Saturation of Stellar Winds from Young Suns

Takeru K. Suzuki

Department of Physics, Nagoya University

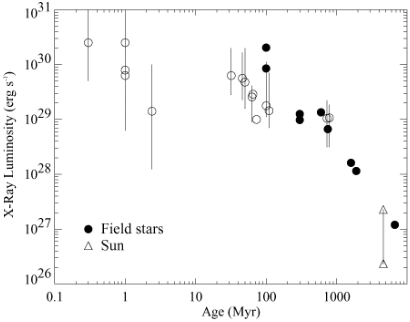
Nov. 14th., 2013

Suzuki, T. K.[1], Imada, S.[2], Kataoka, R.[3], Kato, Y.[4], Matsumoto, T.[1], Miyahara, H.[5], Tsuneta S.[6], 2013 (Oct.25th.), PASJ, 65, 98

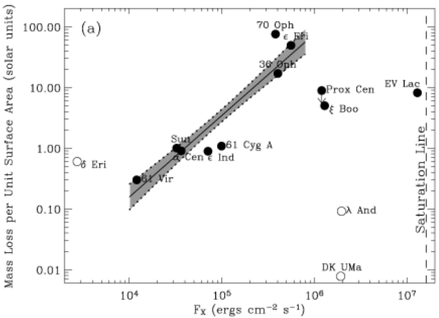
1: Physics, Nagoya U; 2: STELab, Nagoya U.; 3: NIPR; 4:NAOJ;
5: Musashino Art U.; 6: ISAS/JAXA

Solar-type Stars

L_X Güdel et al.2004



$\dot{M}$ Wood et al.2005



Age

F_X ⇒ Active

Young Solar-type Stars:

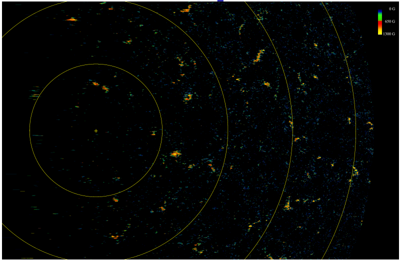
- Active: larger L_X & $\dot{M}$
  $L_X \lesssim 1000 \times L_{X,\odot}$ & $\dot{M} \lesssim 100 \times \dot{M}_\odot$
- Saturation of wind for very active stars
  - blocked by closed structure ?

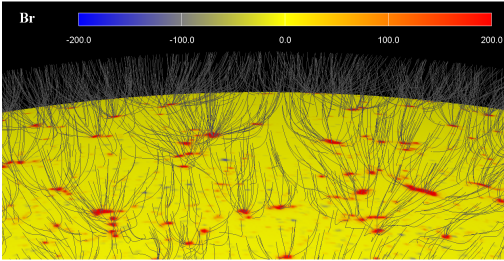
Outline

Aim of Work:
Extending our MHD simulations for Alfvén wave-driven solar wind from the present Sun to young active suns.

- Corona & Wind in open flux tubes.

Open flux tubes on the Sun



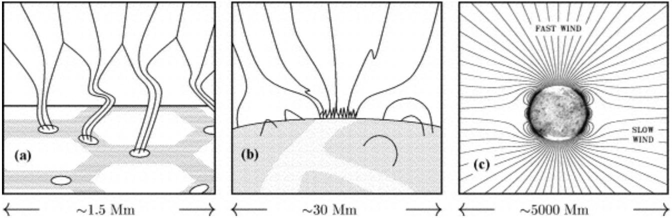


HINODE Obs:Tsuneta et al.2008; Shimojo et al.2009; Itoh et al.2010; Shiota et al.2012

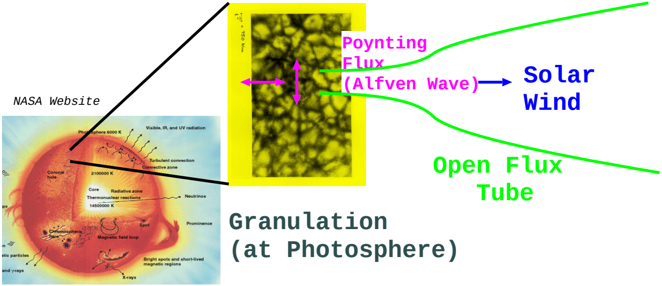
~1kG at the photosphere & 1-10G in the corona

⇒ Super-radially open flux tubes (100–1000 times)

