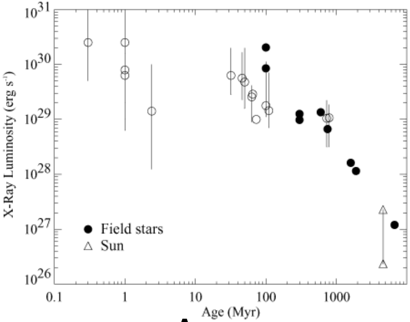

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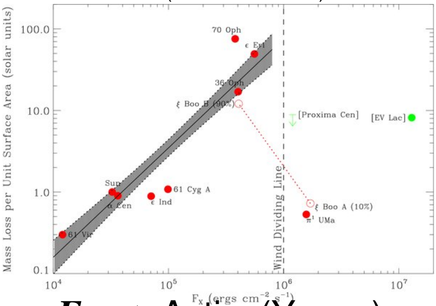

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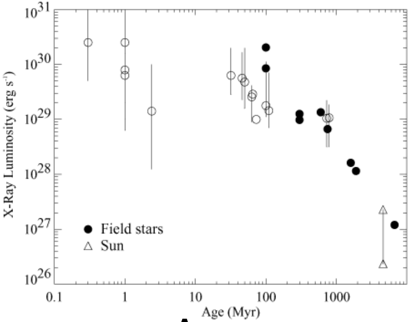

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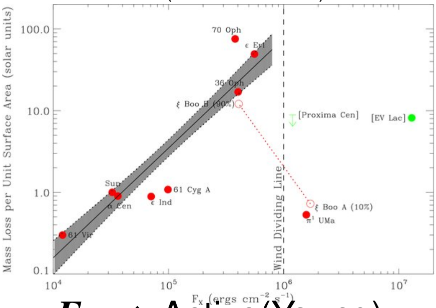

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Active Young Solar-type Stars:

- Larger L_X & $\dot{M} \Leftarrow$ fast rotation Skumanich '72; Ayres '97

  $L_X \lesssim 1000 \times L_{X,\odot}$ & $\dot{M} \lesssim 100 \times \dot{M}_\odot$

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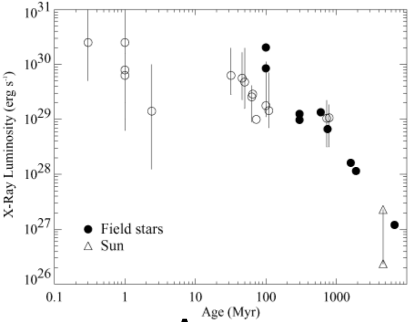

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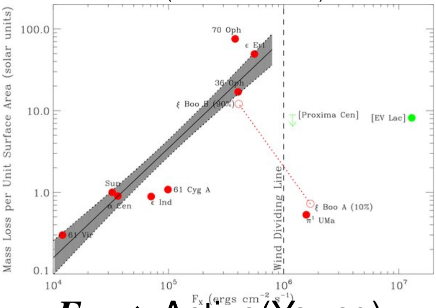

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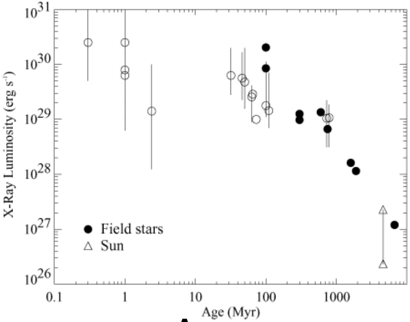

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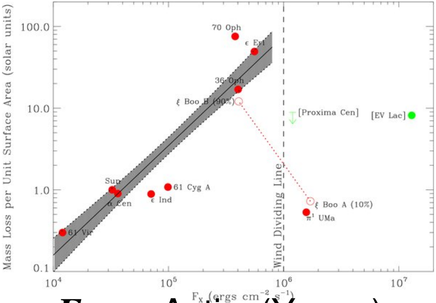

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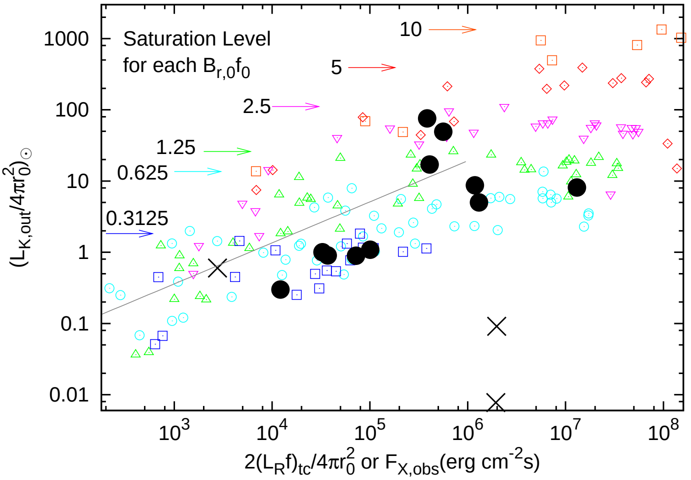
Young Suns: Active & Dense Wind but Saturation

$L_R - L_K$ from Numerical Simulations



●: Observation (Wood et al.2005)

Colors: 1D Simulation (Suzuki et al.2013)

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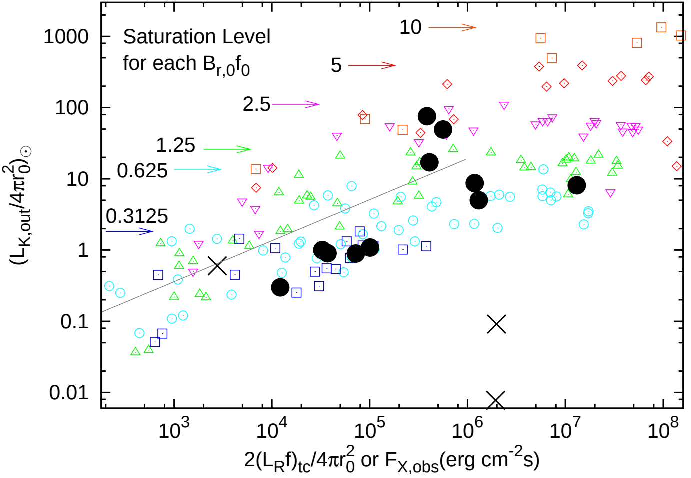

