Evolution of the Sun & Solar Wind

A02: 「太陽風進化と放射変動」

Takeru K. Suzuki (鈴木 建)

Department of Physics, Nagoya University (名大 理 物理)

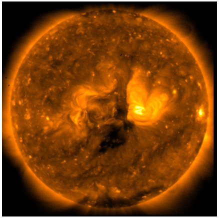
Feb. 20th., 2014

Seki, K.(Nagoya STE), Terada, N.(Tohoku), Yokoyama T.(U.Tokyo),
Imamura, T.(ISAS/JAXA), Nakamura, T.(NIPR), Nakagawa, H., Kuroda, T.(Tohoku),
Fujimoto, M.(U.Tokyo), Isobe, H., Nogami, D.(Kyoto)

Based on the following paper
Suzuki, T. K. (Nagoya Phys.), Imada, S. (Nagoya STE), Kataoka, R. (NIPR,Japan),
Kato, Y. (NAOJ), Matsumoto, T. (Nagoya Phys.), Miyahara, H. (Musashino Art U.)，
Tsuneta S. (ISAS/JAXA), 2013, PASJ, 65, 98

⇐ Time Evolution ⇐

Present Sun



HINODE/XRT

⇐

Young Active Sun

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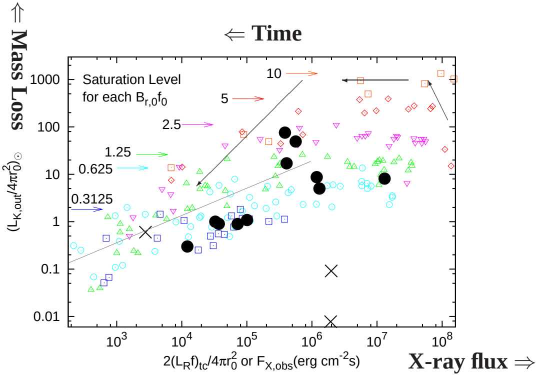

- Black Symbols: Observation by Wood et al.(2005)
- Color Symbols: Numerical Simulation by Suzuki et al.(2013)

Evolution of Solar Luminosity
–Early Faint Sun–

Reason for L(bolometric luminosity)$\Uparrow$ with time

e.g. Gough 1981

4H$\Rightarrow$He (nuclear fusion) with time

$\Rightarrow$ μ (mean mol. weight)$\Uparrow$

$\Rightarrow$ $p = \rho k_{\rm B}T/\mu m_{\rm H} \Downarrow$ ($n \Downarrow \Rightarrow p \Downarrow$)

$\Rightarrow$ Contraction of Core $\Rightarrow \rho \Uparrow$, Grav.E. $\approx -GM/r \Downarrow$

$\Rightarrow$ U(Internal E$\propto T$) $\Uparrow$ by Virial theorem

4H$\Rightarrow$He in Core $\Rightarrow \rho, T \Uparrow$

Nuclear reaction rate is positively correlated with ρ, T (sensitive on T)

$\Rightarrow$ Energy Generation ($\propto$reaction rate)$\Uparrow \Rightarrow L \Uparrow$

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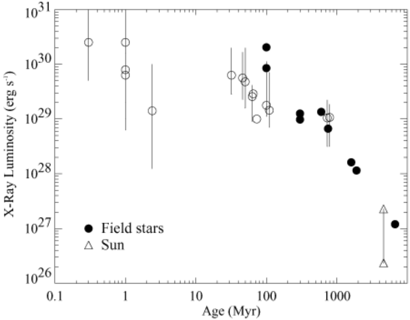
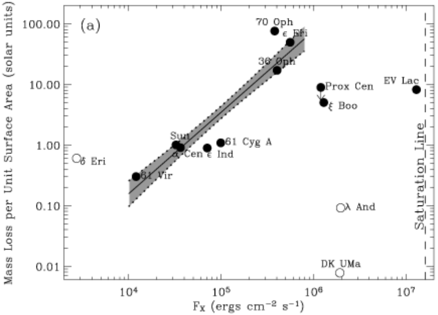
Young Sun is Faint.

X-rays & Winds from "Solar-type" Stars

$L_X (= 4\pi R_\star^2)$ 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 ?

Early Sun: Standard Picture

Early Sun: Standard Picture

Faint but Active

- Bolometric Luminosity: 20-30 % smaller
- Mass Loss Rate: could be 100 times larger
- X-ray Flux: could be 1000 times larger

Note: Energy loss by X-ray and solar wind is $\sim \mathbf{10^{-6}}$ times of the bolometric luminosity for the present Sun.