Cranmer & van Ballegooijen 2005

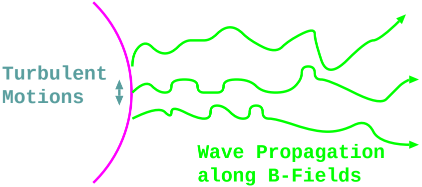


Alfvén(ic) wave-driven wind

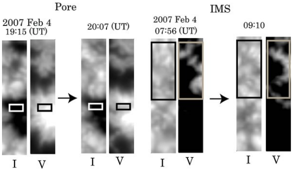


Alfvén Wave-driven wind

Alazraki & Couturier 1971; Belcher & MacGregor 1976



Observation



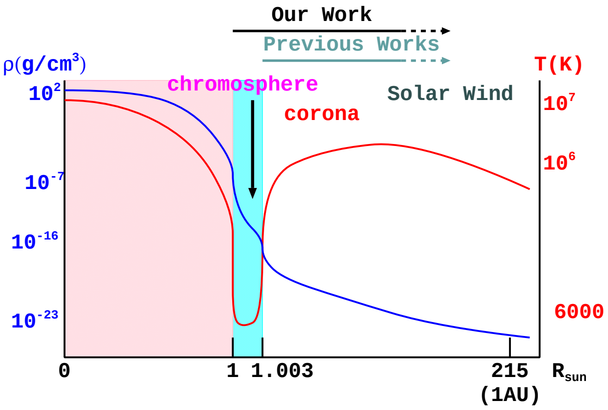
Get information of

$$z_{\pm} = \delta v \mp \delta B / \sqrt{4\pi\rho}$$

(Fujimura & Tsuneta 2009)

Other obs.
Okamoto et al.2007;
Tomczyk et al.2007;
...

Simulation Region



(not to scale)

- cool photosph. & chromosph. ⇔ hot corona & wind
- huge density contrast
  (photosphere ⇐ 8-10 orders of mag. ⇒ corona)

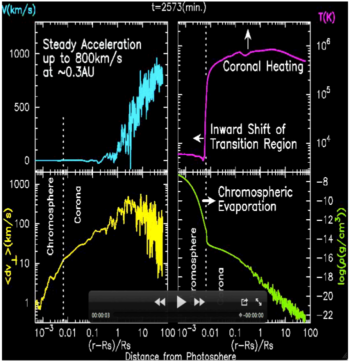
Simulation from Photosphere (many obs. data):
Forward-type simulations ⇒ $\dot{M}$.

Simulations for the present Sun

Focus on the dynamics in a single open flux tube

1D (1.5D) 2D (2.5D)

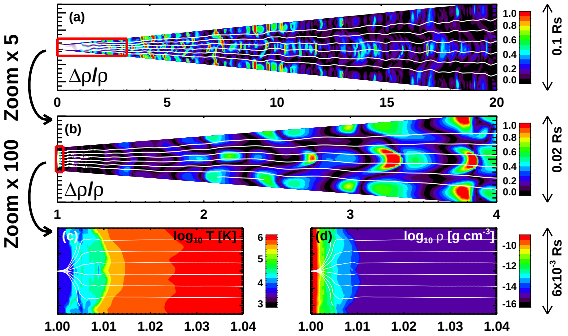
Suzuki & Inutsuka (2005), ApJ, 632,L49



(mesh#: 14,000)

Solar Wind Simulation (1D)

Matsumoto & Suzuki 2012, ApJ, 749, 8

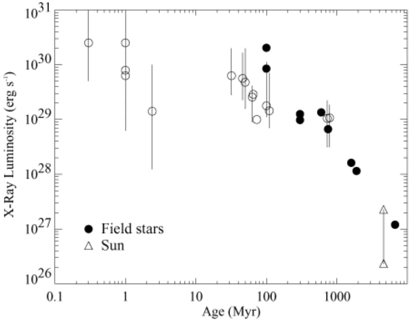


mesh#: 8,000× 32

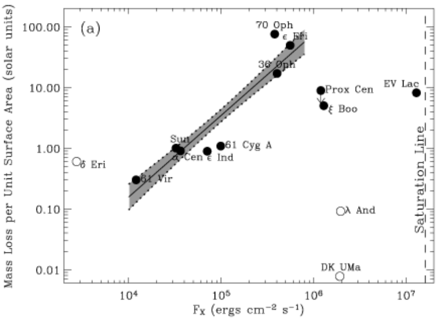
Simulation by Matsumoto

Solar-type Stars

L_X Güdel et al.2004



$\dot{M}$ Wood et al.2005



Age $\qquad F_X \quad \Rightarrow$ Active

Young Solar-type Stars:

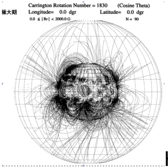
- Active: larger L_X & $\dot{M}$
  $L_X \lesssim 1000 \times L_{X,\odot}$ & $\dot{M} \lesssim 100 \times \dot{M}_\odot$
- Saturation of wind for very active stars
  - blocked by closed structure ?

