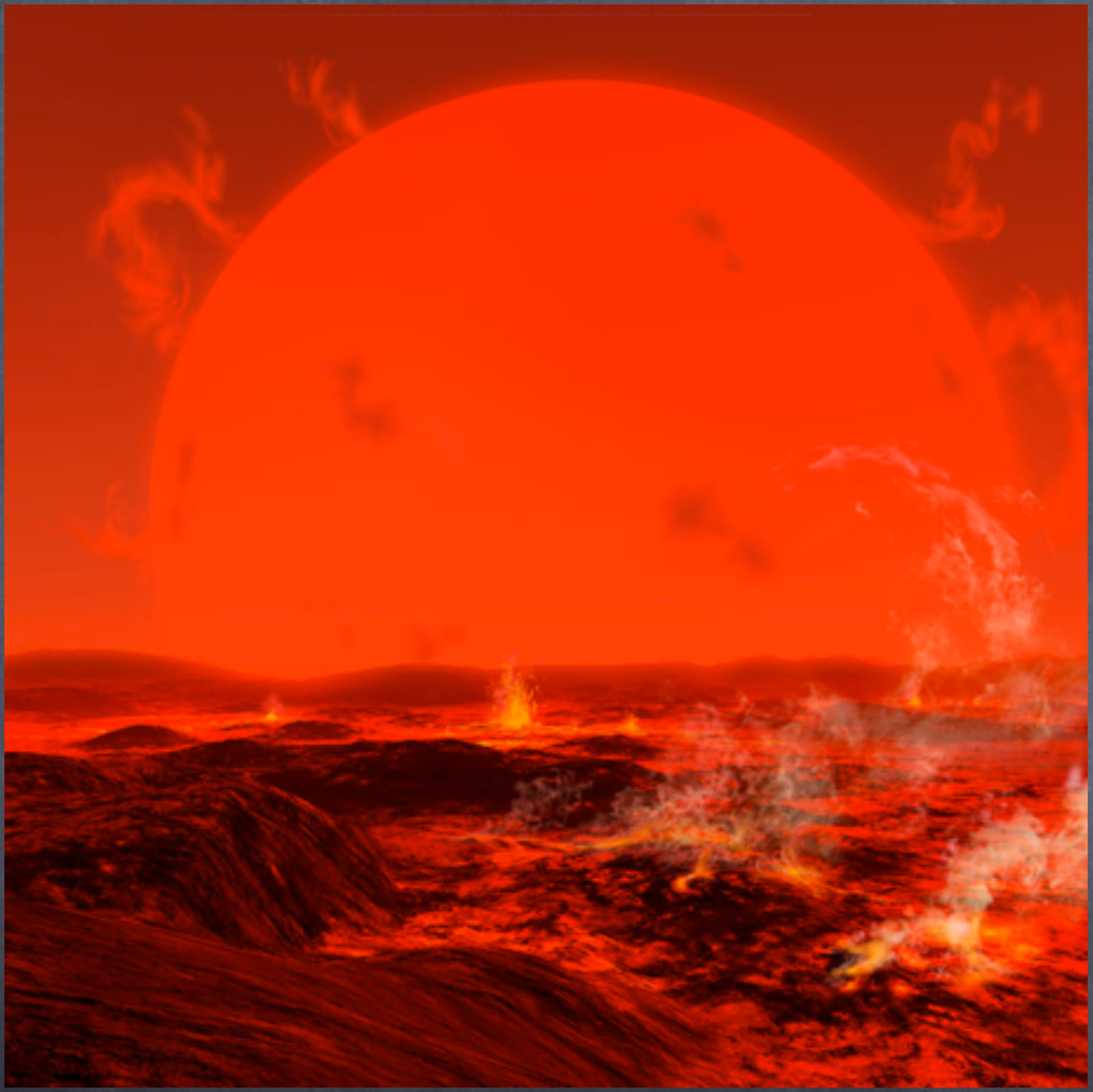
Habitability on Earth During the Early Sun (1)



Ofer Cohen - NSO 2014

Space weather of the early Sun: Inferences from new solar and stellar observations workshop

Outline

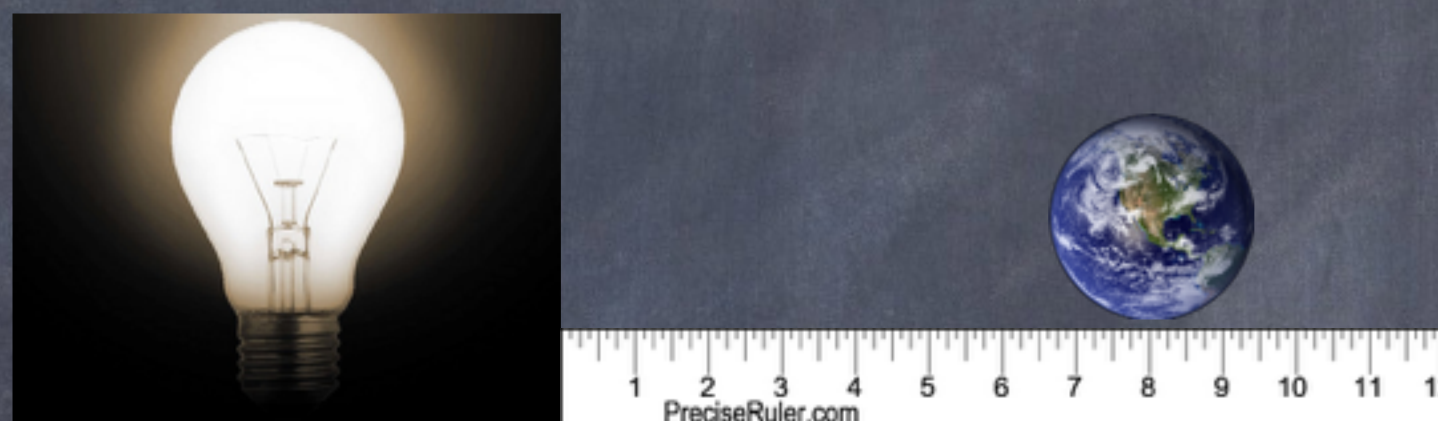
1. Definition(s) of habitability.
2. The heliosphere of the young Sun.
3. Consequences for the Earth and habitability.

Traditional Definition of Planet Habitability

Traditional definition of habitability - planet's equilibrium surface temperature.

Temperature depends on:

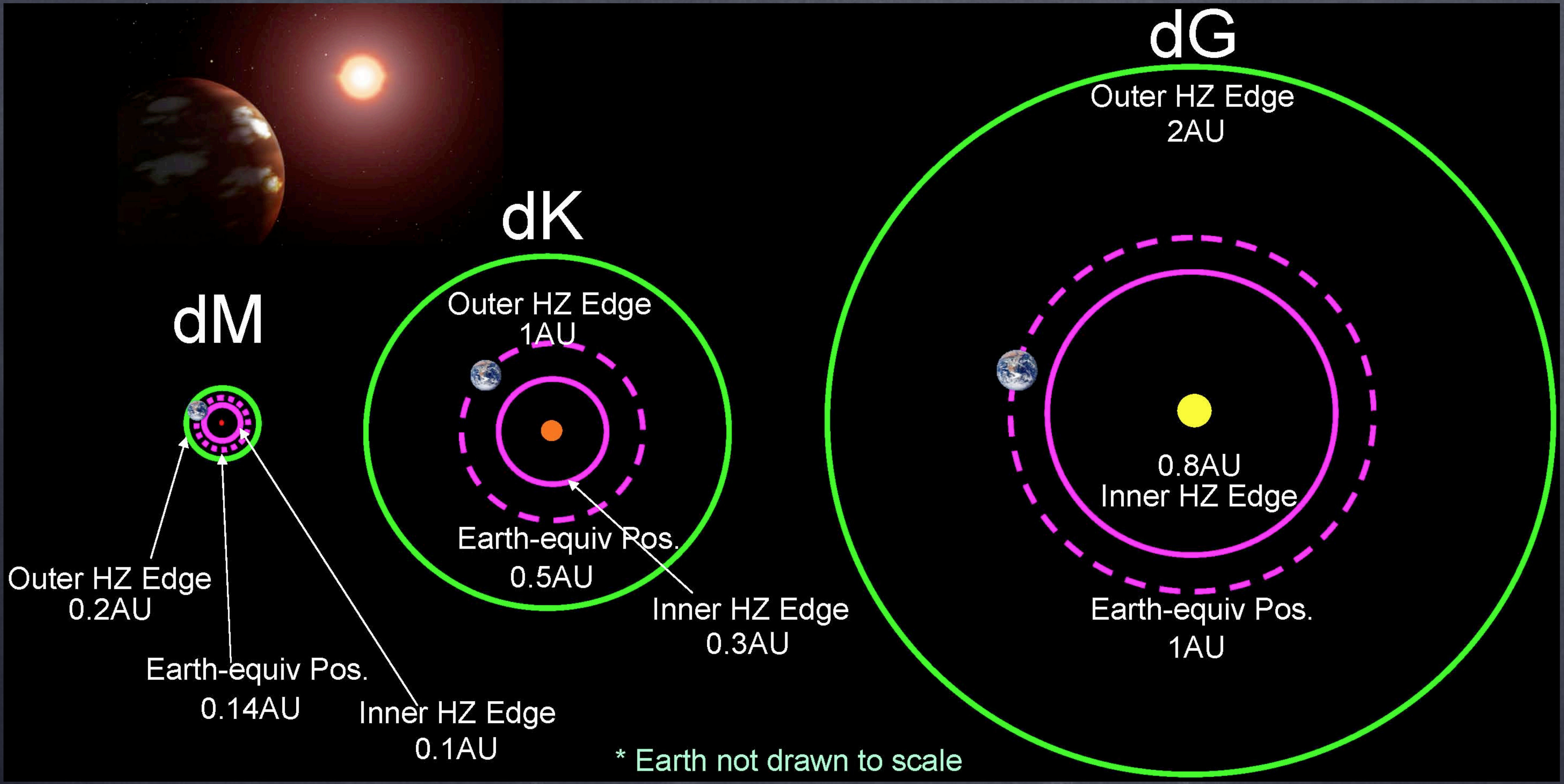
The distance of the planet from the star