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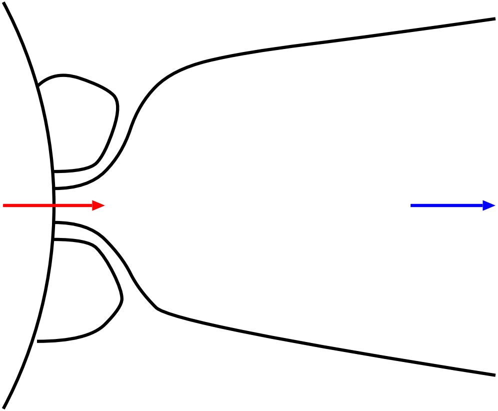
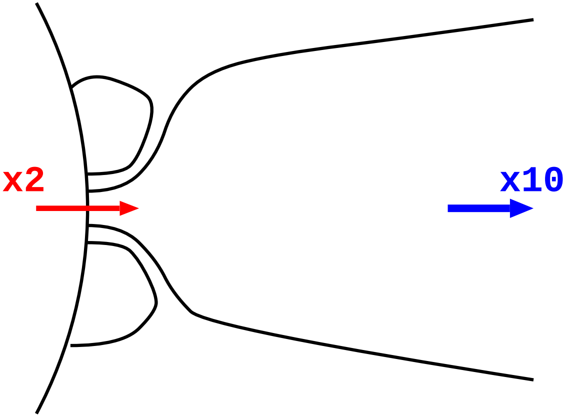
Solar wind could be ×1000

Nonlinear Solar Wind



Nonlinear Solar Wind

If the input energy $\times 2$



The kinetic energy of solar wind $\times 10$!

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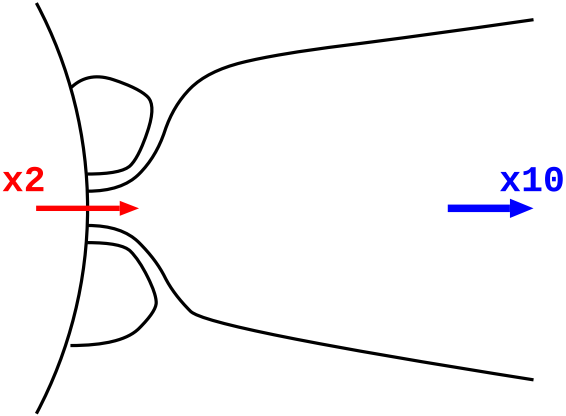
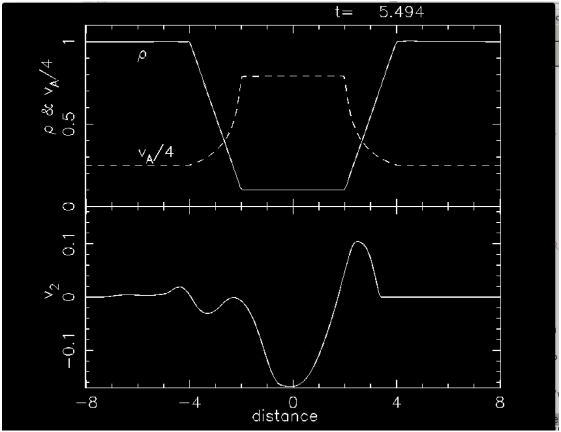


The kinetic energy of solar wind $\times 10$!
Conservation Law ???

Reflection

ρ-gradient $\Rightarrow$ Change of $v_A (= B/\sqrt{4\pi\rho})$

$\Rightarrow$Deformation of Wave Shape(=Partial Reflection)



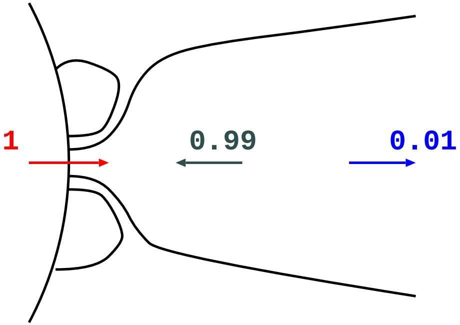
Reflection test

Nonlinear Response of Solar Winds

▸ Reflection test

Nonlinear Response of Solar Winds

$E_{\text{input}} \times 1$



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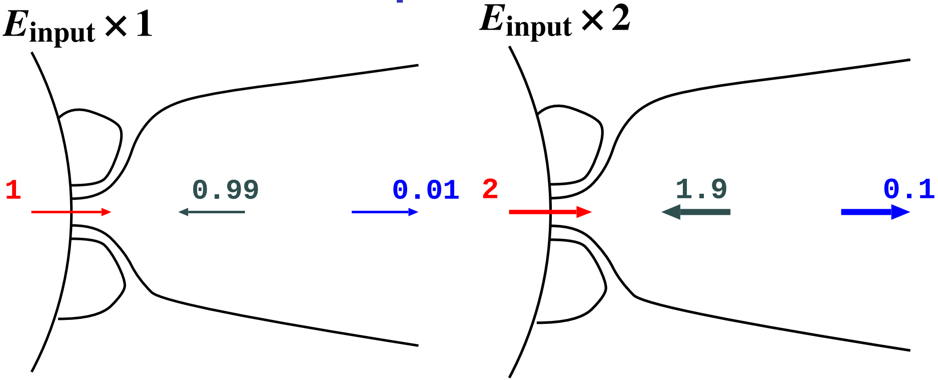

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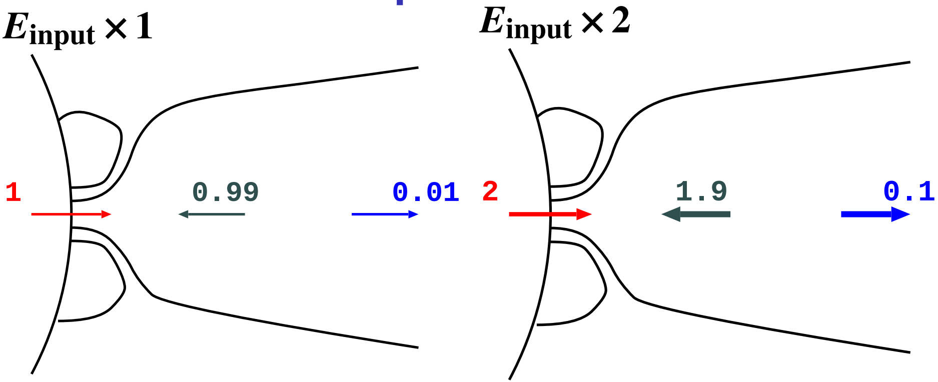