Extending to Young Active Suns

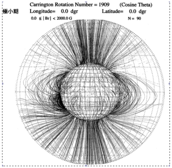
Active young suns: covered with strong closed $\boldsymbol{B}$

(Donati & Collier Comeron 1997; Saar 2001; ...)

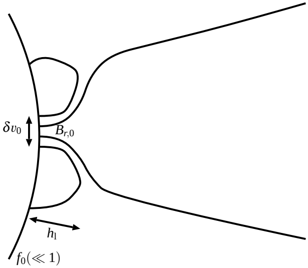
Solar Maximum



Solar Minimum



Hakamada et al.2006



performed 163 runs

4 parameters in our simulations

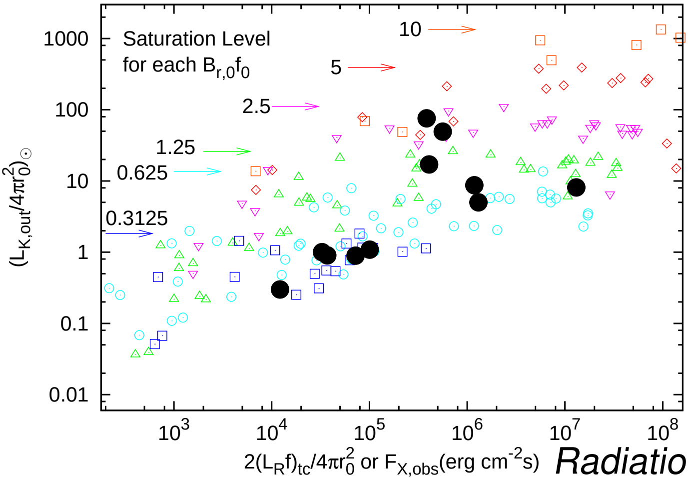
- $\boldsymbol{B_0 = (0.5 - 16)}$ kG
- $\boldsymbol{\delta v_0 = (0.7 - 7.6)}$ km/s
- filling factor of open flux tubes $\boldsymbol{f_0 = (1/800 - 1/6400)}$
- Loop Height $\boldsymbol{h_{\rm l} = (0.01 - 0.1) R_\odot}$

"F_X–$\dot{M}$"

Wind Kin.E.(/⊙ value)

Suzuki et al.2013

●: OBS by Wood et al.2005



Radiation Loss
(~ X/EUV flux)

Different COLORS ⇔ $(B_{r,0}f_0)$

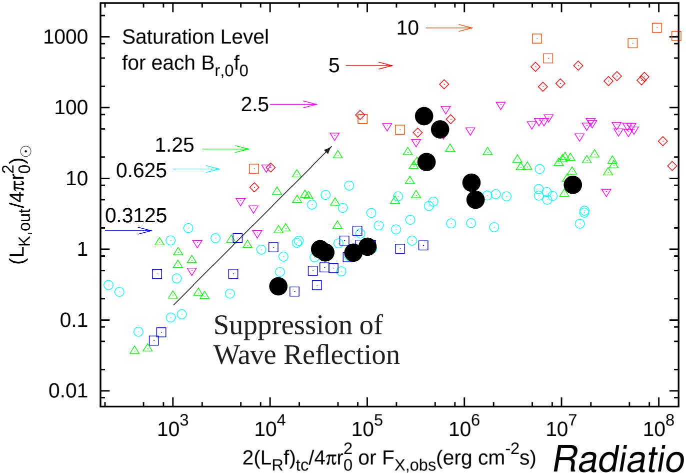
(average B_0 (G) in open flux regions)

"F_X–$\dot{M}$"

Wind Kin.E.(/⊙ value)

Suzuki et al.2013

●: OBS by Wood et al.2005



Radiation Loss

(~ X/EUV flux)