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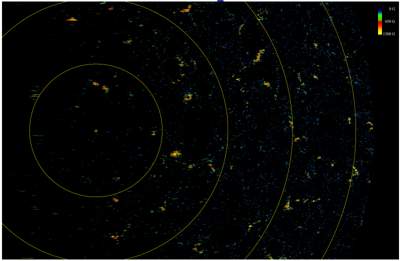
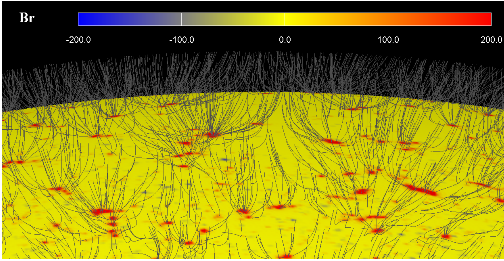
⇒ Numerical Simulations for $\dot{M}$ & L_{X}(this work)

Open flux tubes on the Sun



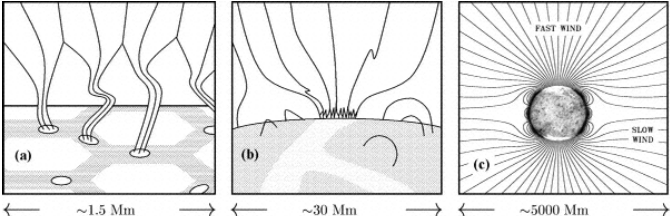


HINODE Obs:Tsuneta et al.2008; Shimojo et al.2009; Itoh et al.2010; Shiota et al.2012

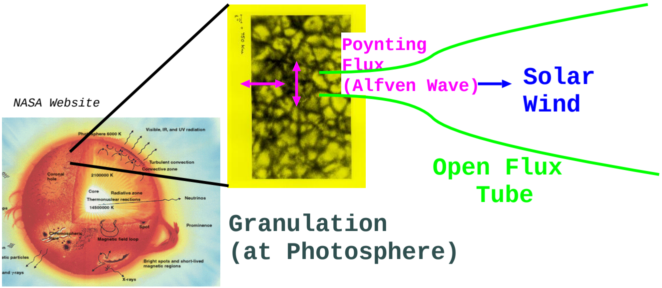
~1kG at the photosphere & 1-10G in the corona

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

Cranmer & van Ballegooijen 2005

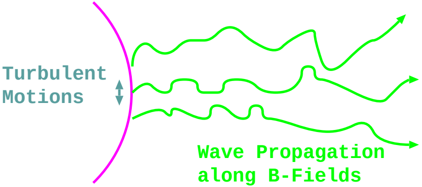


Alfvén(ic) wave-driven wind

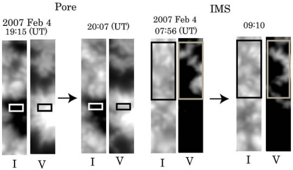


Alfvén Wave-driven wind

Alazraki & Couturier 1971; Belcher & MacGregor 1976



Observation



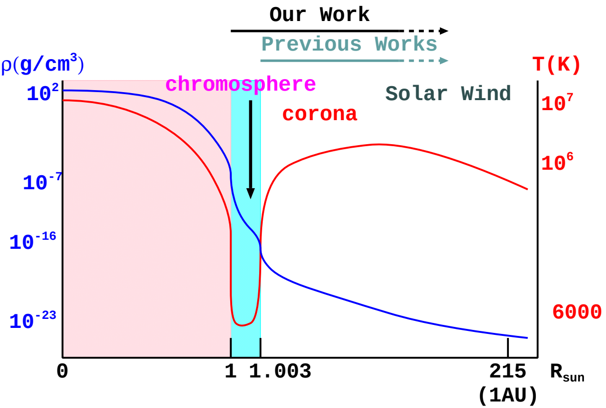
Get information of

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

(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)

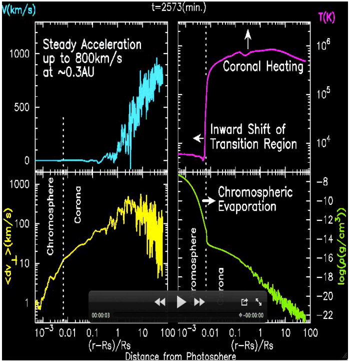
Simulation from Photosphere (many obs. data):
Forward-type simulations ⇒ $\dot{M}$.