The brightness of the star

Habitable planets:
surface temperature not too hot

and not too cold



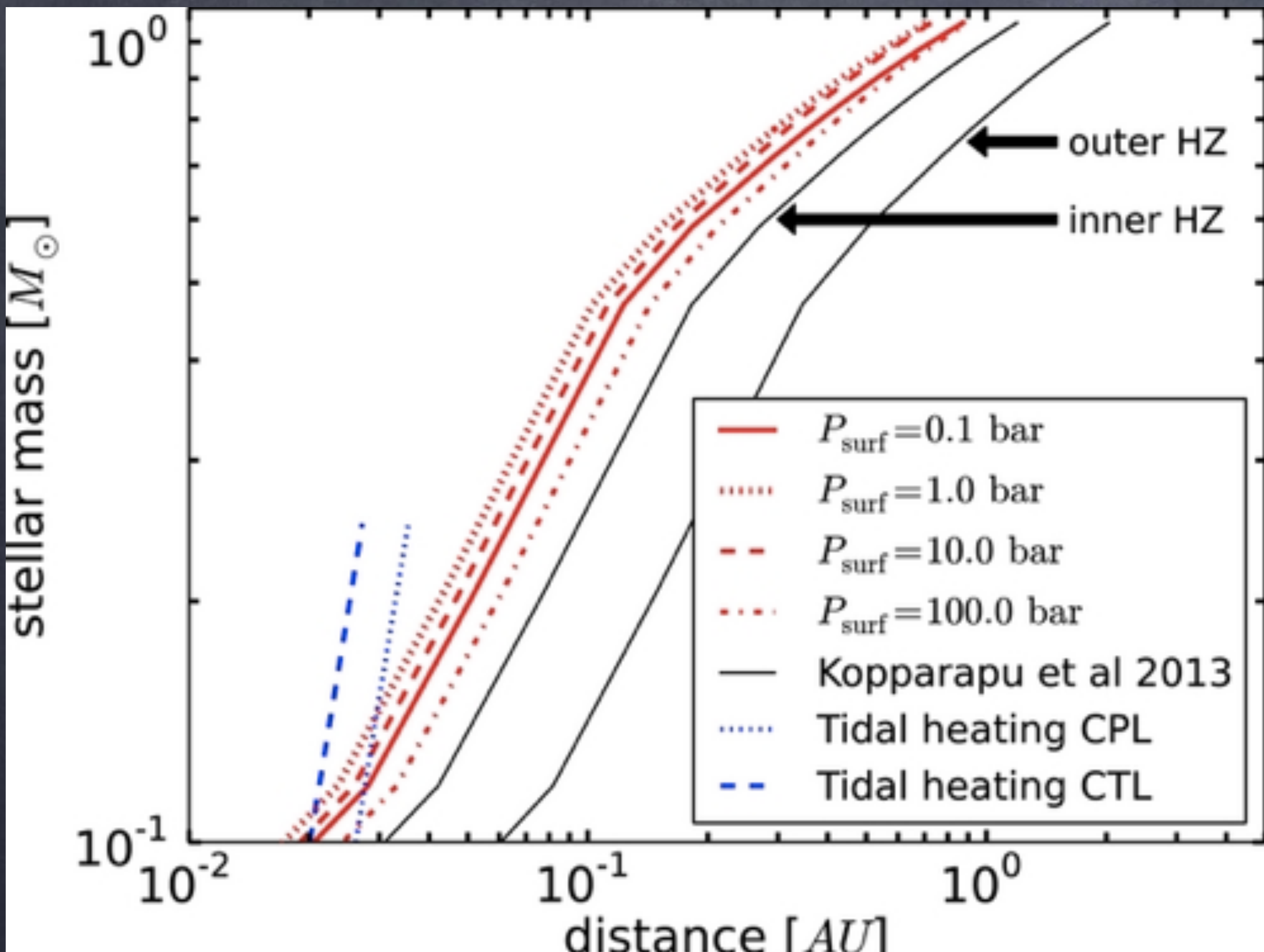
From the Living with a Red Dwarf project
http://astronomy.villanova.edu/livingwithareddwarf

Habitability on Earth During the Early Sun (1)

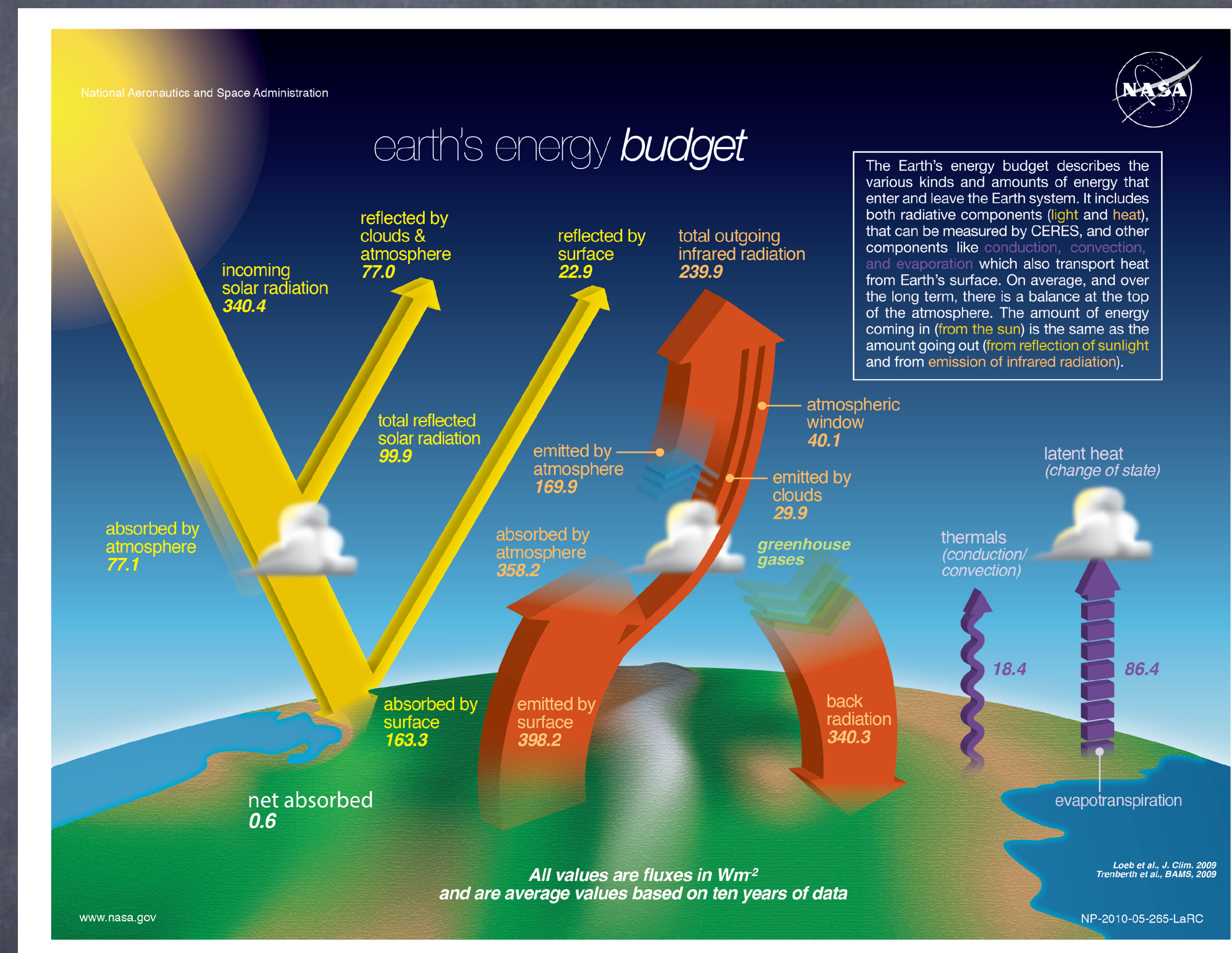
BUT

Habitability could be affected by other processes!!!

The surface temperature on Earth:



Zsom et. al ApJ 2013



http://science-edu.larc.nasa.gov/energy_budget/

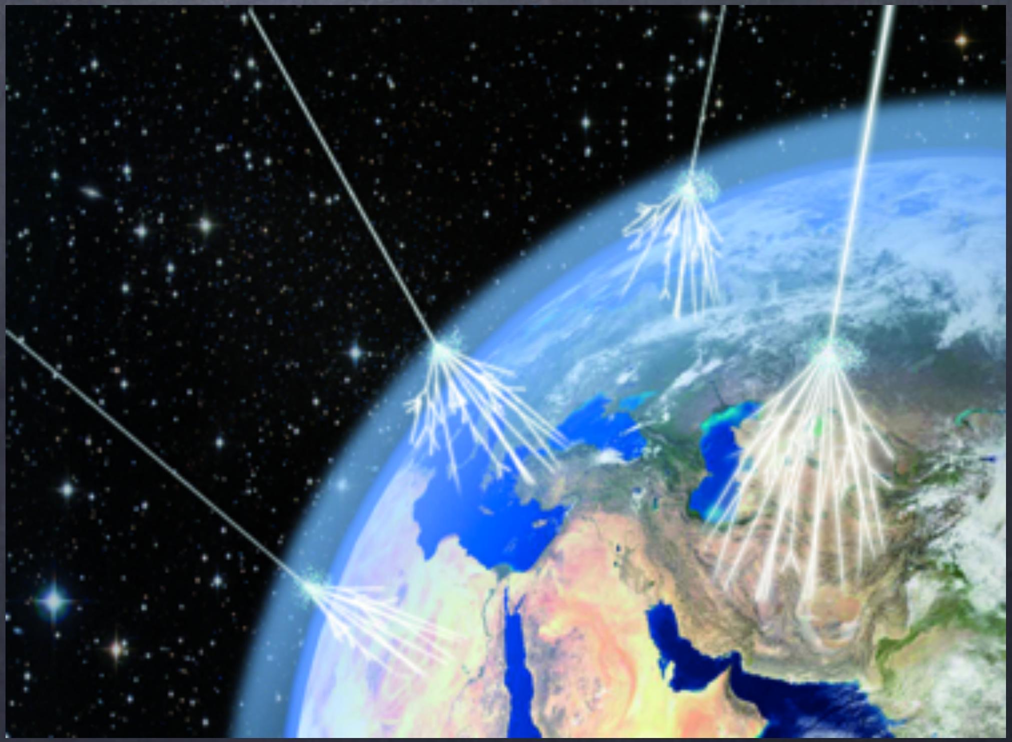
Increased EUV/X-ray flux can lead to faster photo-evaporation of the atmosphere

The space environment of a planet

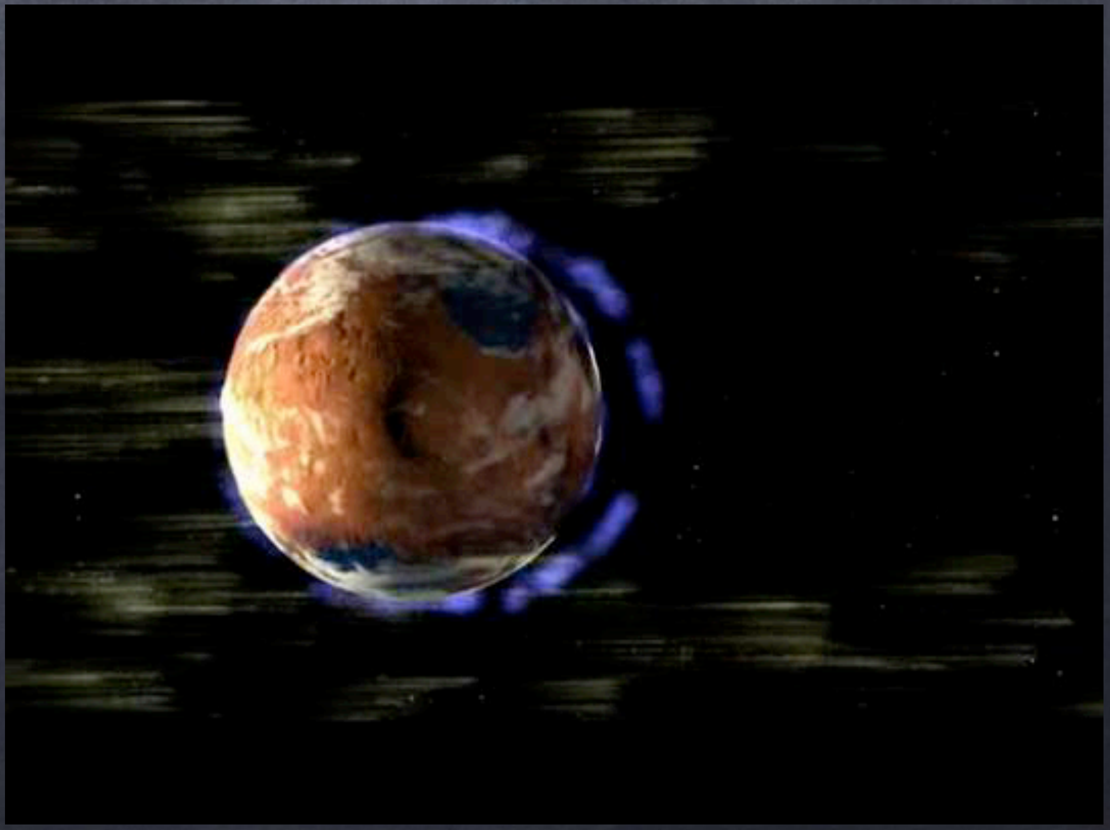
http://www.nasa.gov

GCR (SEPs?) and the evolution of Earth:

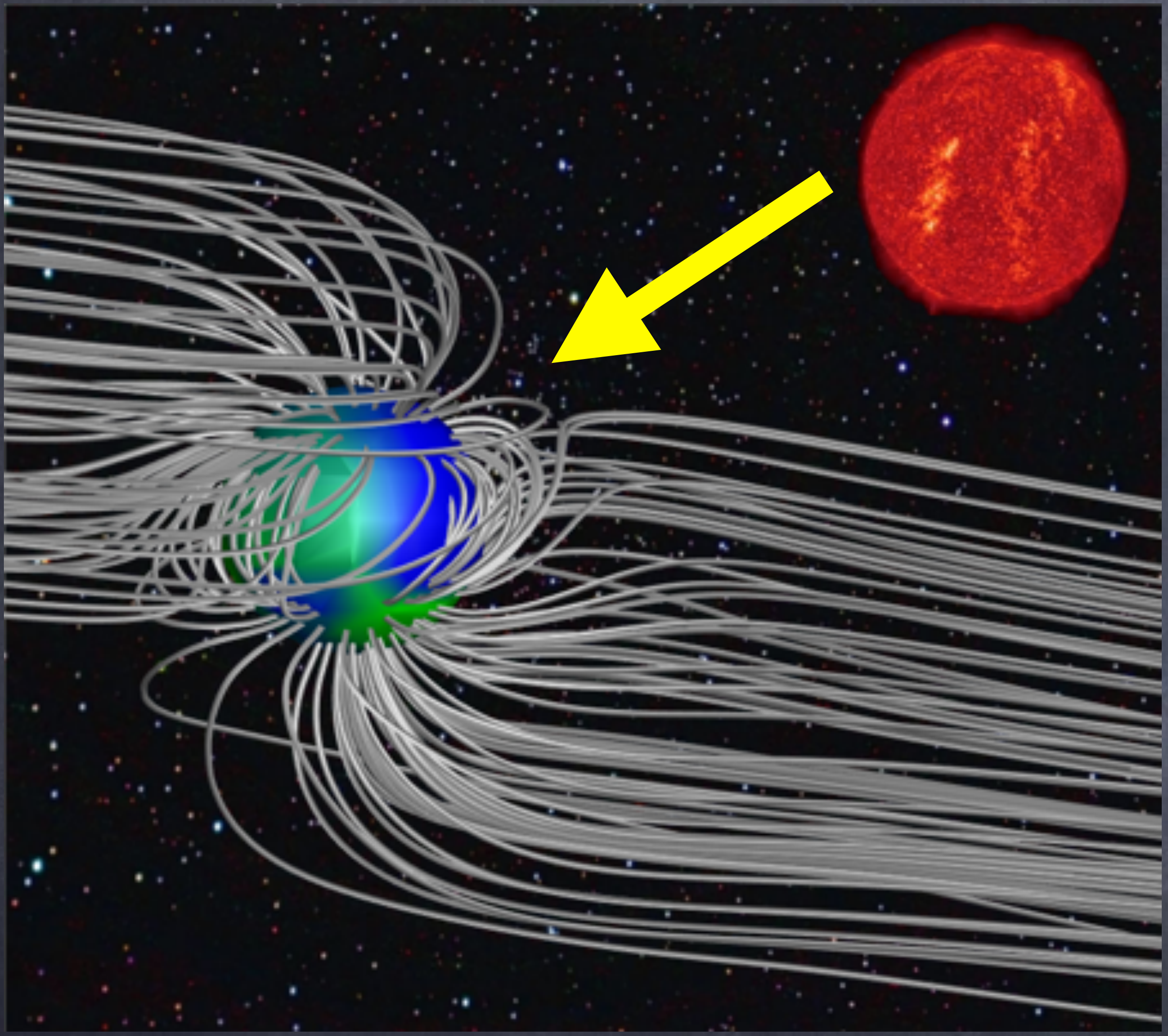
1. An ionization source for the production and creation of complex organic molecules and nucleotides.
2. Cause cellular mutation through direct and indirect processes.
3. Lightning triggering.
4. May change the Earth's albedo by affecting cloud condensation (under debate).

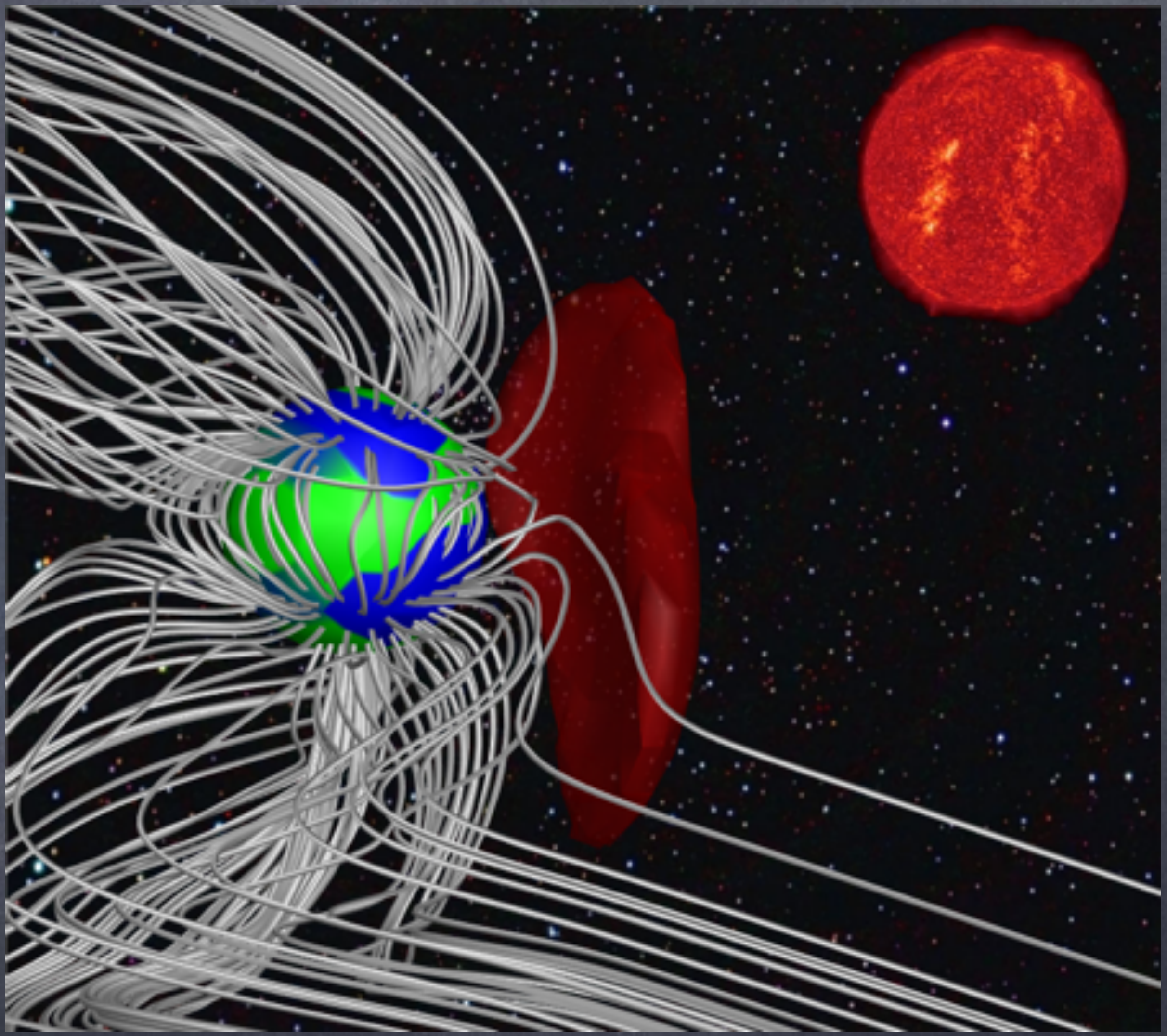


Stellar winds:



Habitability on Earth During the Early Sun (1)