Different COLORS ⇔ $(B_{r,0}f_0)$

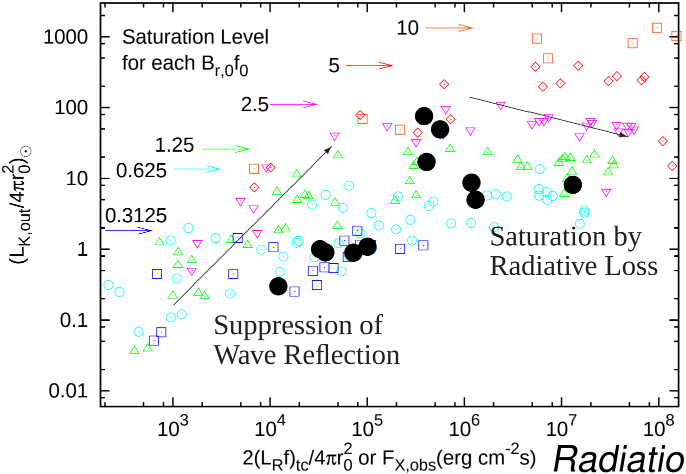
(average B_0 in open flux regions)

“$F_X - \dot{M}$”

Wind Kin.E.(/⊙ value)

Suzuki et al.2013

●: OBS by Wood et al.2005

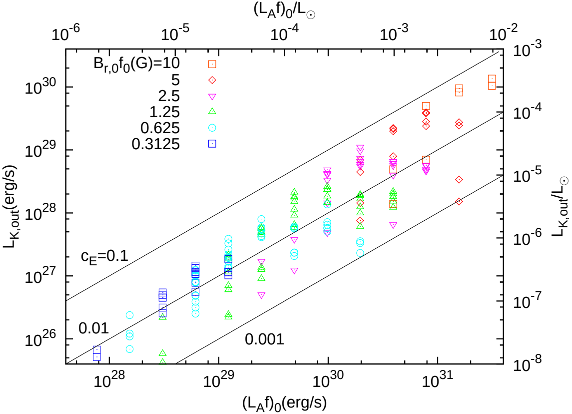


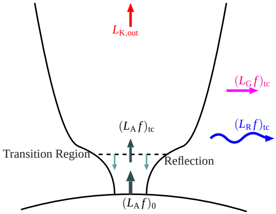
Radiation Loss
(~ X/EUV flux)

Different COLORS ⇔ $(B_{r,0}f_0)$

(average B_0 in open flux regions)

Surface Poynting E.⇒ Wind K. E.





Different colors ⇔ $(B_{r,0} f_0)$ (average B_0 in open flux regions)

- x-axis: Injected Alfvén wave energy, $L_A f_0$
- y-axis: Wind K.E., $L_{K,out} = \dot{M}\frac{v_r^2}{2}$

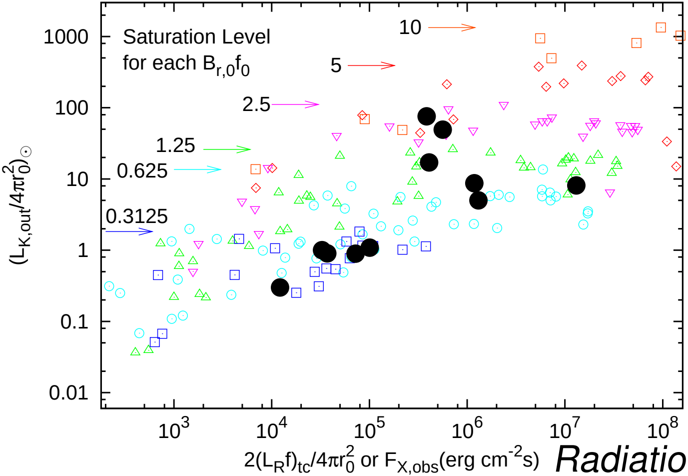
Energy Conversion Rate : 0.1-10%

"F_X–$\dot{M}$"

Suzuki et al.2013

Wind Kin.E.(/⊙ value)

●: OBS by Wood et al.2005



Radiation Loss
(~ X/EUV flux)