Simulations for the present Sun

- Focus on the dynamics in a single open flux tube
- MHD + rad.cooling & thermal conduction

1D (1.5D)

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

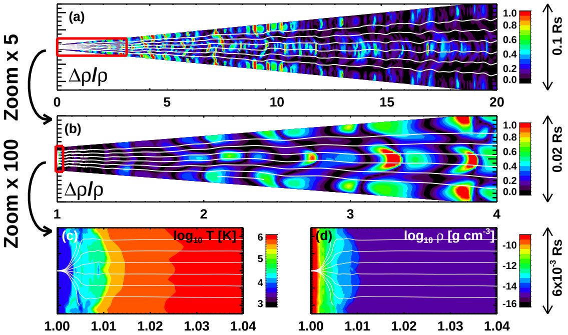


(mesh#: 14,000)

Solar Wind Simulation (1D)

2D (2.5D)

Matsumoto & Suzuki 2012, ApJ, 749, 8



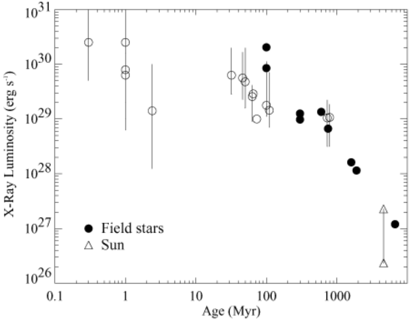
mesh#: 8,000× 32

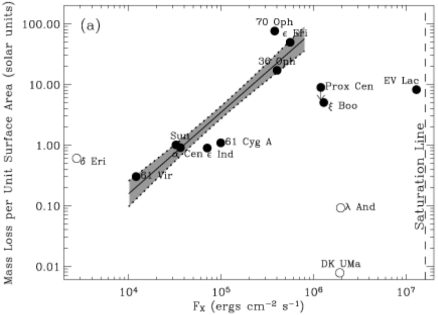
Simulation by Matsumoto

X-rays & Winds from Solar-type Stars

$L_X (= 4\pi R_\star^2)$ Güdel et al.2004

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





Age

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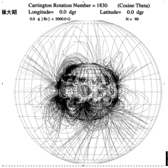
Extending to Young Active Suns

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

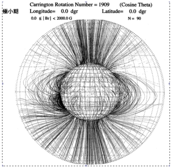
(Donati & Collier Comeron 1997; Saar 2001; ...)

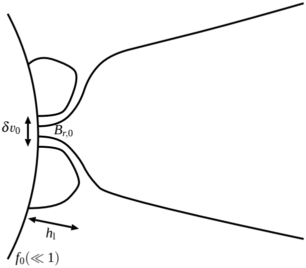
Solar Maximum



Hakamada et al.2006

Solar Minimum





performed 163 runs

4 parameters in our simulations

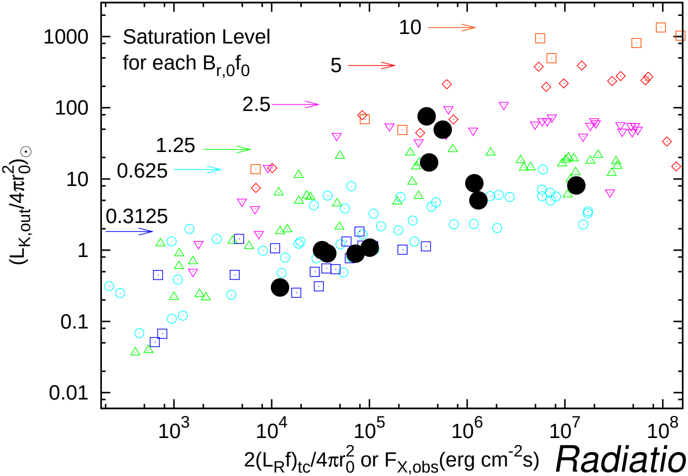
- $B_0 = (0.5 - 16)$ kG
- $\delta v_0 = (0.7 - 7.6)$ km/s
- filling factor of open flux tubes $f_0 = (1/800 - 1/6400)$
- Loop Height $h_{\rm l} = (0.01 - 0.1) R_\odot$

"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(G) in open flux regions)

“F_X–$\dot{M}$”

Wind Kin.E.(/⊙ value)

Suzuki et al.2013

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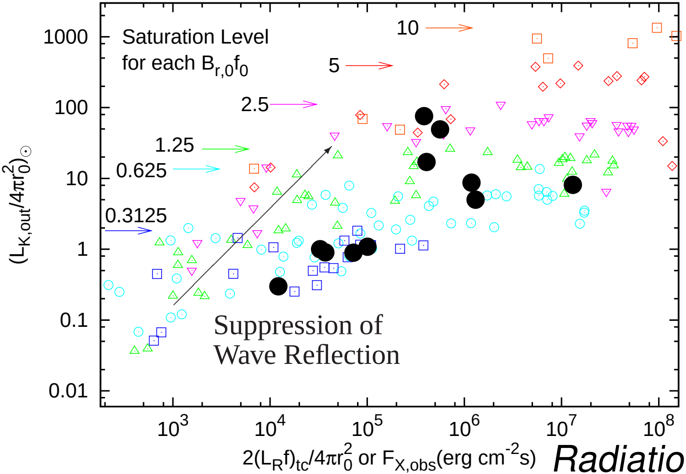