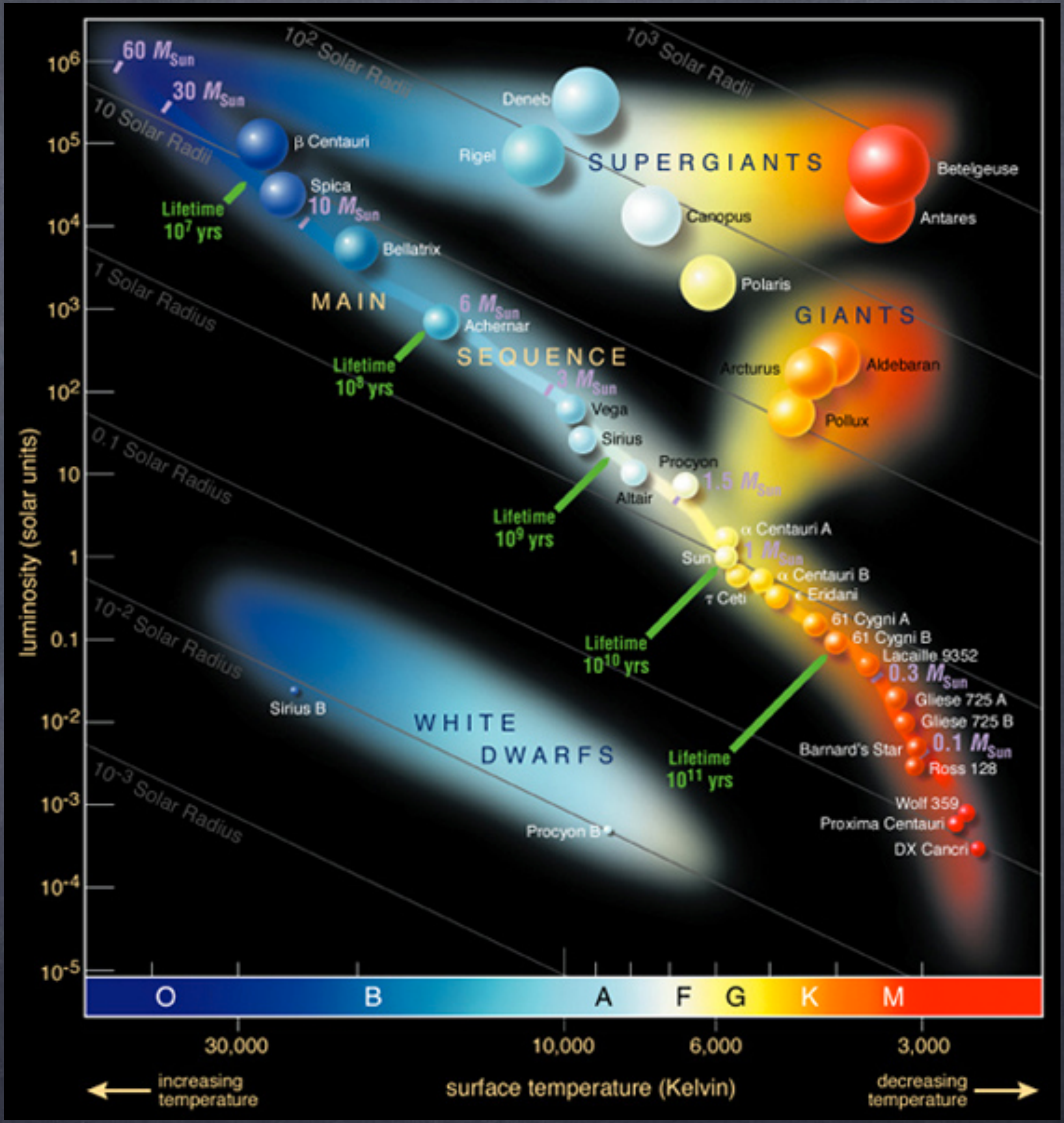


Cohen et. al ApJ 2014

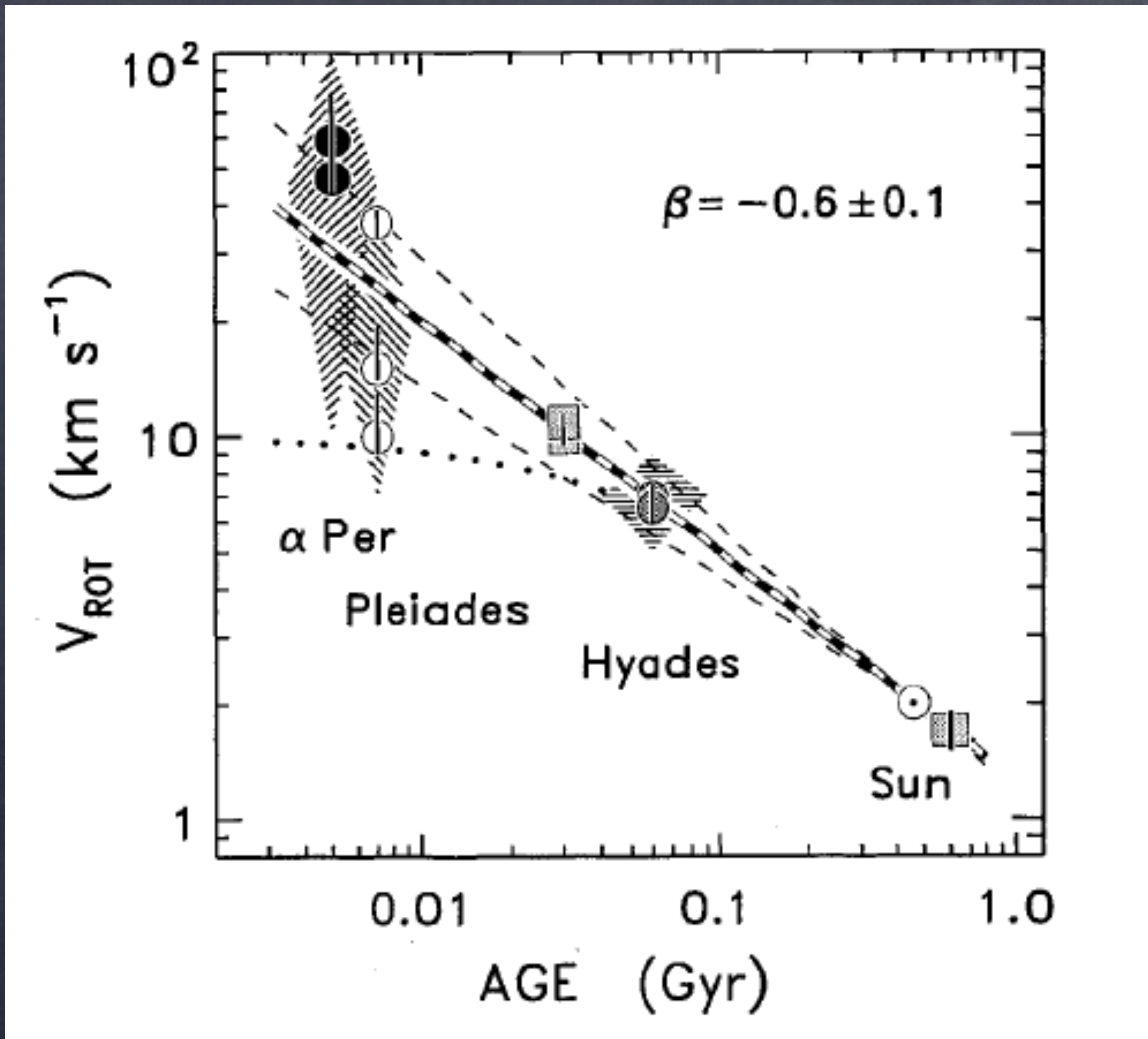
Habitability on Earth During the Early Sun (1)

Stellar Evolution

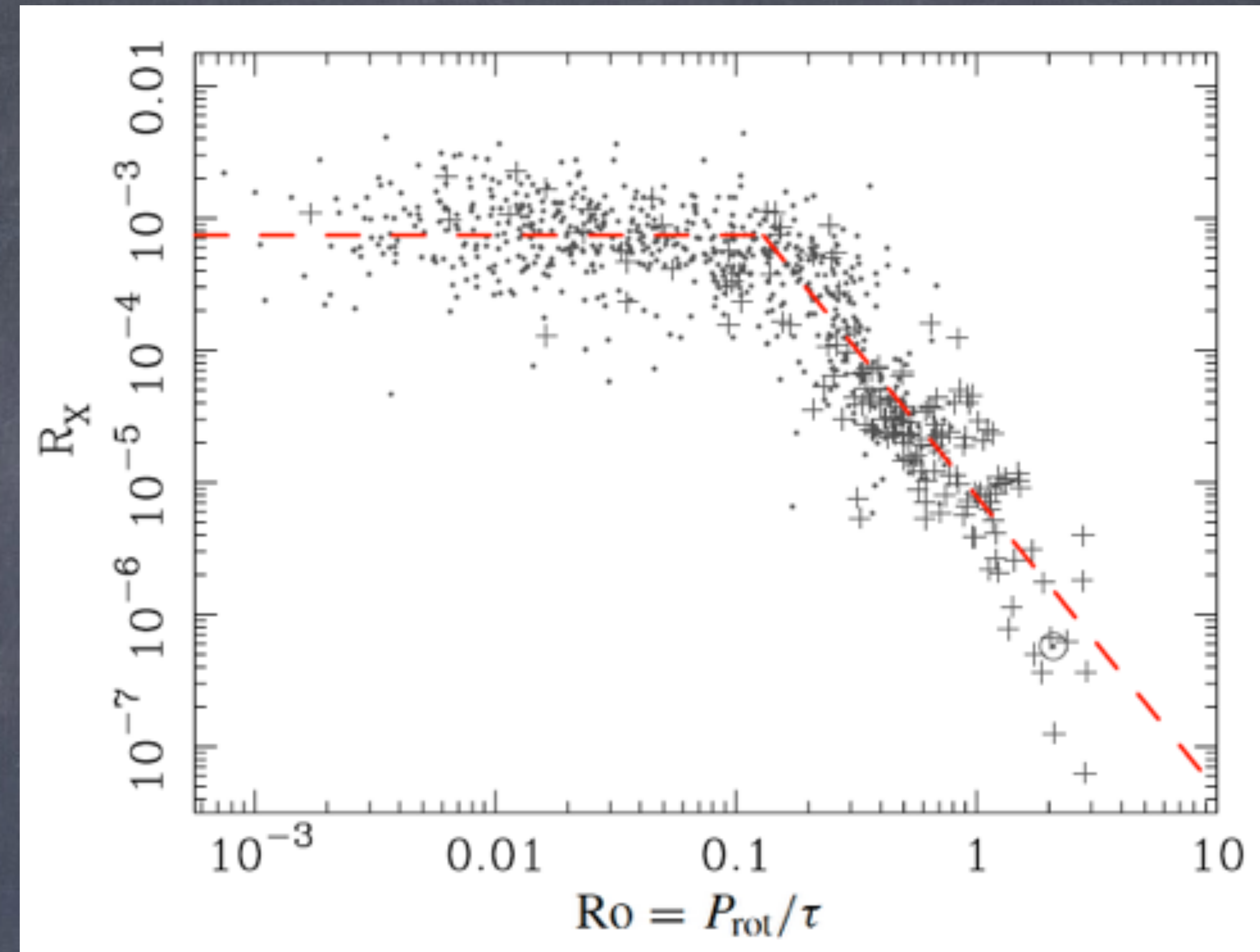
Class	Temperature (kelvins)	Conventional color	Apparent color
O	≥ 33,000 K	blue	blue
B	10,000–30,000 K	blue to blue white	blue white
A	7,500–10,000 K	white	white to blue white
F	6,000–7,500 K	yellowish white	white
G	5,200–6,000 K	yellow	yellowish white
K	3,700–5,200 K	orange	yellow orange
M	≤ 3,700 K	red	orange red



Credit: ESO



Ayres 1997

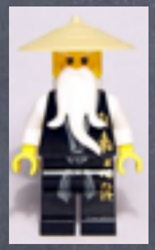


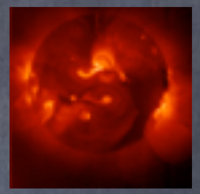
Wright et. al 2011

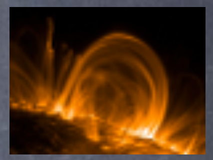
Skumanich Law:

$$\Omega \propto t^{-1/2}$$

Rotation 

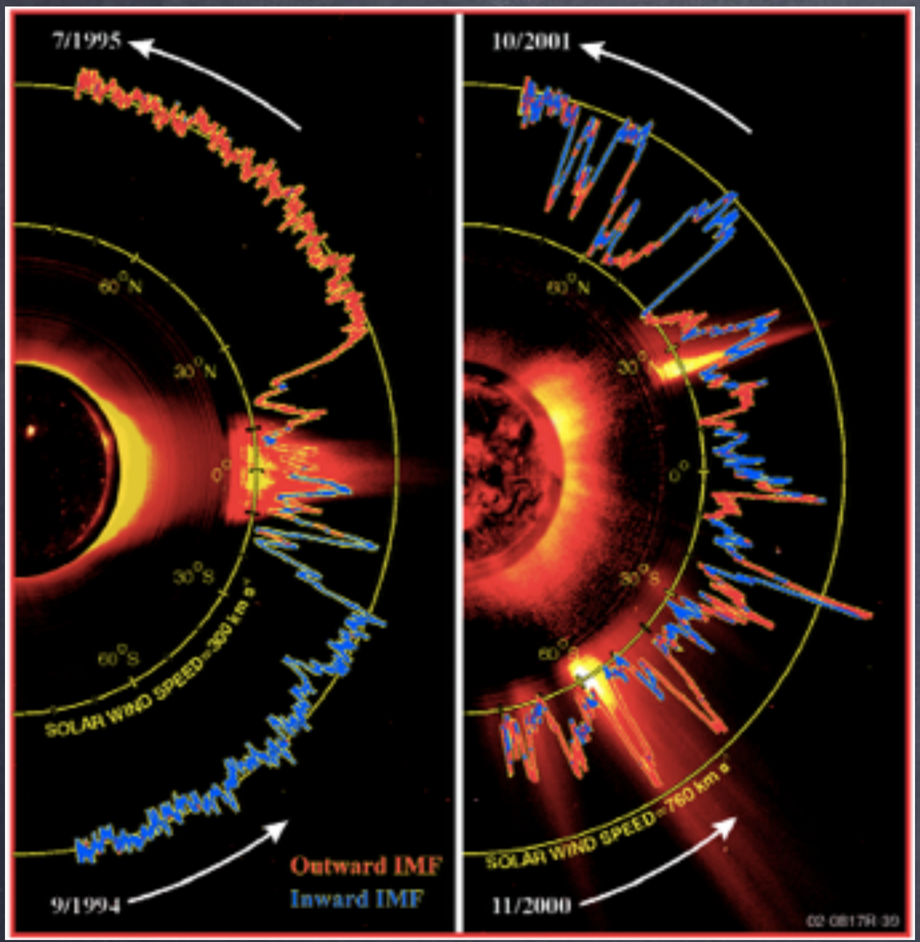
Age 

Stellar activity 

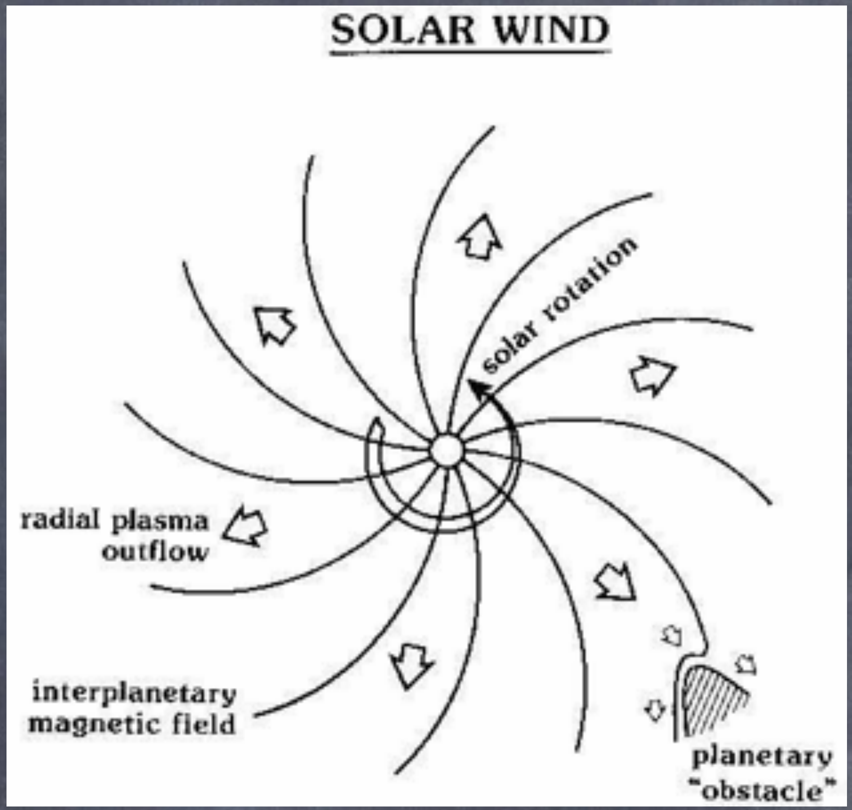
Magnetic field 

What are the consequences for the Astrosphere?