Different COLORS ⇔ $(B_{r,0}f_0)$

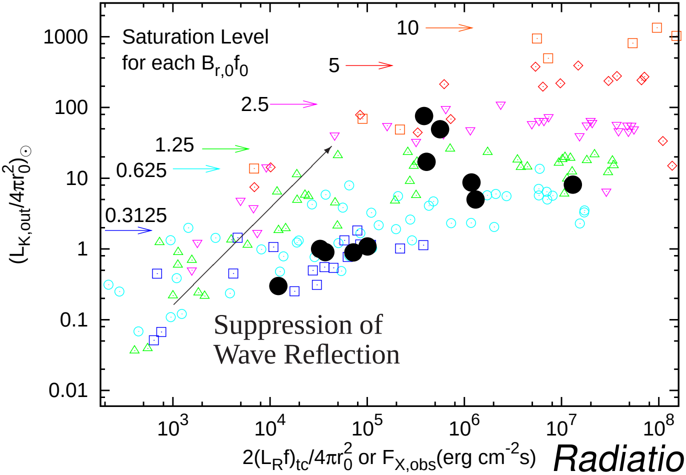
(average B_0 in open flux regions)

"F_X–$\dot{M}$"

Wind Kin.E.(/⊙ value)

Suzuki et al.2013

●: OBS by Wood et al.2005



Radiation Loss
(~ X/EUV flux)

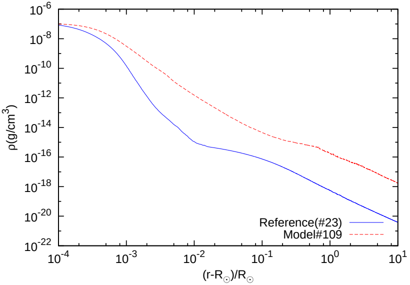
Different COLORS ⇔ $(B_{r,0}f_0)$

(average B_0 in open flux regions)

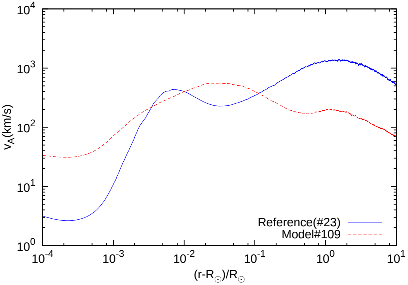
Extended Chromosphere in Active Stars

Comparing active & present Sun cases

ρ structure



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



Gas Lifted up by δB^2 ⇒ Extended Chromosphere

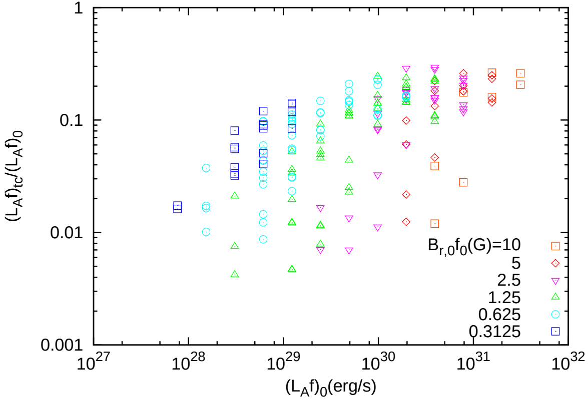
⇒ v_A changes more slowly.

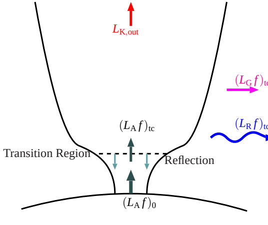
⇒ suppression of wave reflection.

Hollweg 1984; Moore et al.1991 ‣ Reflection test

Reflection in Chromosphere

Transmission Fraction to Corona



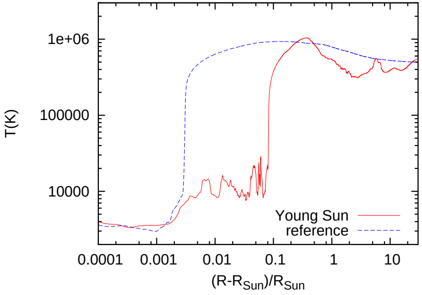


Smaller $(L_A f)_0$ suffers more reflection (transmissivity $< 1\%$).

Reflection test

Extended Chromosphere in Active Suns

A snapshot of one case



Very thick chromosphere

($\sim \mathbf{0.1}R_\star$) in the active case.