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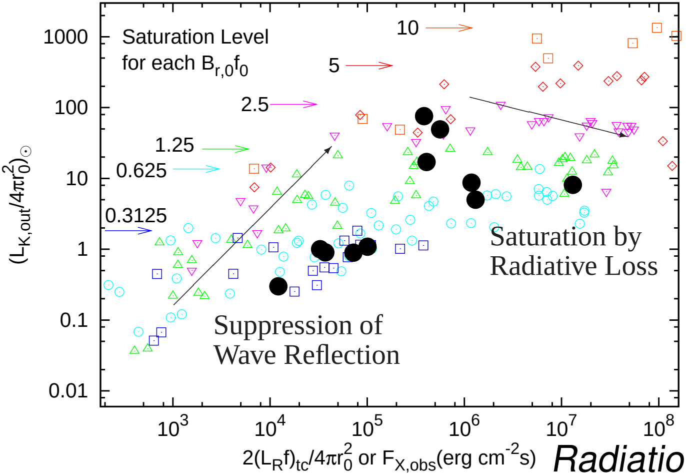

Radiation Loss (~ X/EUV flux)

Different COLORS ⇔ $(B_{r,0}f_0)$

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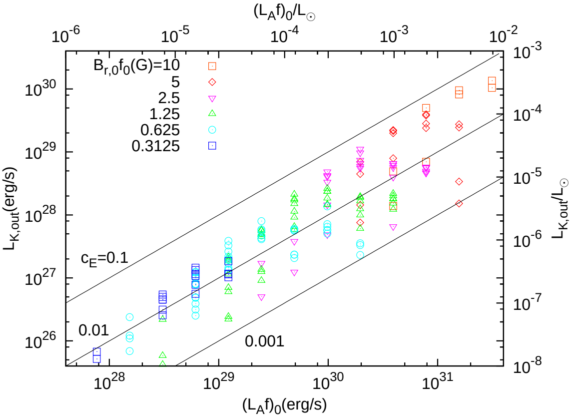
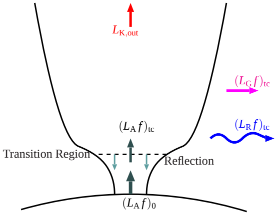
Surface Poynting E.⇒ Wind K. E.





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

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

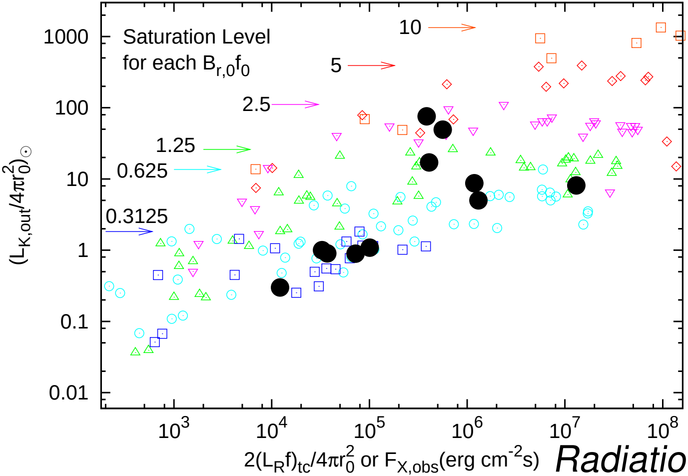
Energy Conversion Rate : 0.1-10%

“F_X–$\dot{M}$”

Suzuki et al.2013

Wind Kin.E.(/⊙ value)

●: OBS by Wood et al.2005



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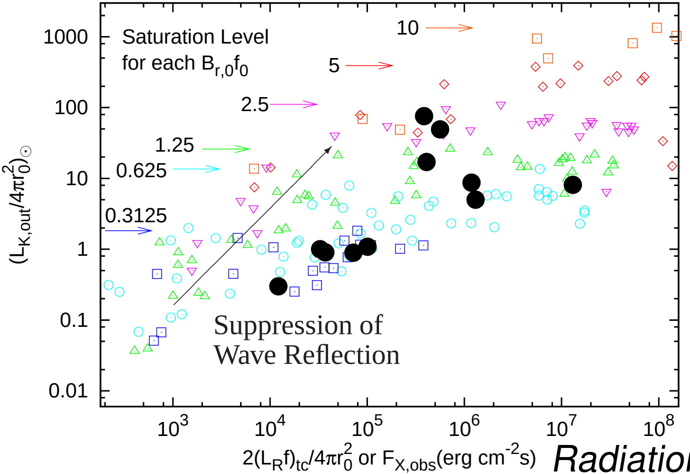


Radiation Loss
(~ X/EUV flux)