- Reflected Energy 99% ⇒ 95%

▸ Reflection test

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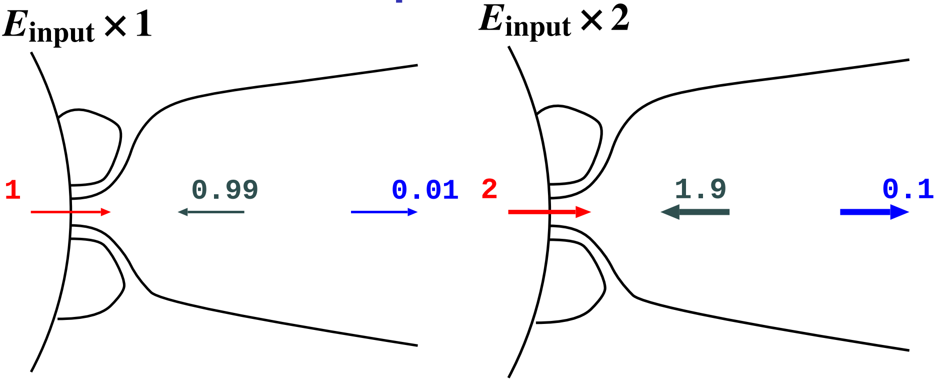

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- Wind Energy 1% ⇒ 5%

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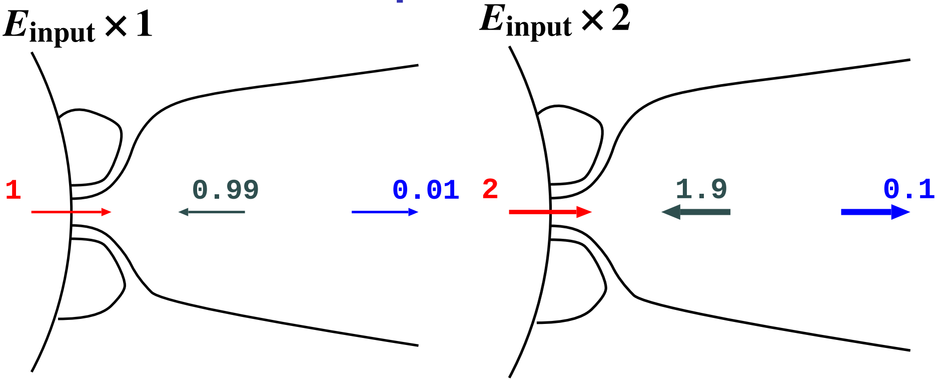

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Reflection test

A tiny change at the surface

⇒ A big change in the wind

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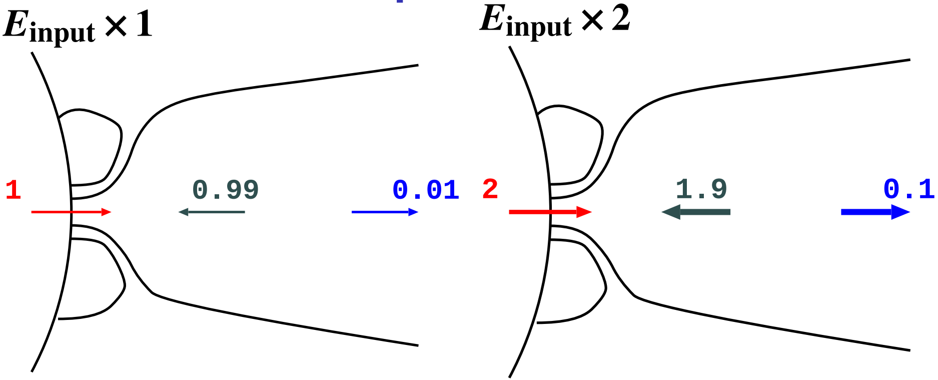

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c.f.Disappearance of SW on May 11, 1999

Extended Chromosphere in Active Stars

Comparing active & present Sun cases

Suzuki, Imada + 2013

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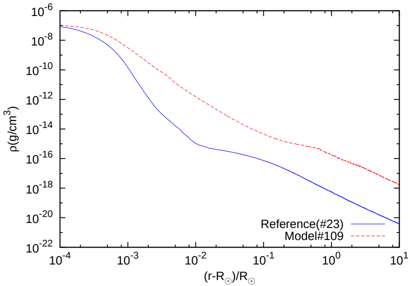
ρ structure



Gas Lifted up by $\delta B^2 \Rightarrow$ Extended Chromosphere

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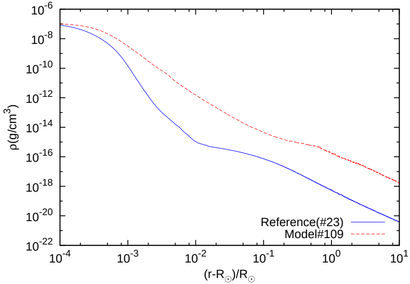
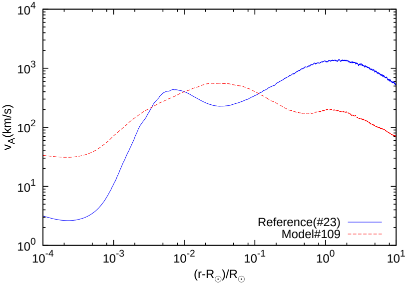


v_A $(= B_r/\sqrt{4\pi\rho})$ structure



Gas Lifted up by $\delta B^2 \Rightarrow$ Extended Chromosphere

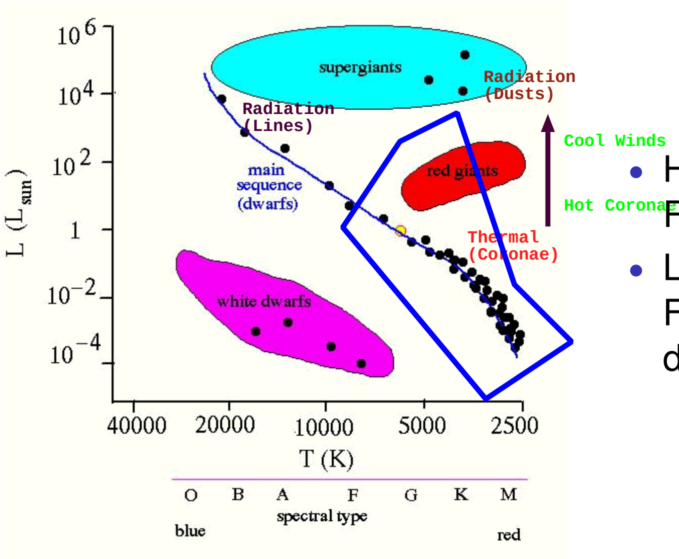
$\Rightarrow$ v_A changes more slowly.