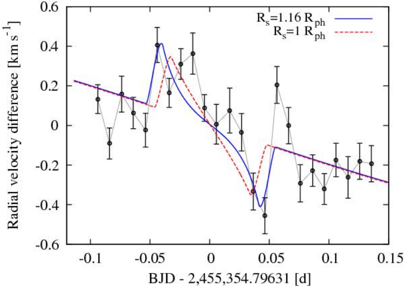
CoRoT-2A: young sun-like star

(Age~0.1-0.3 Gyr)

Rossiter-McLaughlin effect

(planet eclipse) by

Chromosphere (Ca II H& K lines)



Czesla et al.2012

$$r_{\mathbf{chrm}} - R_\star \approx \mathbf{0.16}R_\star$$

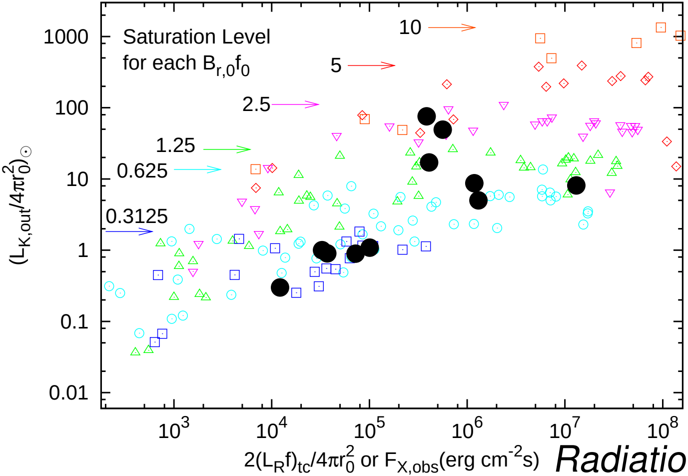
c.f. Present Sun: $\lesssim \mathbf{0.005}R_\odot$

"$F_X - \dot{M}$"

Wind Kin.E.(/⊙ value)

Suzuki et al.2013

●: OBS by Wood et al.2005



Radiation Loss

(~ X/EUV flux)

Different COLORS ⇔ $(B_{r,0} f_0)$

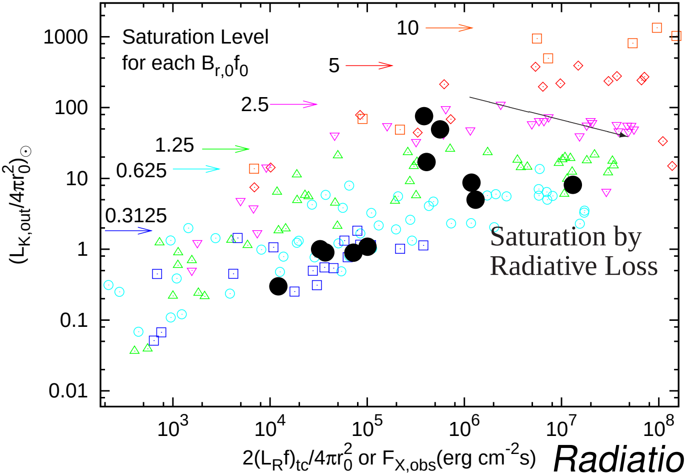
(average B_0 in open flux regions)

“F_X–$\dot{M}$”

Suzuki et al.2013

Wind Kin.E.(/⊙ value)

●: OBS by Wood et al.2005



Radiation Loss

(~ X/EUV flux)

Different COLORS ⇔ $(B_{r,0}f_0)$

(average B_0 in open flux regions)

Wind Energetics

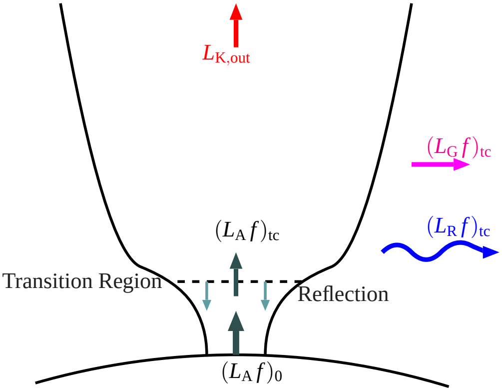
Pick up dominant terms ('tc'= Top of Chromosphere):

$$L_{\mathrm{K,out}} \approx (L_{\mathrm{A},+}f)_{\mathrm{tc}} - (L_{\mathrm{R}}f)_{\mathrm{tc}} - (L_{\mathrm{G}}f)_{\mathrm{tc}}$$