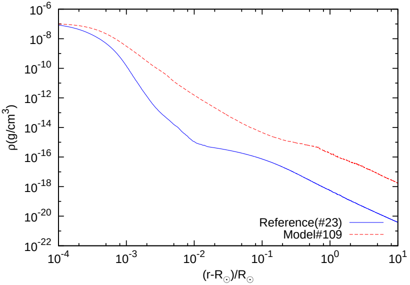
Different COLORS ⇔ $(B_{r,0}f_0)$

(average B_0(G) in open flux regions)

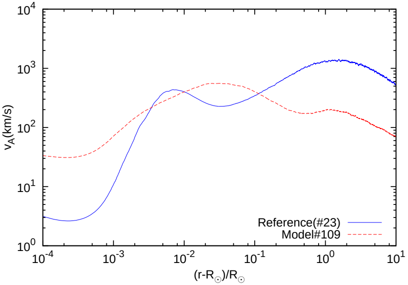
Extended Chromosphere in Active Stars

Comparing active & present Sun cases

ρ structure



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



Gas Lifted up by δB^2 ⇒ Extended Chromosphere

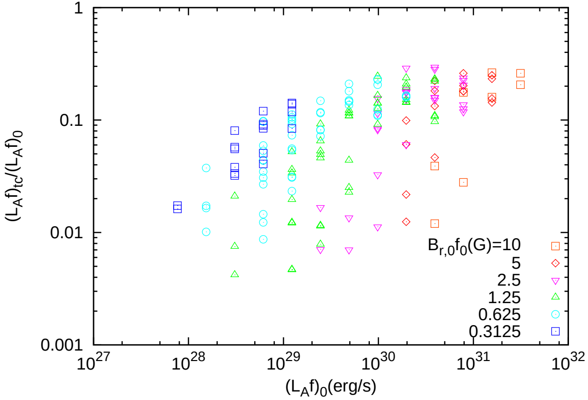
⇒ v_A changes more slowly.

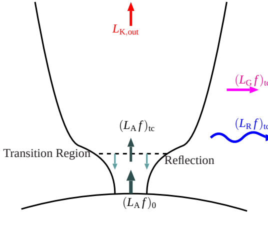
⇒ suppression of wave reflection.

Hollweg 1984; Moore et al.1991 ▸ Reflection test

Reflection in Chromosphere

Transmission Fraction to Corona



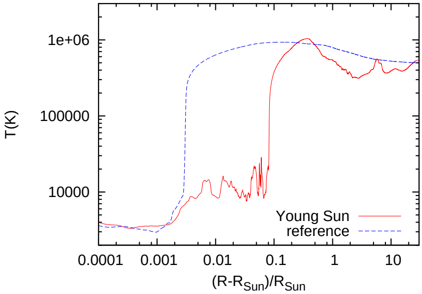


Smaller $(L_A f)_0$ suffers more reflection (transmissivity $< 1\%$).

Reflection test

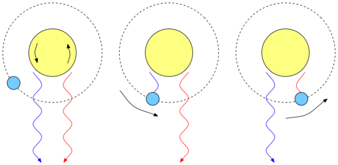
Extended Chromosphere in Active Suns

A snapshot of one case



Very thick chromosphere

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



Wikipedia

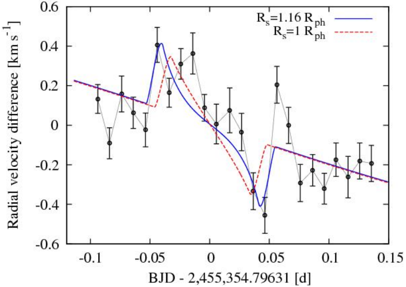
CoRoT-2A: young sun-like star

(Age~0.1-0.3 Gyr)

Rossiter-McLaughlin effect

(planet eclipse) by

Chromosphere (Ca II H& K lines)



Czesla et al.2012

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

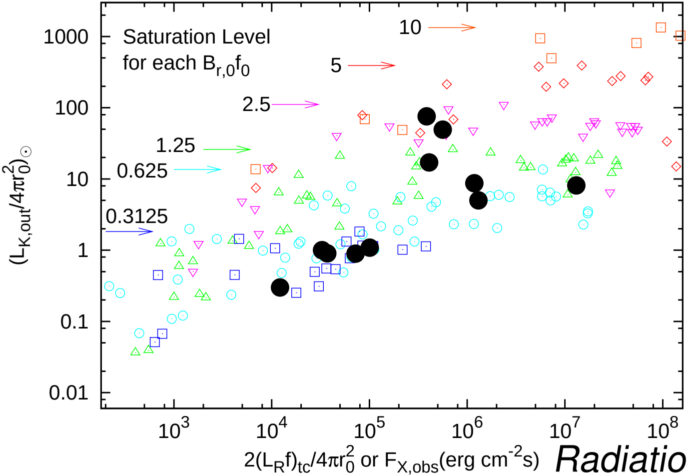
c.f. Present Sun: $\lesssim \mathbf{0.005} R_\odot$