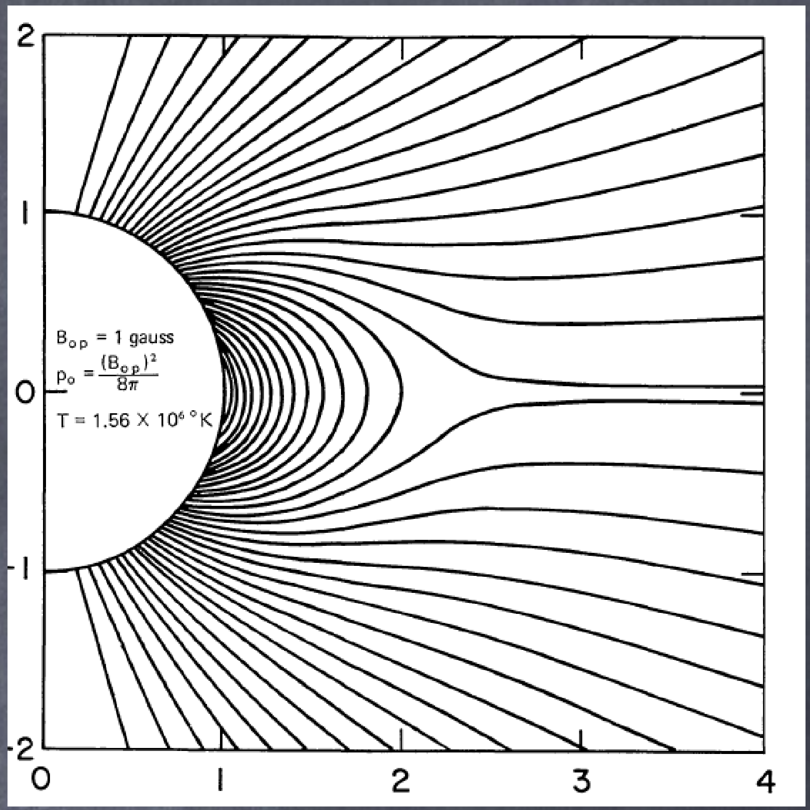
The structure of the Astrospheric Magnetic Field (Parker Spiral):



SWRU/Ulysses/SWOOPS team



By J. Luhmann



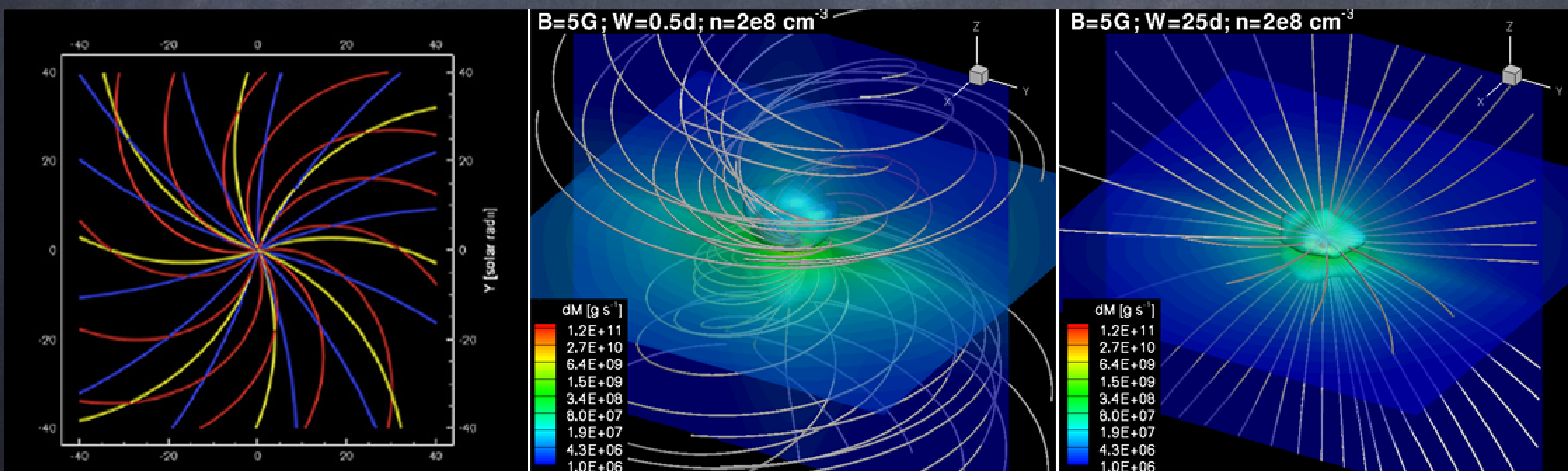
Pneumann & Kopp 1971

$$\mathbf{B}(\mathbf{r}) = B_s \left(\frac{r_0}{r}\right)^2 \left[\hat{r} - \frac{r\Omega_\odot \sin\theta}{u_{sw}}\hat{\phi}\right]$$

The effect of stellar rotation:

$$\mathbf{B}(\mathbf{r}) = B_s \, \Omega_\odot \, \frac{\Omega_\odot \sin\theta}{u_{sw}} \hat{\phi} \Big]$$

For faster rotations, the azimuthal component dominates the AMF:



Cohen, drake & Kota, 2012; Cohen & Drake 2014

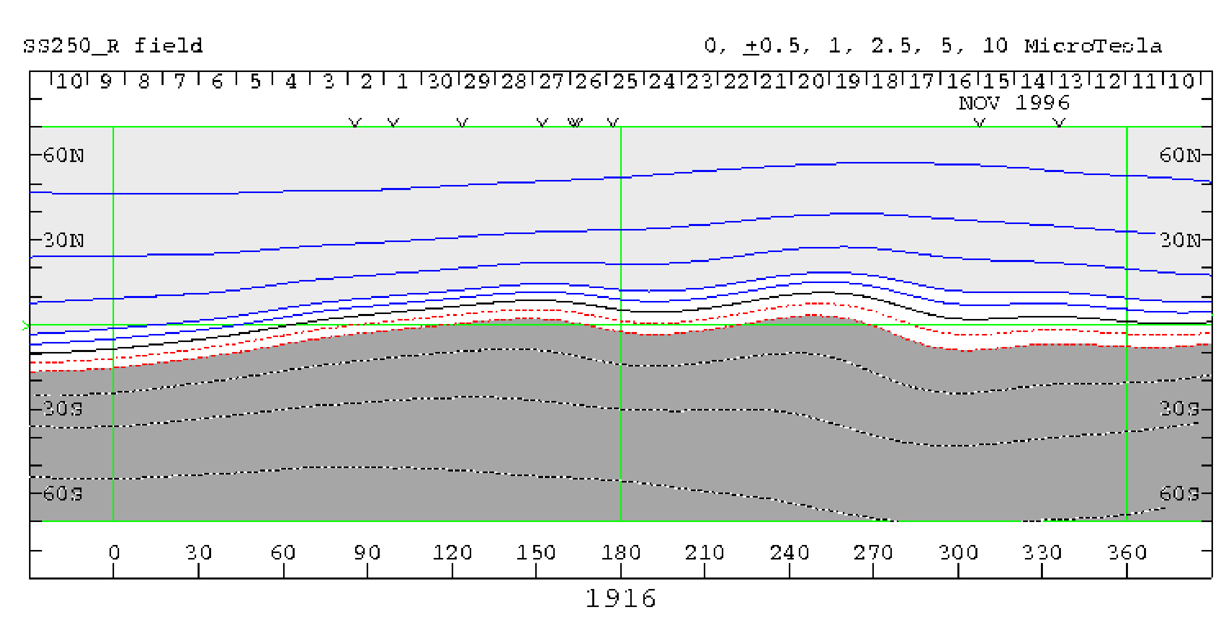
The effect of B_s:

$$\mathbf{B}(\mathbf{r}) = B_s \Big(\ldots \frac{r\Omega_\odot \sin\theta}{u_{sw}} \hat{\phi} \Big]$$

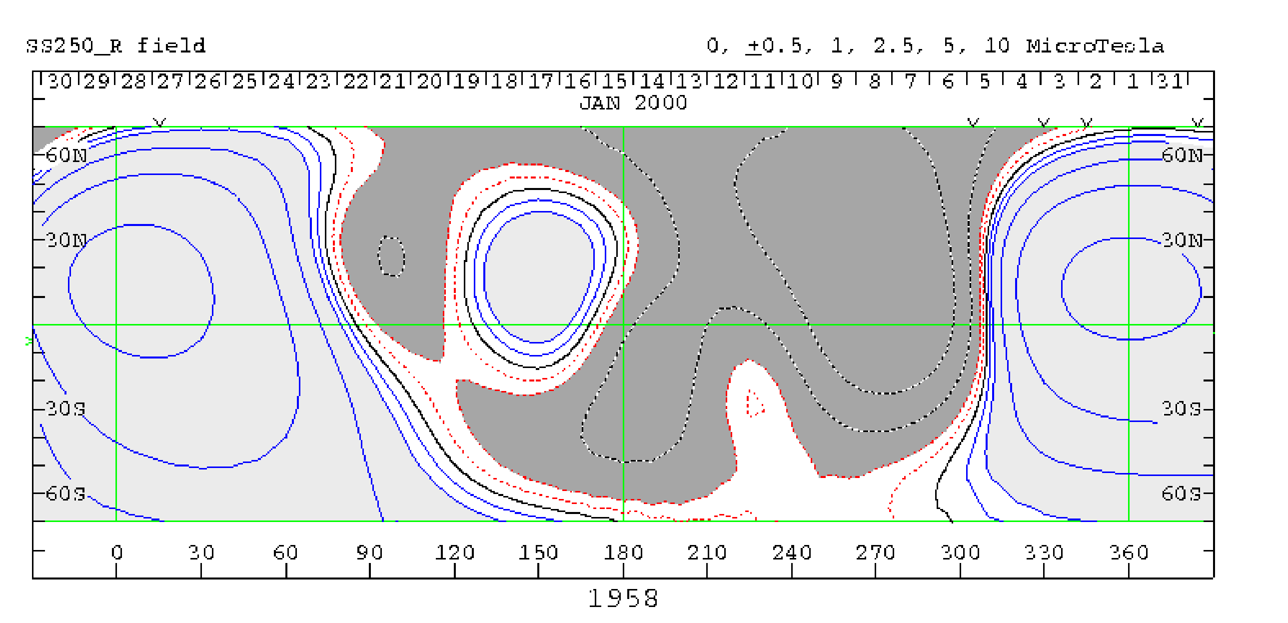
$$B_s$$

B_s is not uniform and $u_{sw}(B_s)$.