Wind K.E. ⇐ (Net +Wave E.)-(Rad.Loss)-(Grav.Loss)

Conductive loss is included in (Rad.Loss)

$$L_{\mathrm{K,out}} \equiv \dot{M}\frac{v_r^2}{2}$$



$$L_{\mathrm{A},\pm}f \equiv \mp\Phi_B\frac{v_\perp B_\perp}{4\pi}$$

Energy flux of Alfvén waves

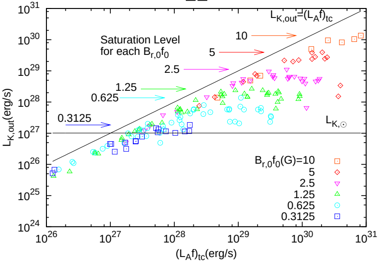
$$(L_{\mathrm{G}}f)_0 \equiv \dot{M}\frac{GM_\odot}{r_0}$$

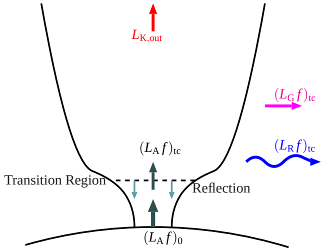
$$(L_{\mathrm{R}}f)_0 \equiv 4\pi\int_{r_0}^{r_{\mathrm{out}}} q_{\mathrm{R}}r^2 f\,dr$$

Wave E. – K.E., Rad.loss, Grav.loss

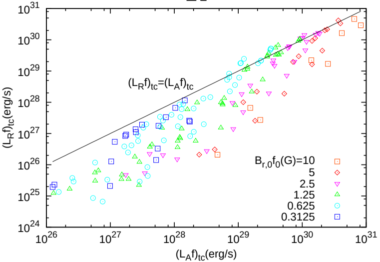
$$L_{K,out} \approx (L_A f)_{tc} - (L_R f)_{tc} - (L_G f)_{tc}$$

L_K

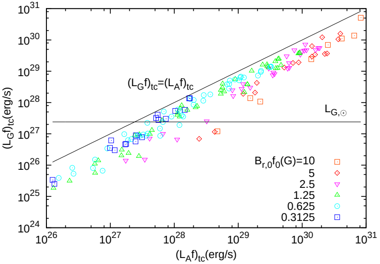




L_R



L_G



Saturation of Wind by Radiation Loss

$$L_{\mathrm{K,out}} \approx (L_{\mathrm{A}} f)_{\mathrm{tc}} - (L_{\mathrm{R}} f)_{\mathrm{tc}} - (L_{\mathrm{G}} f)_{\mathrm{tc}}$$

Wind K.E. ⇐ (Net Wave E.) - (Rad.Loss) - (Grav.Loss)

As $L_{\mathrm{A}} \Uparrow$

- $L_{\mathrm{R}}/L_{\mathrm{A}} \Uparrow$

  $L_{\mathrm{R}} \propto \rho^2$ (optically thin)

- $L_{\mathrm{K}}/L_{\mathrm{A}} \Downarrow$

With increasing the injected Alfvén waves, most of the energy is used up by the radiation loss.

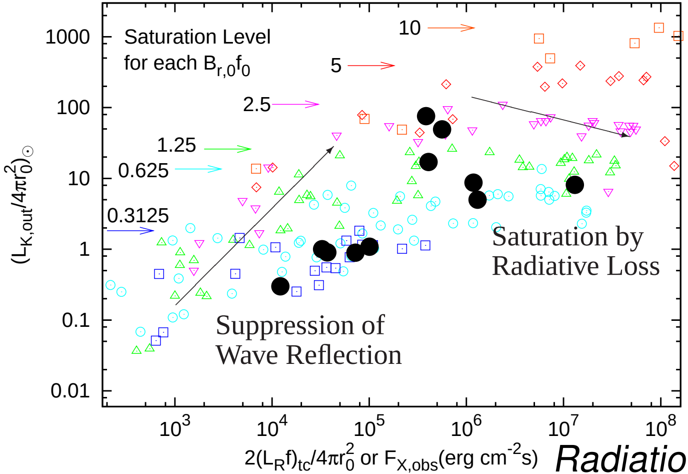
⇒ No more energy for the stellar wind.