"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)

"$F_X - \dot{M}$"

Suzuki et al.2013

Wind Kin.E.(/⊙ value)

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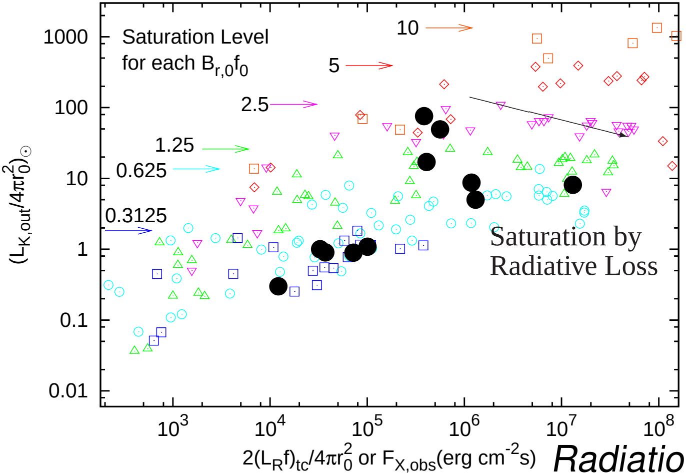


Radiation Loss
(~ X/EUV flux)

Different COLORS ⇔ $(B_{r,0} f_0)$

(average B_0 in open flux regions)

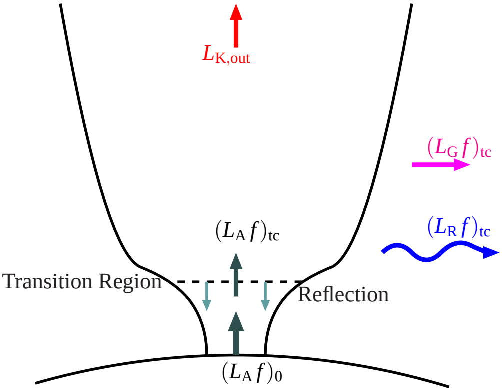
Wind Energetics

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

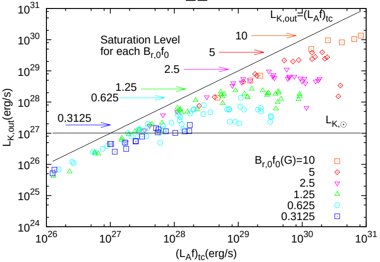
$$(L_{\mathrm{G}}f)_0 \equiv \dot{M}\frac{GM_\odot}{r_0}$$

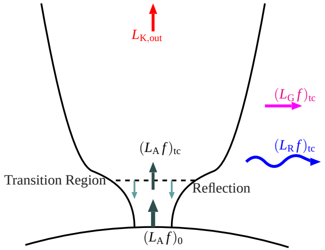
$$(L_{\mathrm{R}}f)_0 \equiv 4\pi\int_{r_0}^{r_{\mathrm{out}}} q_{\mathrm{R}} r^2 f\, dr$$

Wave E. – K.E., Rad.loss, Grav.loss

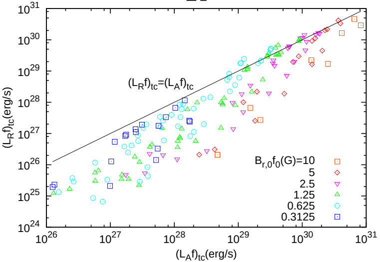
$$L_{\mathrm{K,out}} \approx (L_{\mathrm{A}}f)_{\mathrm{tc}} - (L_{\mathrm{R}}f)_{\mathrm{tc}} - (L_{\mathrm{G}}f)_{\mathrm{tc}}$$

L_{K}

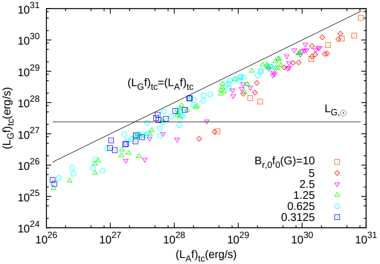




L_{R}



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_{A} ⇑

- $L_{\mathrm{R}}/L_{\mathrm{A}}$ ⇑

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

- $L_{\mathrm{K}}/L_{\mathrm{A}}$ ⇓

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

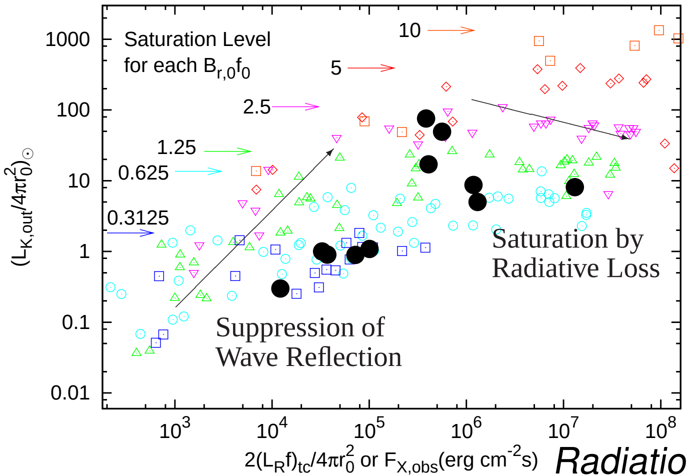
⇒ No more energy for the stellar wind.