$\Rightarrow$ suppression of wave reflection.

Hollweg 1984; Moore et al.1991 ▸ Reflection test

Stellar Winds in a HR diagram

Univ.of California San Diego HP



- High L Radiation-driven
- Low L Fluctuation-driven

Metallicity Dependence of Winds

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Massive Main Sequence Stars

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Lucy & Solomon 1970; Castor+ 1975

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AGB Stars

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How about Low-mass Main Sequence Stars ?

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- Evolution of Elements in the Universe
  - Big Bang: H, He ,Li
  - In Stars: up to Fe + beyond Fe (S-process)
  - Supernovar & Neutron Star Merger: Beyond Fe (R-process)

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  First Stars ≈ Zero-Metal Stars
- Lifetime of Stars
  - Massive stars have shorter $\tau_{\rm life}$
    $\tau_{\rm life} \propto M_\star / L_\star \sim M_\star^{-3}$

Low-mass Zero-metal (Pop.III) Stars

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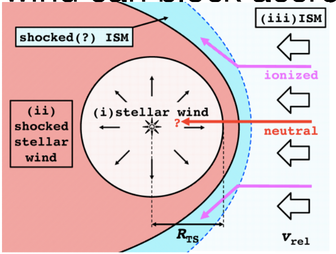

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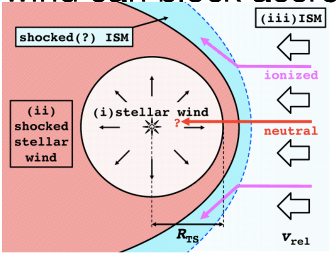

Solid objects with $\gtrsim$ 3km can accrete. Tanikawa+

Low-mass & Low/Zero-metallicity Stars

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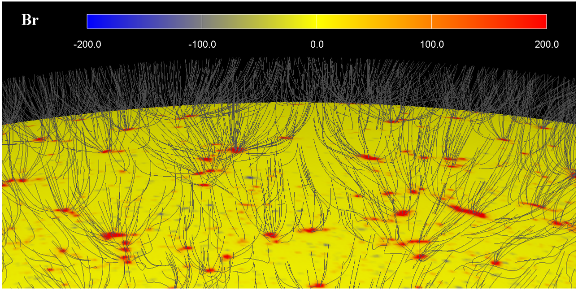
- Super-radially expanding flux tubes
  $\langle B \rangle = Bf = 1.25$ G f: filling factor



Tsuneta et al.2008; Shimojo et al.2009; Itoh et al.2010; Shiota et al.2012

Characters of low-metallicity stars

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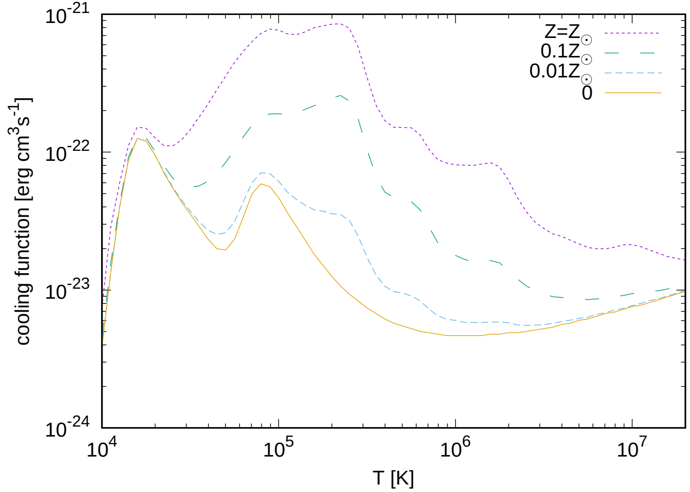
Main Sequence Stars with $M_\star = 0.7 M_\odot$ Yi+ 2001

$Z(Z_\odot)$	$R_\star(R_\odot)$	$T_{\rm eff}(K)$	$L(L_\odot)$	δv_0(km s^{-1})	$B_{r,0}$(kG)
1	0.632	4657	0.169	0.641	2.51
0.1	0.620	5576	0.333	0.760	3.05
0.01	0.618	5815	0.391	0.812	3.06
0	0.617	5842	0.397	0.787	3.25

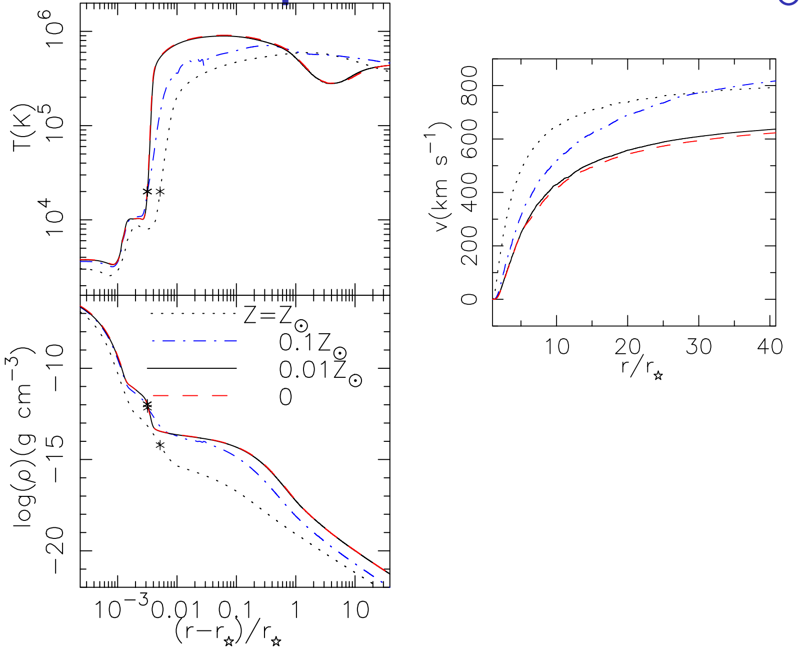
Radiative Cooling Function



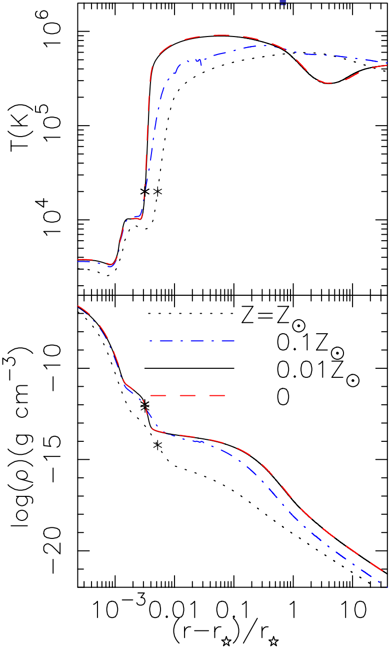
Cooling Rate (optically thin)