Solar Minimum



Solar Maximum

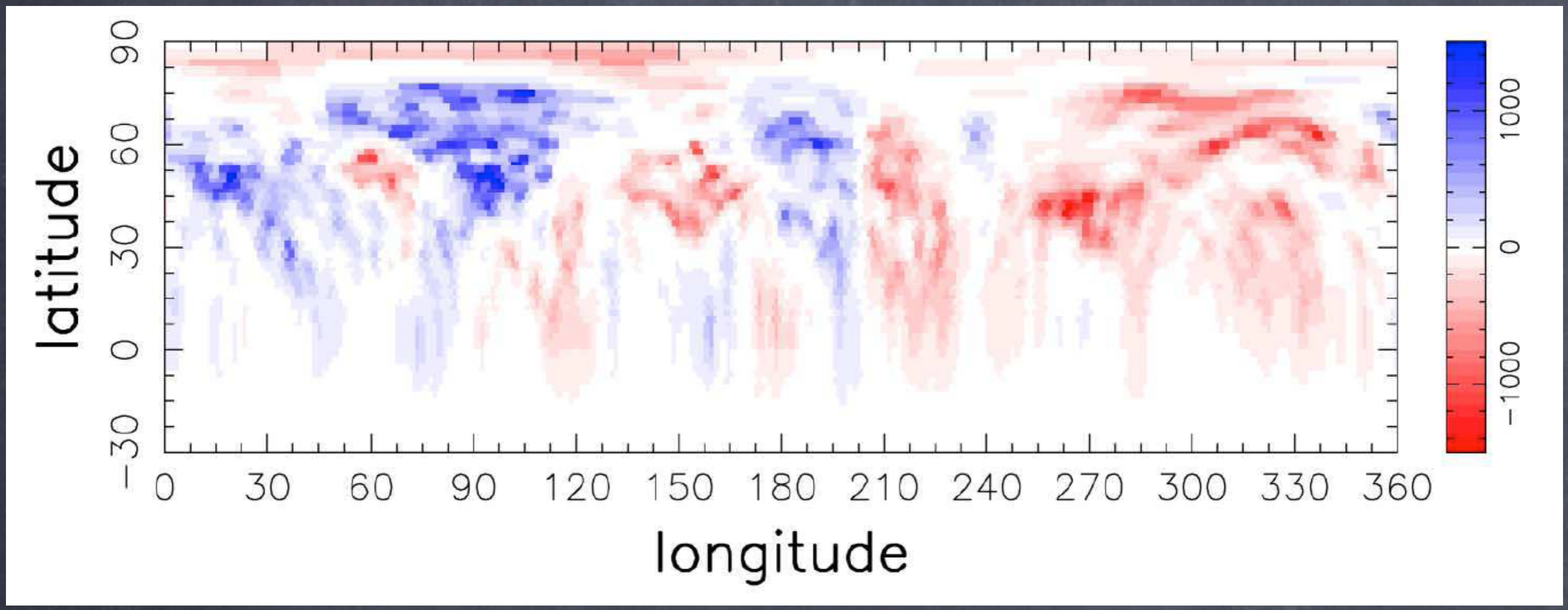


Wilcox Solar Observatory data

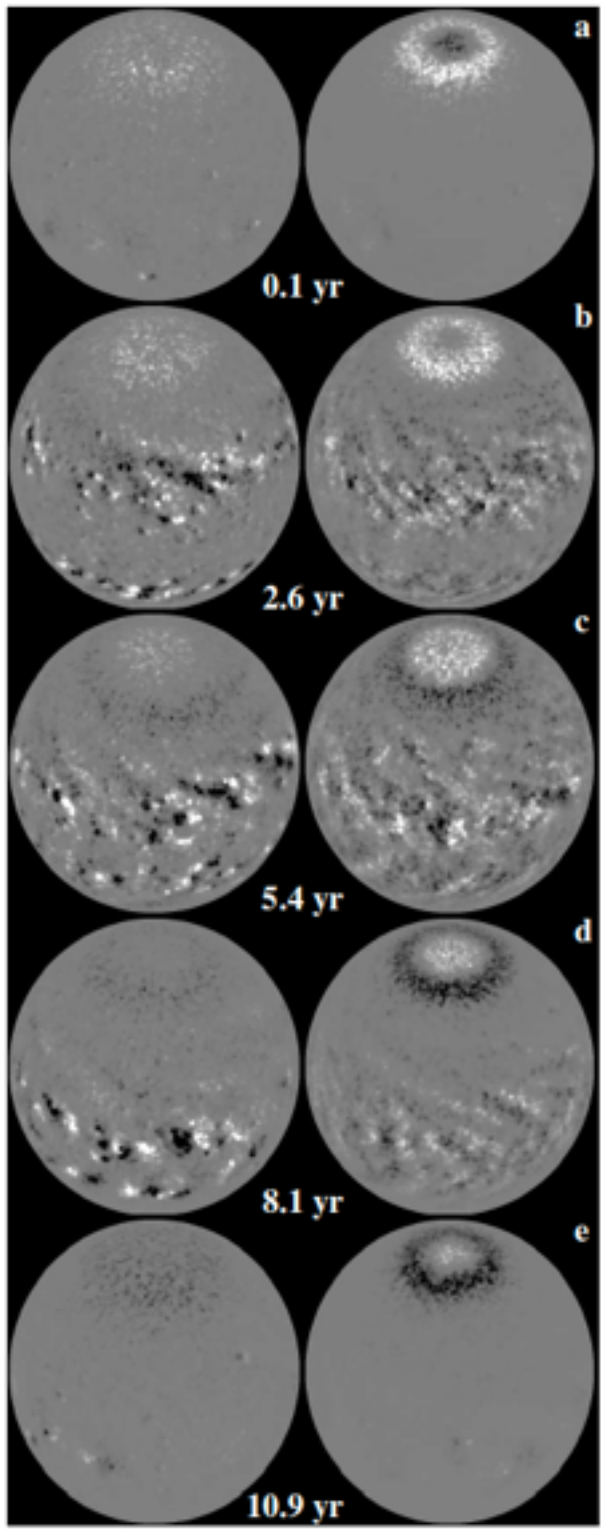
For stellar time-scales, let's consider only changes in the rotation rate, Ω, and the general field distribution.

Young, active, fast-rotating stars seem to have their magnetic activity concentrated at high latitudes.

AB Doradus - young active Sun (P=0.5 days):



Hussain et. al 2007

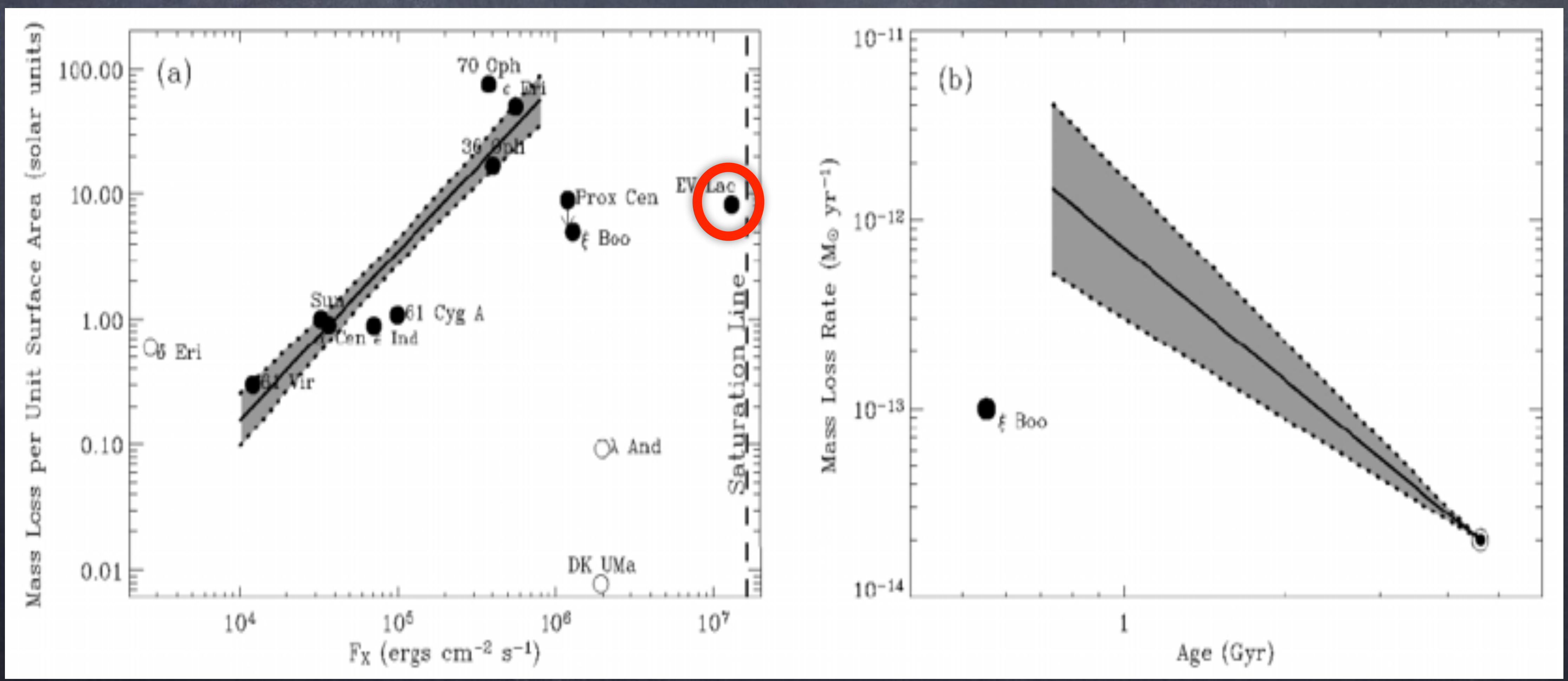


Schrijver & Title 2001

The effect of the stellar wind:

$$\mathbf{B}(\mathbf{r}) = B_s \Big(\;\mathbf{u}_{\mathrm{sw}} \; \frac{r\Omega_{\odot} \sin\theta}{u_{sw}} \hat{\phi} \Big]$$

Scaling laws for stellar mass-loss rates as a function of Lx and age (the faint young Sun paradox):