“F_X–$\dot{M}$”

Suzuki et al.2013

Wind Kin.E.(/⊙ value)

●: OBS by Wood et al.2005



Radiation Loss

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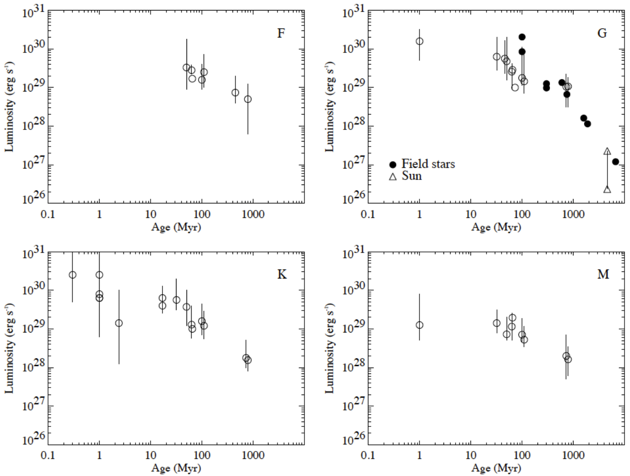
(average B_0 in open flux regions)

$F_X - T_{age}$

Güdel 2004

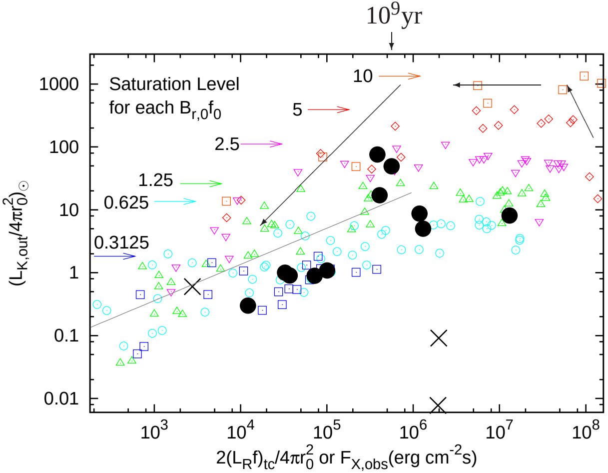


Mainly from star clusters (Age= $T_{\rm cluster}$)

- $L_X \approx (3 \pm 1) \times 10^{28} \left(\frac{T_{\rm age}}{10^9 {\rm yr}} \right)^{-1.5 \pm 0.3}$ erg s^{-1}

Time Evolution in $L_R - L_K$ diagram

Suzuki et al.2013



Black Symbols: Wood et al.2005

An Optimistic Case: $1000\dot{M}_\odot$ during $\sim \mathbf{10^9}$yr

$\Rightarrow \mathbf{0.02}M_\odot$

Summary & Plan

- Young Solar-type Stars: Faint but Active
- When the energy inputs from the surface ⇑
  - X,EUV radiation rapidly increases
    ⇐ Suppressing reflection of Alfvén waves (?)
  - Stellar wind rapidly increases but is saturated
    ⇐ Saturation by Radiative Loss (?)
    Saturation level ⇔ $\boldsymbol{B}$

Future Plan

- Time evolution of convection & $\boldsymbol{B}$ in the Sun ?
- Importance of Coronal Mass Ejections
- Role of Faster Rotation
- Realistic 3D treatment ? –turbulent cascade–

Early Faint Sun Paradox

Sagan & Mullen 1972; Karhu & Epstein 1986

- Standard Model with constant $M_\odot$
  $\Rightarrow$ The early Sun is 20-30% fainter (Gough 1981)
  $\Rightarrow$ Freezing early Earth & Mars
  $\Leftrightarrow$ Life on Earth & Liquid water on Mars ?
- Radiation flux at the Earth:
  $$F(\propto \sigma T_\oplus^4) = \frac{L}{4\pi r^2} \propto \frac{M^{4.75}}{M^{-2}} = M^{6.75}$$
  - $L \propto M^{4.75}$ Minton & Malhotra 2007
  - $r \propto M^{-1} \Leftarrow$ Conservation of Ang.Mom.

  (Earth temperature) $T_\oplus \propto M^{1.7375}$
  2% Change of $M_\odot \Rightarrow T_\oplus$ changes by 10K.