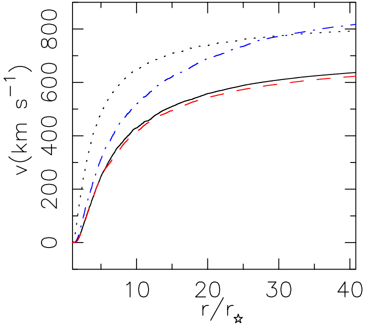
$$q_R = n n_e \Lambda \text{ erg cm}^{-3}\text{s}^{-1}$$

Atmospheres & Winds of $0.7M_{\odot}$



Atmospheres & Winds of $0.7M_\odot$





Lower Z ⇒

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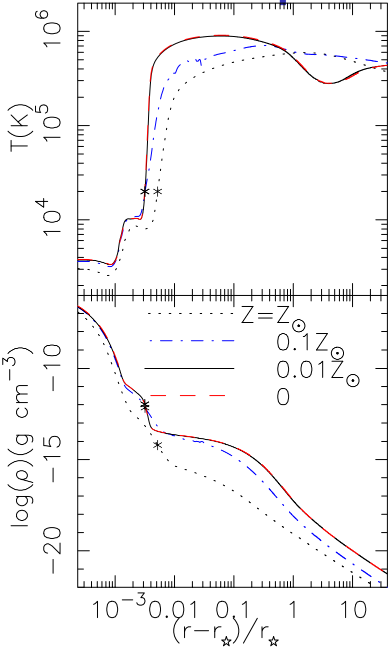

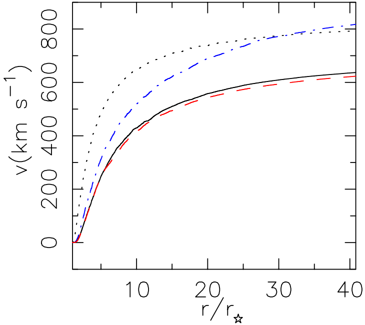

Lower Z ⇒

- Higher ρ ⇒ Larger $\dot{M}$

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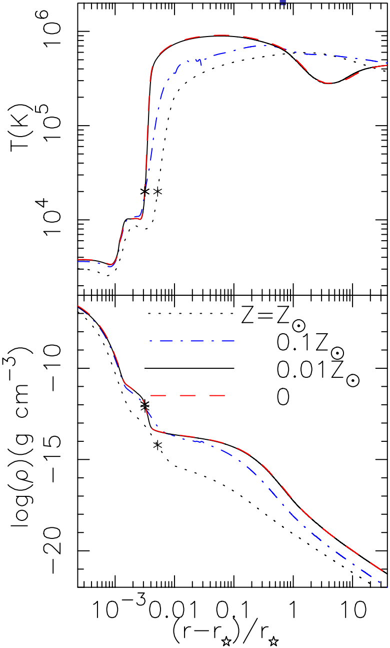
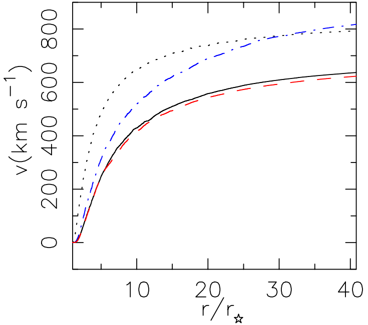
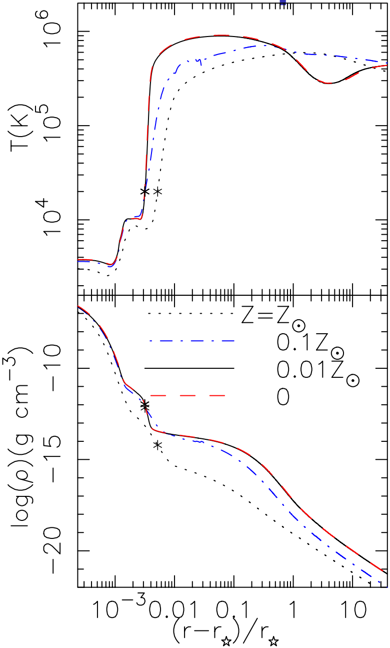


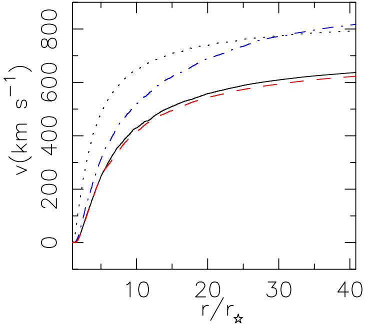


Lower $Z \Rightarrow$

- Higher $\rho \Rightarrow$ Larger $\dot{M}$
- Higher T

Atmospheres & Winds of $0.7 M_{\odot}$

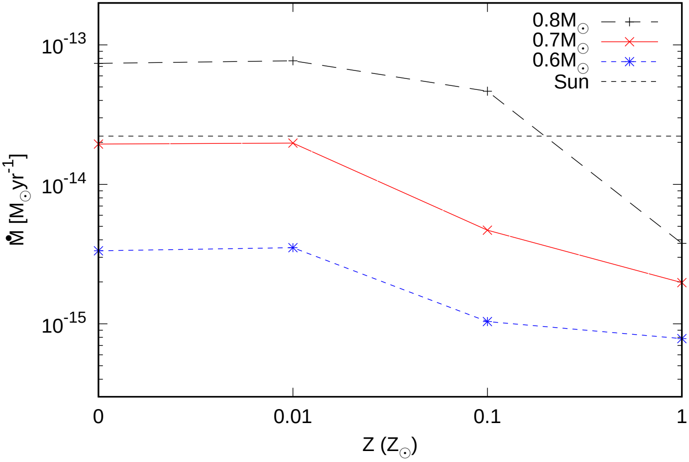




Lower Z ⇒

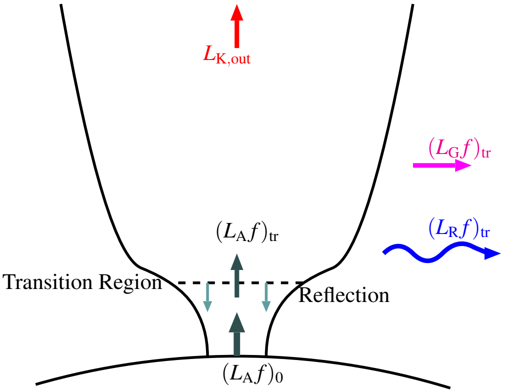
- Higher ρ ⇒ Larger $\dot{M}$
- Higher T
- (Slightly) Slower v