Wood et. al 2005

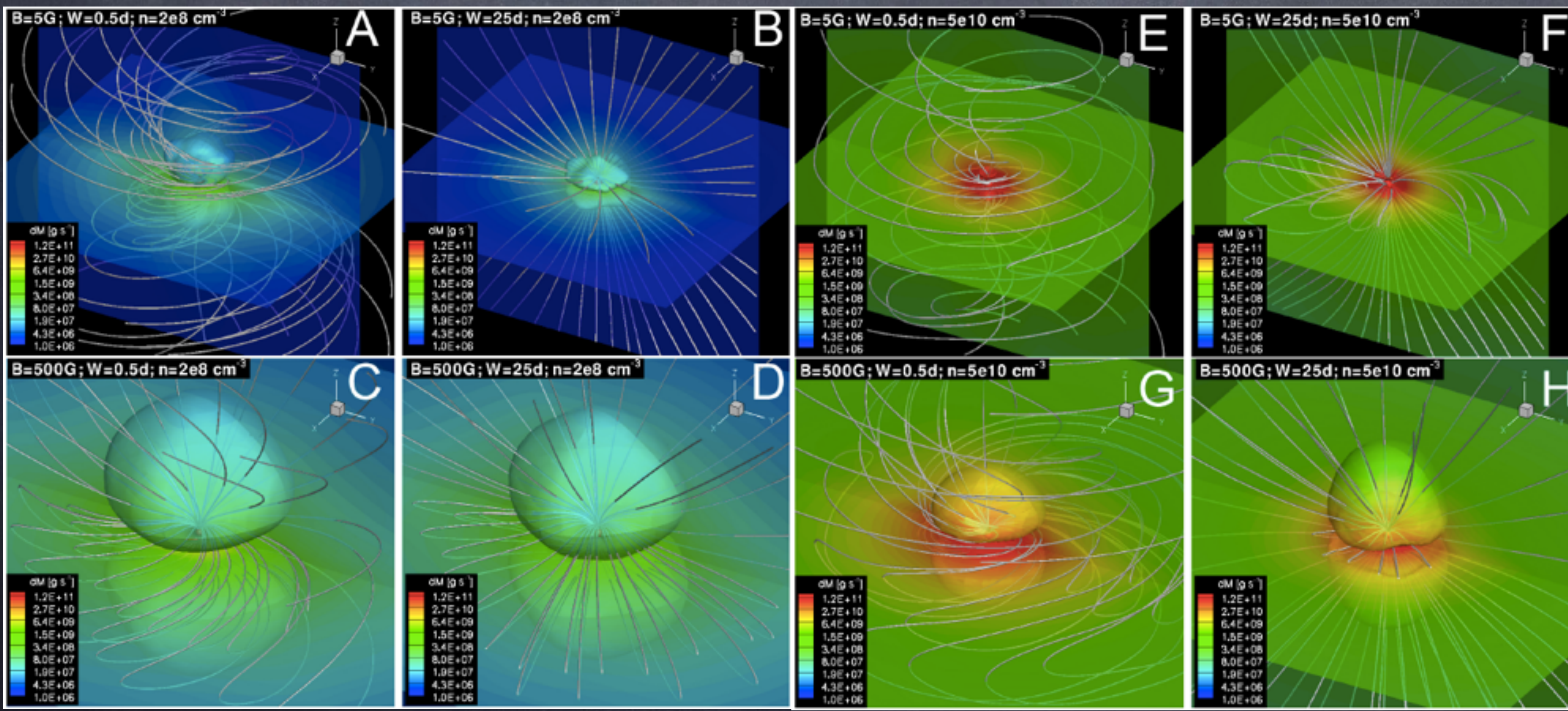
A grid of MHD models for stellar coronae:

Parameters:

Rotation period: 1/2, 2, 5, 10, 25 days

Magnetic dipole field: 5, 10, 50, 100, 500 G

Base density: 2e8, 5e8, 1e9, 5e9, 1e10, 5e10 cm^{-3}



Habitability on Earth During the Early Sun (1)

Cohen & Drake, ApJ 2014

$$\frac{\dot{M}_\star}{\dot{M}_\odot} = K\left(\frac{n_\star}{n_\odot}\right)^\alpha \left(\frac{B_\star}{B_\odot}\right)^{\left(\frac{n_\odot}{n_\star}\right)^\beta} \left(\frac{P_\odot}{P}\right)^{\left(1-\frac{n_\odot}{n}\right)^\gamma}$$

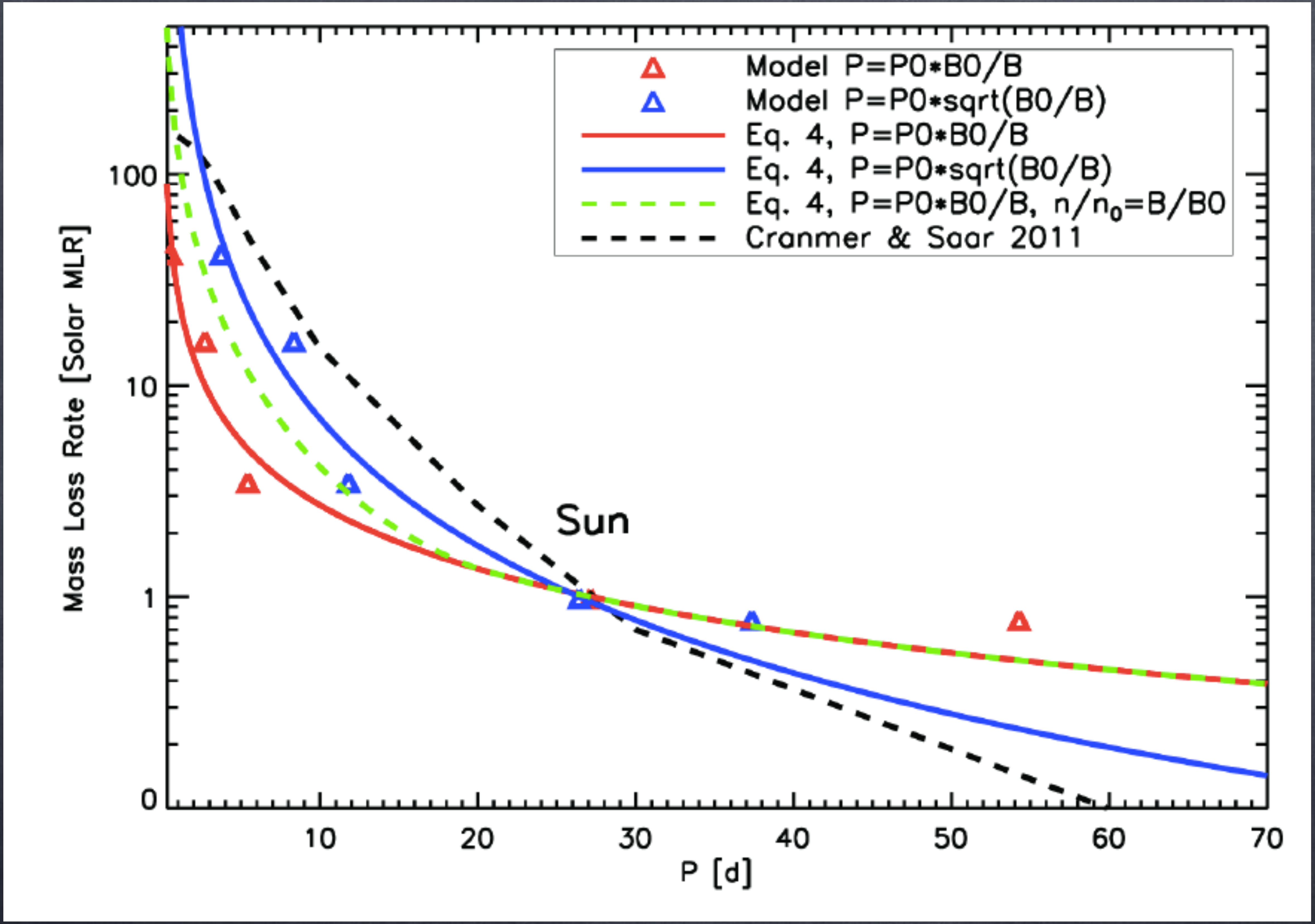
$$\frac{\dot{J}_\star}{\dot{J}_\odot} = \left(\frac{P_\odot}{P_\star}\right)\left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)$$

$K = 3$, $\alpha = 0.8$, $\beta = 0.2$, and $\gamma = 0.1$

$$\frac{\dot{M}_\star}{\dot{M}_\odot} = K\left(\frac{B_\star}{B_\odot}\right)$$

$$\frac{\dot{J}_\star}{\dot{J}_\odot} = \left(\frac{P_\odot}{P_\star}\right) K \left(\frac{B_\star}{B_\odot}\right)$$

Cohen & Drake, ApJ 2014



$B_p \propto \Omega$ (red) and $B_p \propto \Omega^2$ (blue)

Cohen & Drake, ApJ 2014

What are the consequences for planets and planet habitability?

Transport of GCR (Parker 1965):

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_i}\right] - v_i\frac{\partial f}{\partial x_i} - V_{di}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial v_i}{\partial x_i}\left[\frac{\partial f}{\partial \ln p}\right] + Q + L$$