"F_X–$\dot{M}$"

Wind Kin.E.(/⊙ value)

Suzuki et al.2013

●: OBS by Wood et al.2005



Radiation Loss (~ X/EUV flux)

Different COLORS ⇔ $(B_{r,0}f_0)$

(average B_0 in open flux regions)

Summary

Young Solar-type Stars: Active

- $\dot{M}$: $\lesssim 100$ times.
- X-rays: $\lesssim 1000$ times.

MHD simulations extending from the present Sun:

- When the energy inputs from the surface ⇑
  - rapid increase of wind $\dot{M}$ ⇐ wave reflection ⇓
  - eventiually saturate by radiation loss (X/EUV) ⇑

    Saturation level ⇔ B
- Extended Chromosphere in Active Stars

  ⇔ Observation by planet eclipse

- If $\dot{M} \sim 1000\dot{M}_{\odot}$ during initial $\sim 10^9$yr ⇔ Early Faint Sun Paradox
- $F_{\rm X} - t$ diagram ⇒ $\dot{M} \propto t^{-1.23}$

Limitations: 1D, no-rotation,... ⇒

- Shelyag et al.S2-P-06; Morton et al. S2-P-08; Hiller et al.S2-P-09
- Pinto & Brun S2-P-15

Wind Energetics

Pick up dominant terms:

$$L_{\mathrm{K,out}} \approx (L_{\mathrm{A},+}f)_0 - (L_{\mathrm{A},-}f)_0 - (L_{\mathrm{R}}f)_0 - (L_{\mathrm{G}}f)_0$$

Wind K.E. ⇐ (Wave E.)-(Reflection)-(Grav.Loss)-(Rad.Loss)

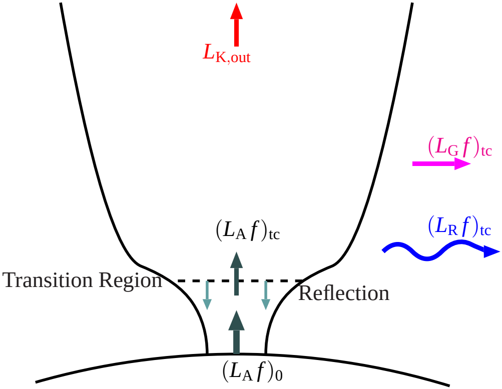
$$L_{\mathrm{K,out}} \equiv \dot{M}\frac{v_r^2}{2}$$

$$L_{\mathrm{A},\pm}f \equiv \mp\Phi_B\frac{v_\perp B_\perp}{4\pi}$$

Energy flux of Alfvén waves

$$(L_{\mathrm{G}}f)_0 \equiv \dot{M}\frac{GM_\odot}{r_0}$$

$$(L_{\mathrm{R}}f)_0 \equiv 4\pi\int_{r_0}^{r_{\mathrm{out}}} q_{\mathrm{R}} r^2 f\, dr$$



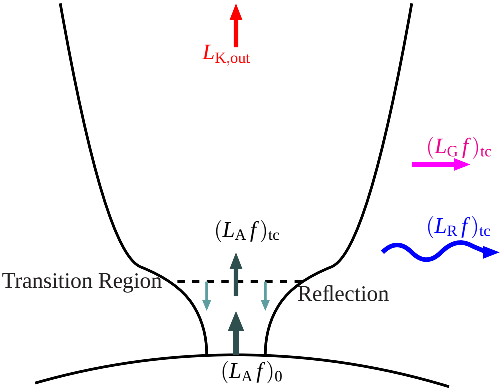
Focusing on Reflection in Chromosphere

Pick up dominant terms:

$$L_{\mathrm{K,out}} \approx (L_{\mathrm{A},+}f)_0 - (L_{\mathrm{A},-}f)_0 - (L_{\mathrm{R}}f)_0 - (L_{\mathrm{G}}f)_0$$

Wind K.E. ⇐ (Wave E.)-(Reflection)-(Grav.Loss)-(Rad.Loss)

$$L_{\mathrm{K,out}} \equiv \dot{M}\frac{v_r^2}{2}$$



$$L_{\mathrm{A},\pm}f \equiv \mp\Phi_B\frac{v_\perp B_\perp}{4\pi}$$

Energy flux of Alfvén waves

$$(L_{\mathrm{G}}f)_0 \equiv \dot{M}\frac{GM_\odot}{r_0}$$

$$(L_{\mathrm{R}}f)_0 \equiv 4\pi\int_{r_0}^{r_{\mathrm{out}}} q_{\mathrm{R}}r^2 f\,dr$$