$\dot{M}$–Z for Different $M_\star$



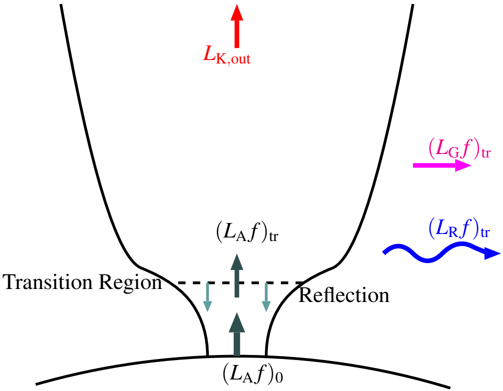
$$\dot{M}(Z \leq 0.01Z_\odot) \approx (5 - 20) \times \dot{M}(Z_\odot)$$

Energetics



Transition Region at $T = 2 \times 10^4$K

Energetics



Poynting flux by Alfvén waves:

$$L_A f = 4\pi r^2 f \rho \langle \delta v^2 \rangle v_A$$

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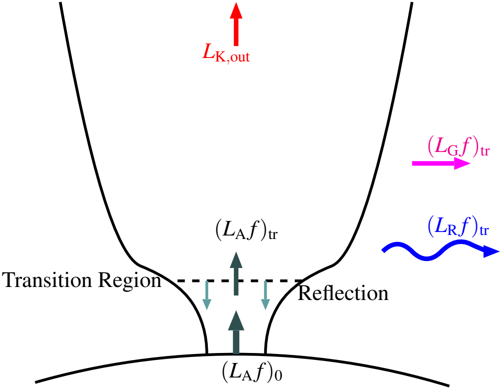

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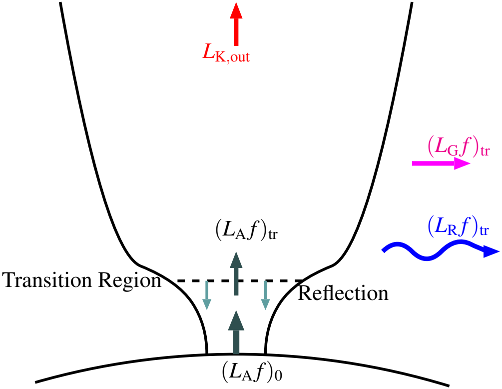

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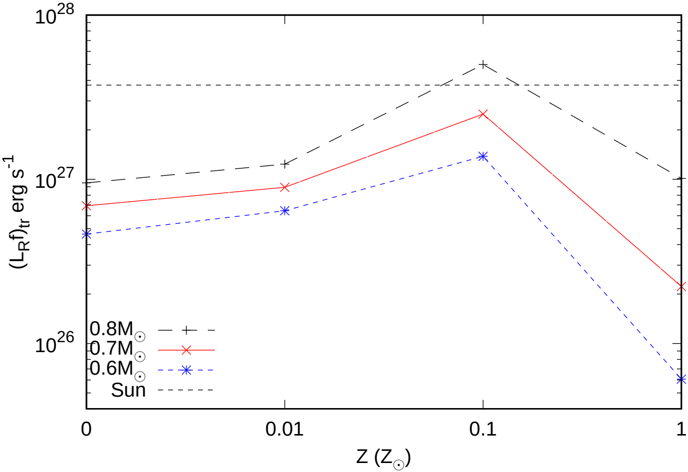
Radiative loss: $\boldsymbol{(L_{\mathrm{R}} f)_{\mathrm{tr}} = 4\pi \int_{r_{\mathrm{tr}}}^{r_{\mathrm{out}}} dr q_{\mathrm{R}} f r^2}$

Transition Region at $\boldsymbol{T = 2 \times 10^4}$K

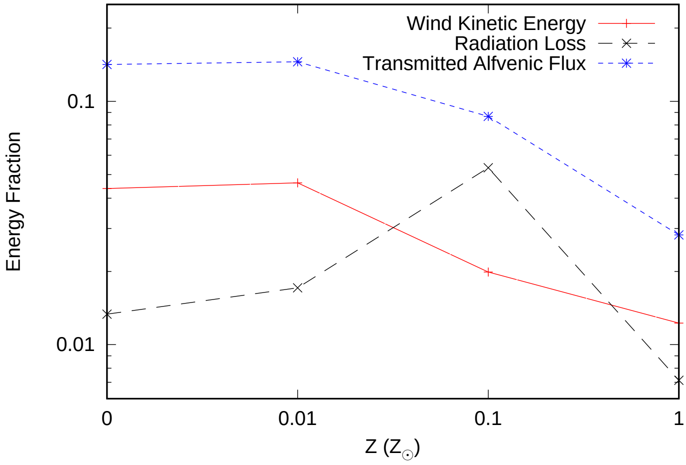
Radiative Loss



$$(L_R f)_{tr} = 4\pi \int_{r_{tr}}^{r_{out}} dr q_R f r^2$$

Total radiation loss from the gas with $T \geq 2 \times 10^4$ K.