2-5% more massive early Sun $\Rightarrow T_\oplus > 273K$

Willson et al.1987; Sackman & Boothroyd 2003

(the same conditions for greenhouse gases, albedo, etc. Kasting 1997)

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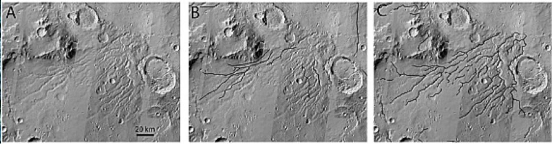
  ⇒ The early Sun is 20-30% fainter (Gough 1981)

  ⇒ Freezing early Earth & Mars

  ⇔ Lives on Earth & Liquid water on Mars ?

Stromatlite in Glacier park, Montana

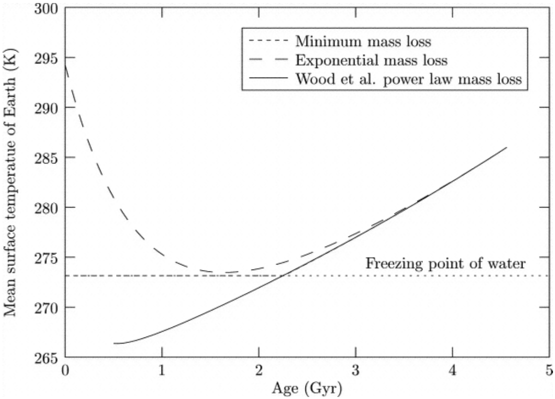


Valley Networks on Mars (Luo & Stepinski 2009)

Early Faint Sun Paradox

Sun in the past: fainter by 20–30%

→ $T_\oplus < 0^{o}$C in $t < 2$Gyr



Minton & Malhotra 2007

$T_\oplus$ (& T_{Mars}) in the past

Warm Era at early times

Sagan & Mullen 1972

- Major Scenario: Greenhouse effects
    - Volcano Eruption vs. Glacier formation
- Some non-major Scenarios:
    - Change of Solar Mass
      Larger $\dot{M}$ in the past $\Rightarrow$ Larger $M_\odot$ in the past
    - Solar $\boldsymbol{B}$ & winds $\Leftrightarrow$ Galactic CRs $\Leftrightarrow$ Terrestrial Clouds
    - Variation of Gravitational Constant

Effects of Mass Loss

- Larger L: $L \propto M^p$; $p \approx 4.75$
- Larger Gravity
  - Force Balance: $\frac{GM}{r^2} = \frac{v^2}{r}$
  - Conservation of Angular Momentum: rv =const.

$r \propto \frac{1}{M}$

$\sigma T_{\oplus}^4 = \frac{L}{4\pi r^2} \propto M^{6.75}$ (if Rad. eq.)

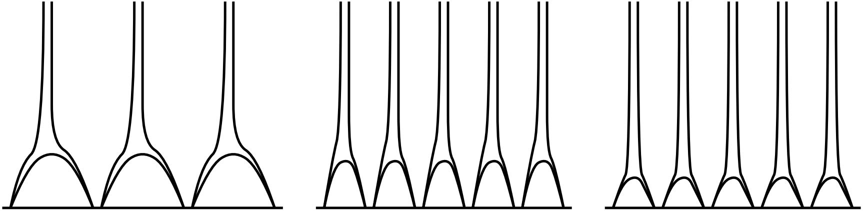
Loss of $0.02 M_{\odot}$ during early times $\Rightarrow T_{\oplus} > 0^{o}$C.

Speculative Scenario

Time Evolution

$\Rightarrow$ $\Rightarrow$

$t_{\mathrm{phase,i}} \lesssim 3.0 \times 10^8\mathrm{yr} \lesssim t_{\mathrm{phase,ii}} \lesssim 1.4 \times 10^9\mathrm{yr} \lesssim t_{\mathrm{phase,iii}}$



$F_X \sim 10^7 \mathrm{erg\ cm^{-2} s^{-1}}$
$B_{r,0} \sim 10$ kG, $f_0 < \frac{1}{10000}$
Saturated
$\dot{M} \lesssim 10\dot{M}_\odot$

$F_X \sim 10^6 \mathrm{erg\ cm^{-2} s^{-1}}$
$B_{r,0} \sim 5$ kG, $f_0 \sim \frac{1}{1000}$
Saturated
$\dot{M} \gtrsim 100\dot{M}_\odot$

$F_X \lesssim 10^5 \mathrm{erg\ cm^{-2} s^{-1}}$
$B_{r,0} \sim 1$ kG, $f_0 \sim \frac{1}{1000}$
Unsaturated
$\dot{M} \sim \dot{M}_\odot$

1. Saturated & Weak Wind
2. Saturated & Strong Wind
3. Unsaturated Wind