Energetics $M_\star = 0.7 M_\odot$



$$(L_{\rm A} f)_{\rm tr}/(L_{\rm A} f)_0 - L_{\rm K,out}/(L_{\rm A} f)_0 - (L_{\rm R} f)_{\rm tr}/(L_{\rm A} f)_0$$

Summary

- Solar Wind and Corona by Alfvénic waves
  - Density perturbations ⇒ Shoda's Talk
- Active & Inactive Solar Winds
  Small change of energy injection ⇒ Huge difference of SW
  Reflection triggered global instability Suzuki+ (2013)
- Low/Zero-metallicity solar-type stars drive strong winds
- Solar wind velocity and Magnetic flux tubes: $v - B/f$

Fast/Slow Solar Winds

InterPlanetary Scintillation Measurement

by STE-lab (Kojima+ 2005)

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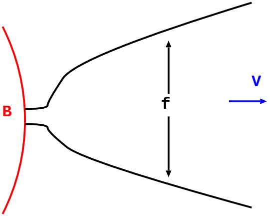

Solar Wind from Coronal Holes

Fast/Slow Solar Winds

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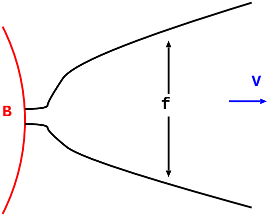

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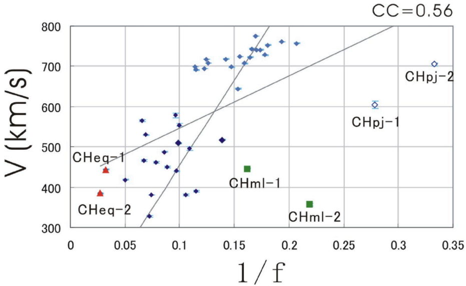

Wang & Sheeley 1991; Arge & Pizzo 2000

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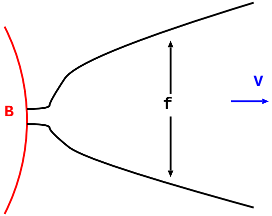

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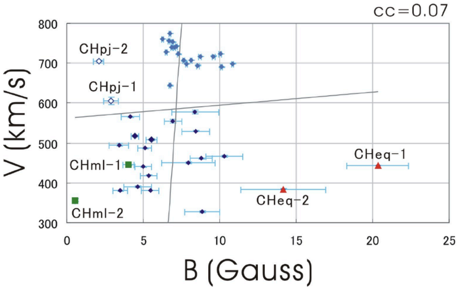

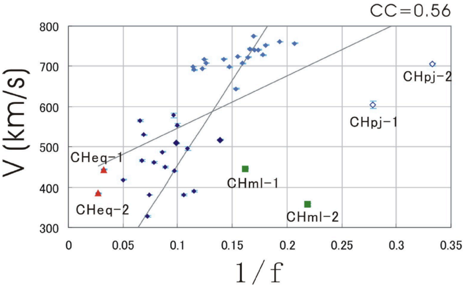

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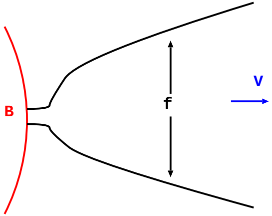

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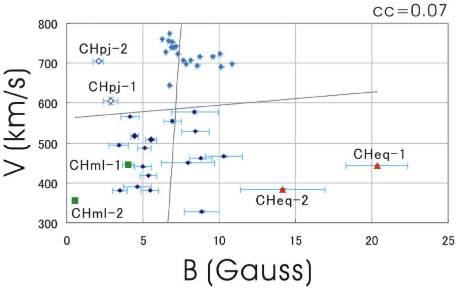

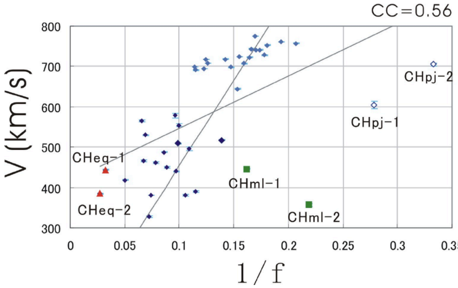

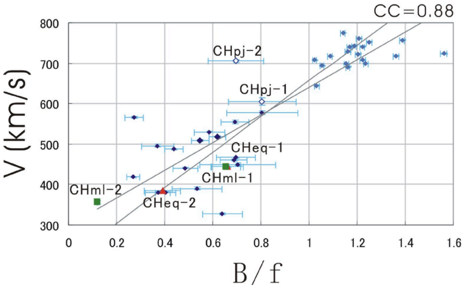

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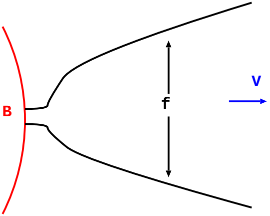

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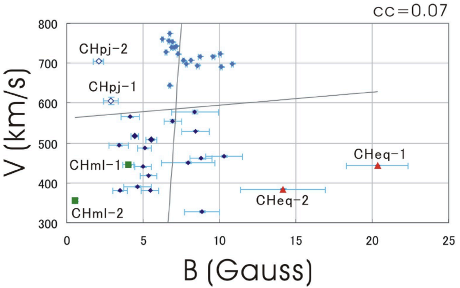

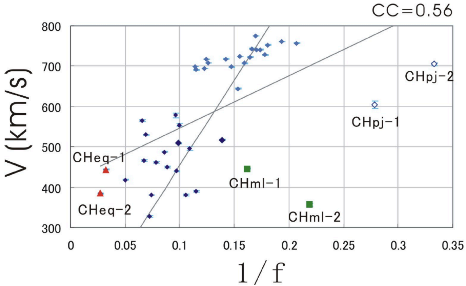

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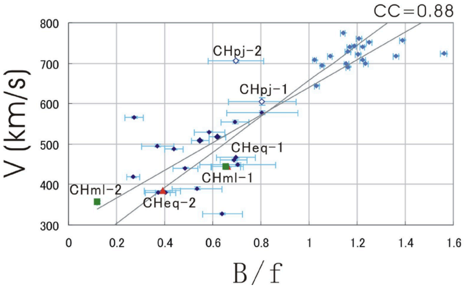

V-B/f gives the best correlation.

v_{1au}-f (Wang & Sheeley)

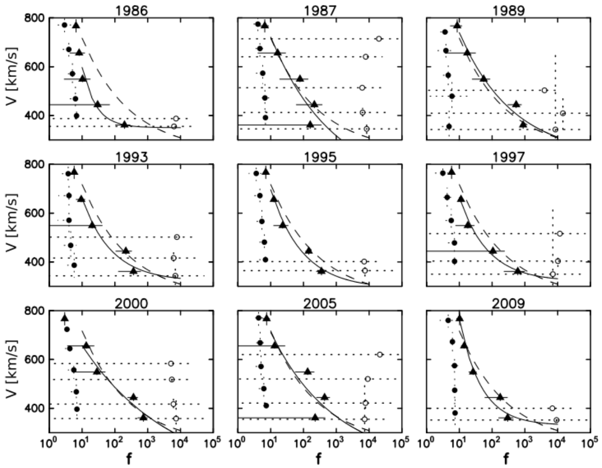

Figure 2 Dependence of velocity on the flux-expansion factor. Triangles are averages of all data in each year. Solid circles are data with weak magnetic-field strength (< 5 G) and small expansion factors (< 100), while open circles are those with strong magnetic-field strength (> 50 G) and a large expansion factor (> 1000). A solid curved line is the best-fit solution for Equation (3), while a dashed line is the average best-fit solution for the 24 years of data from year 1986 to 2009.

Fujiki et al.2015

- ▲: Yearly Average
- ●: Weak ***B*** & Small ***f***
- ○: Strong B & Large ***f***

v_{1au}-$B_{\odot}$

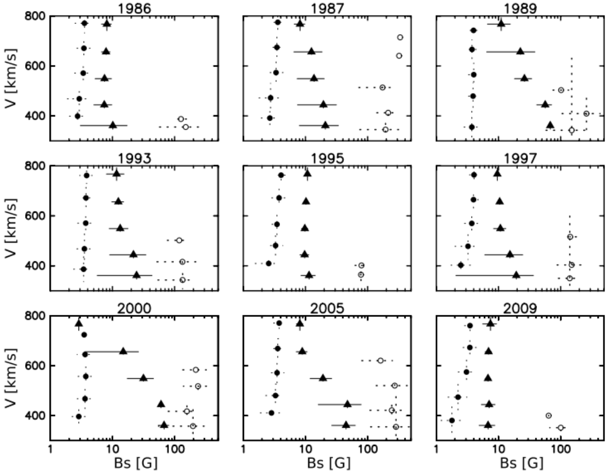

Figure 4 Dependence of velocity on the photospheric magnetic-field strength. Triangles are averages of all data in each year. Solid circles are data with weak magnetic-field strength (< 5 G) and a small expansion factor (< 100), while open circles are data with a strong magnetic-field strength (> 50 G) and a large expansion factor (> 1000).

Fujiki et al.2015

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v_{1au}-$B_{\odot}/f$

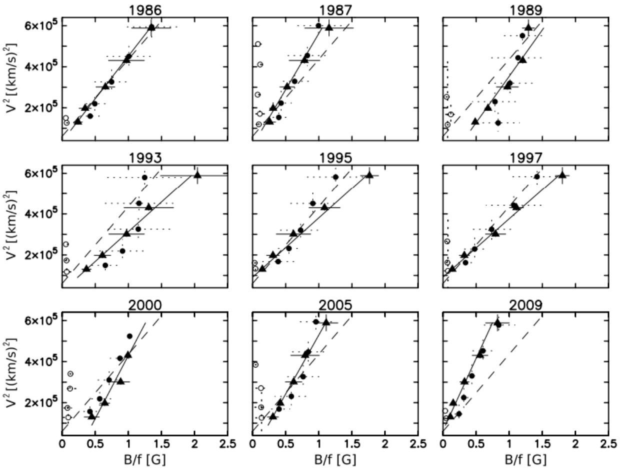

Figure 7 Dependence of velocity on the ratio of photospheric magnetic-field strength and a flux-expansion factor. Triangles are averages of all data in a year. Solid circles are SW1 with weak magnetic-field strength (< 5 G) and a small expansion factor (< 100), and open circles are SW2 with strong magnetic-field strength (> 50 G) and a large expansion factor (> 1000). Solid lines are the best-fit regression lines, while dashed lines are the average for the 24 years of data from 1986 to 2009.

Fujiki et al.2015

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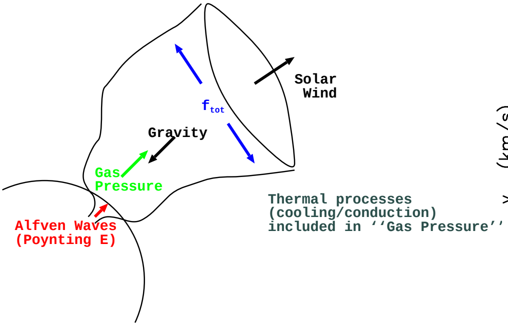
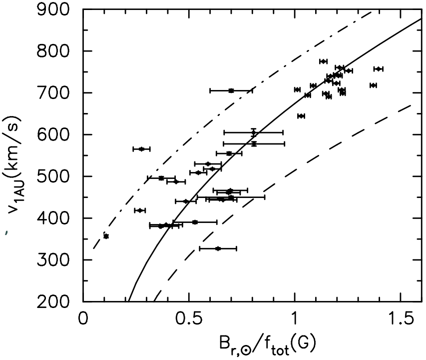
- ○: Strong B & Large ***f***

V–B/f relation

Suzuki 2006, ApJ, 640, L75

Data from Kojima+ (2005)





Energy conservation in a single flux tube gives

$$v_{1AU} = 300(\mathrm{km/s}) \times \sqrt{5.9\left(\frac{-\langle \delta B_\perp \delta v_\perp \rangle_\odot}{8.3\times 10^5 (\mathrm{cm\ s^{-1} G})}\right)\left(\frac{B_{r,\odot}(\mathrm{G})}{f_{tot}}\right) + 3.4\left(\frac{\gamma}{1.1}\right)\left(\frac{0.1}{\gamma - 1}\right)\left(\frac{T_C}{10^6(\mathrm{K})}\right) - 4.2}$$

V–B/f relation

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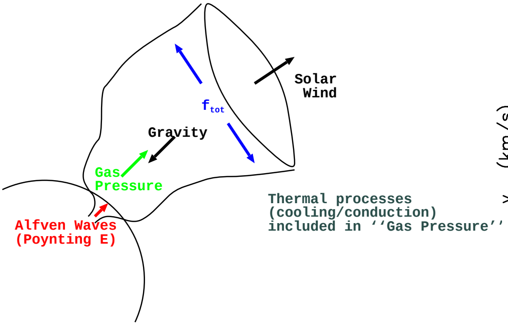

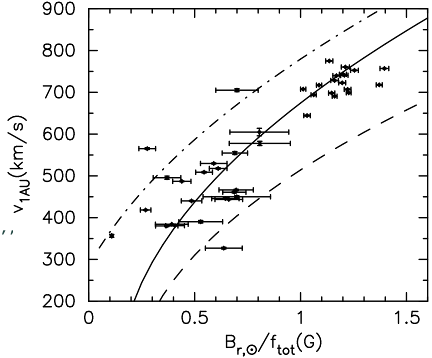

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$v \Leftarrow$ Alfvén waves in super-radially open flux tubes.