diffusion

advection

guiding center drift

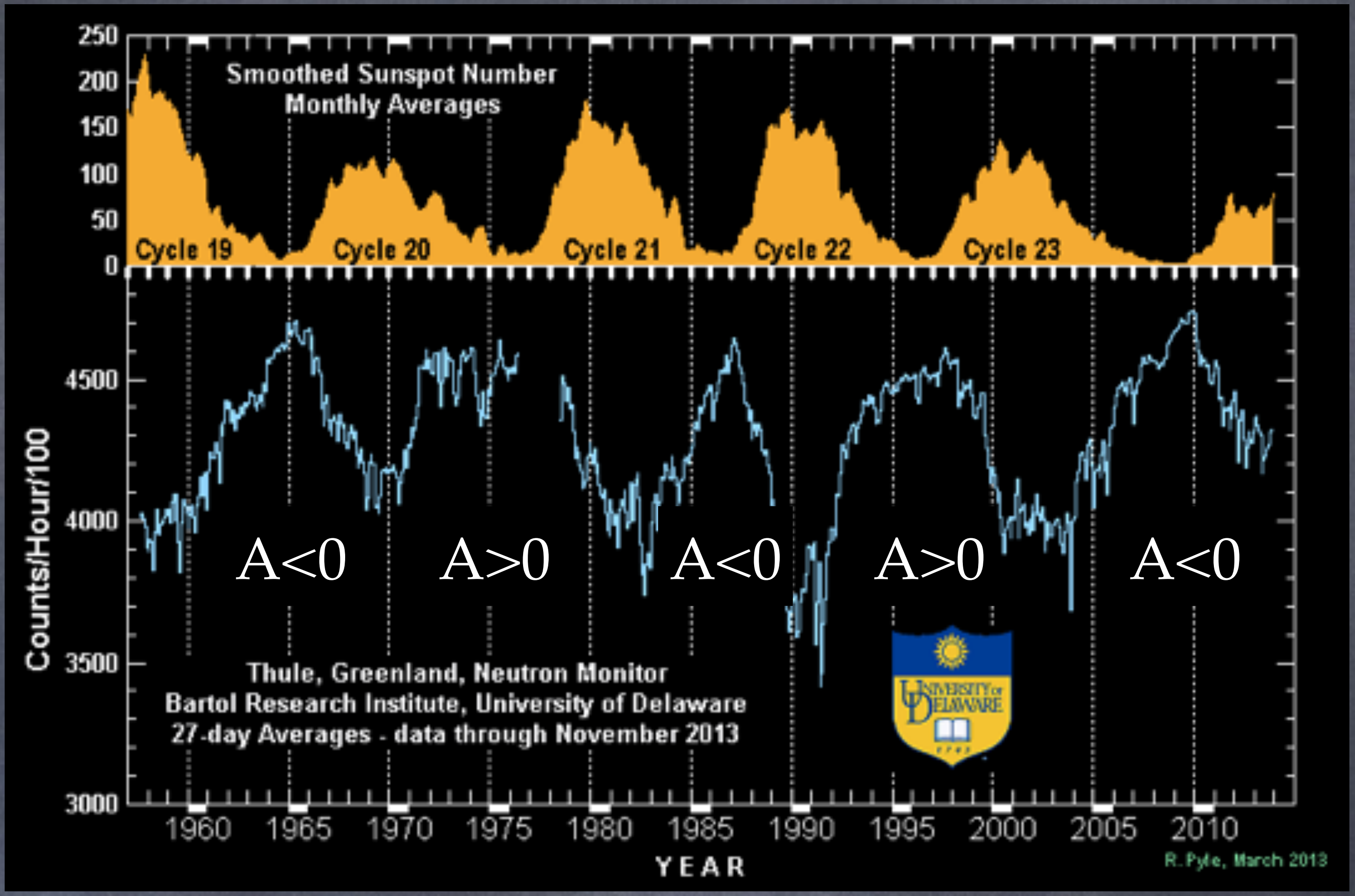
energy change

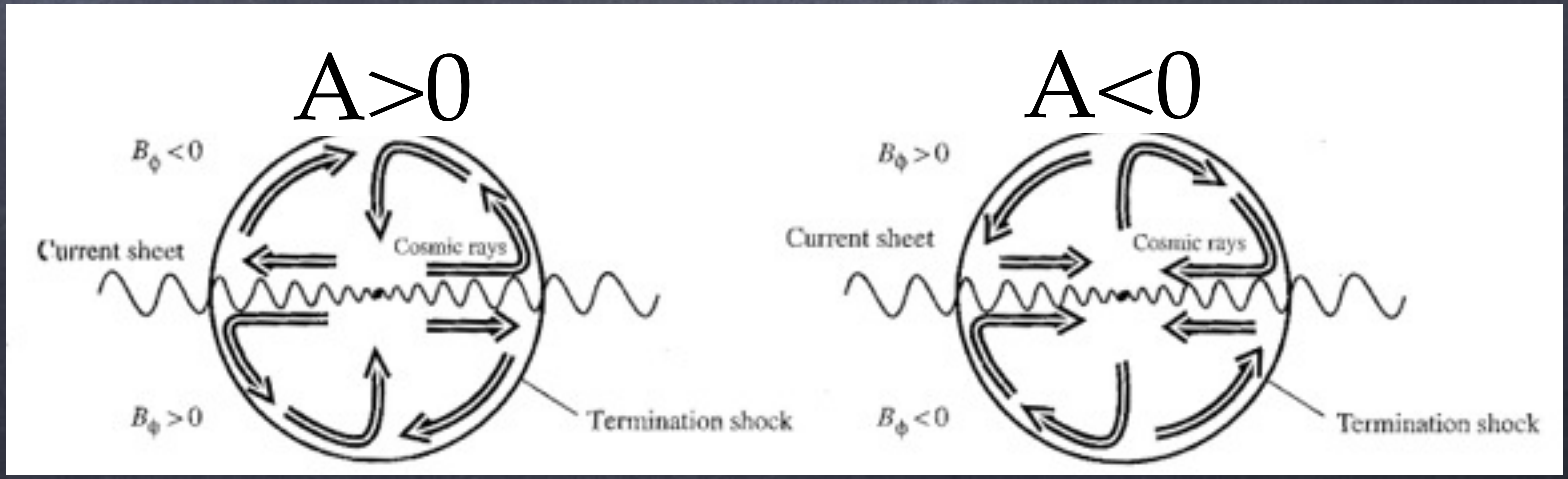
sources and losses

Present day modulation of GCR:

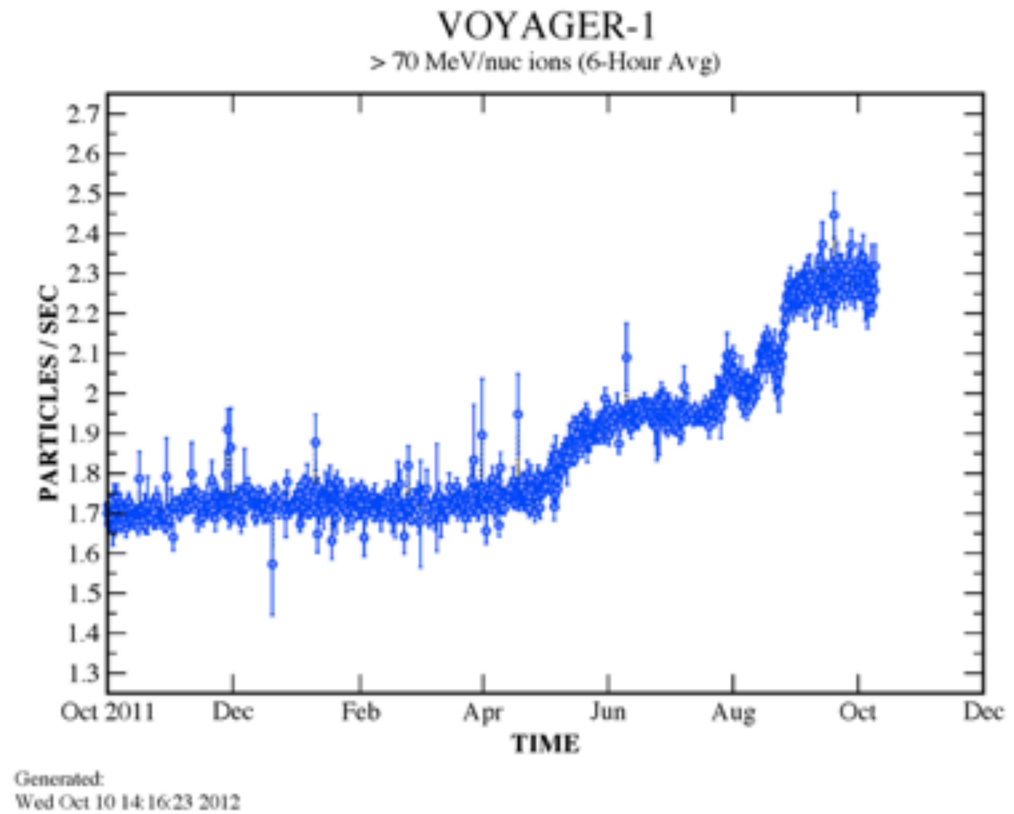
GCR intensity reduction due to:

1. Increase in turbulence in the heliosphere.
2. Increase in CMEs and interplanetary shocks.

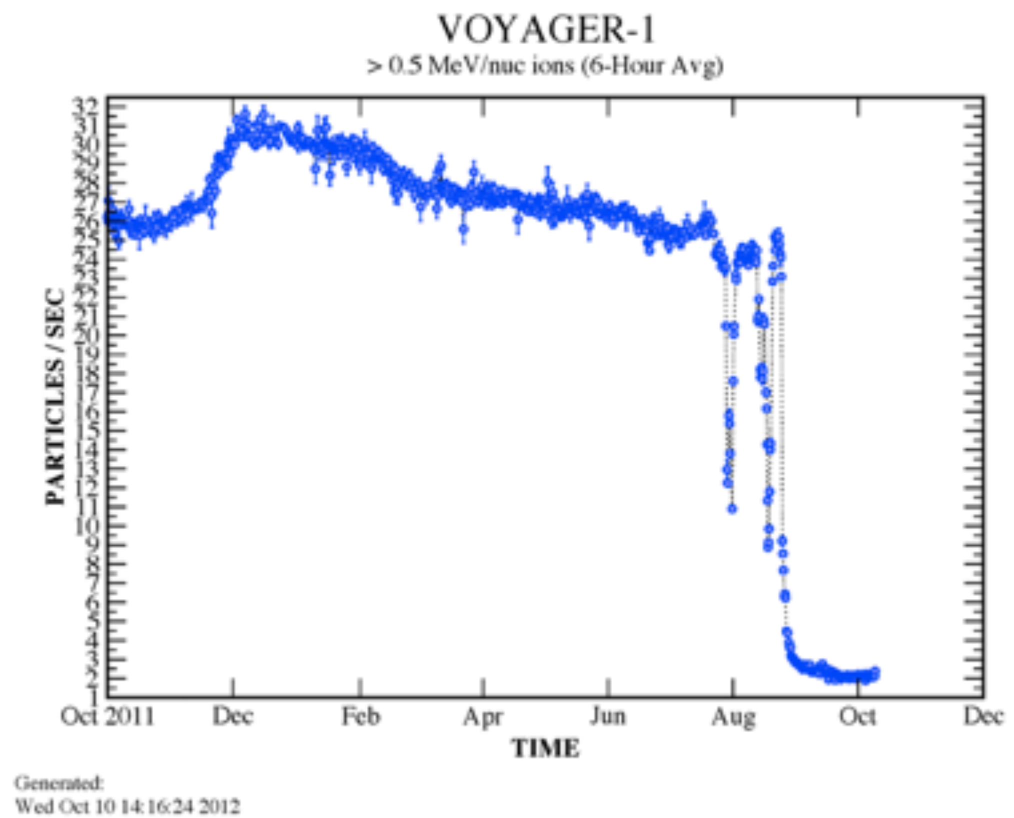




GCR flux



SW particle flux



What was the GCR flux near the early Earth?

The Archean eon - about 3.8 Billion years ago

Why this particular time?
Right after the Late Heavy Bombardment and until the first appearance of fossil evidence for simple life.

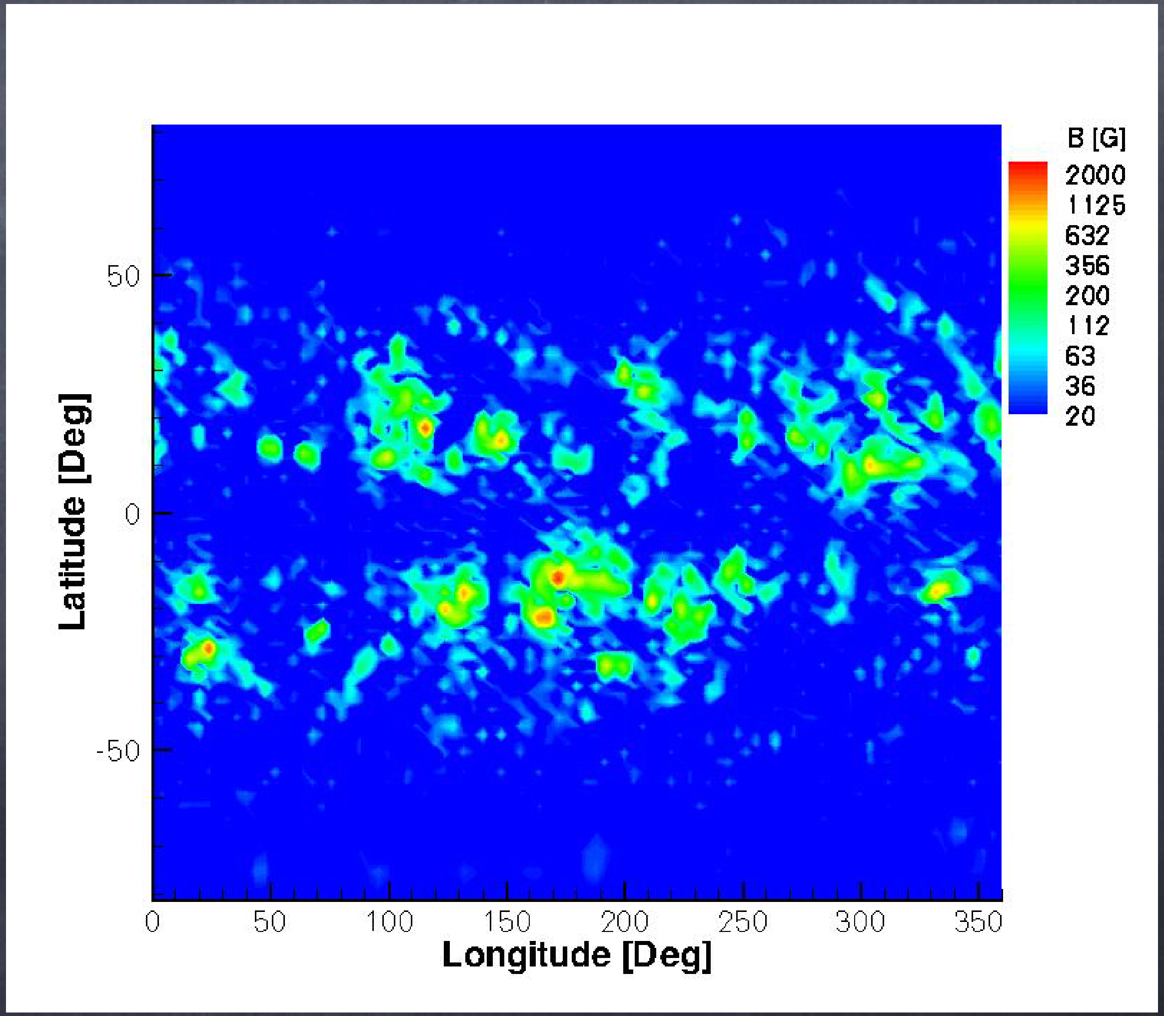
The young Sun during the Archean eon:

• 2-4 faster rotation than the present 27 days period.

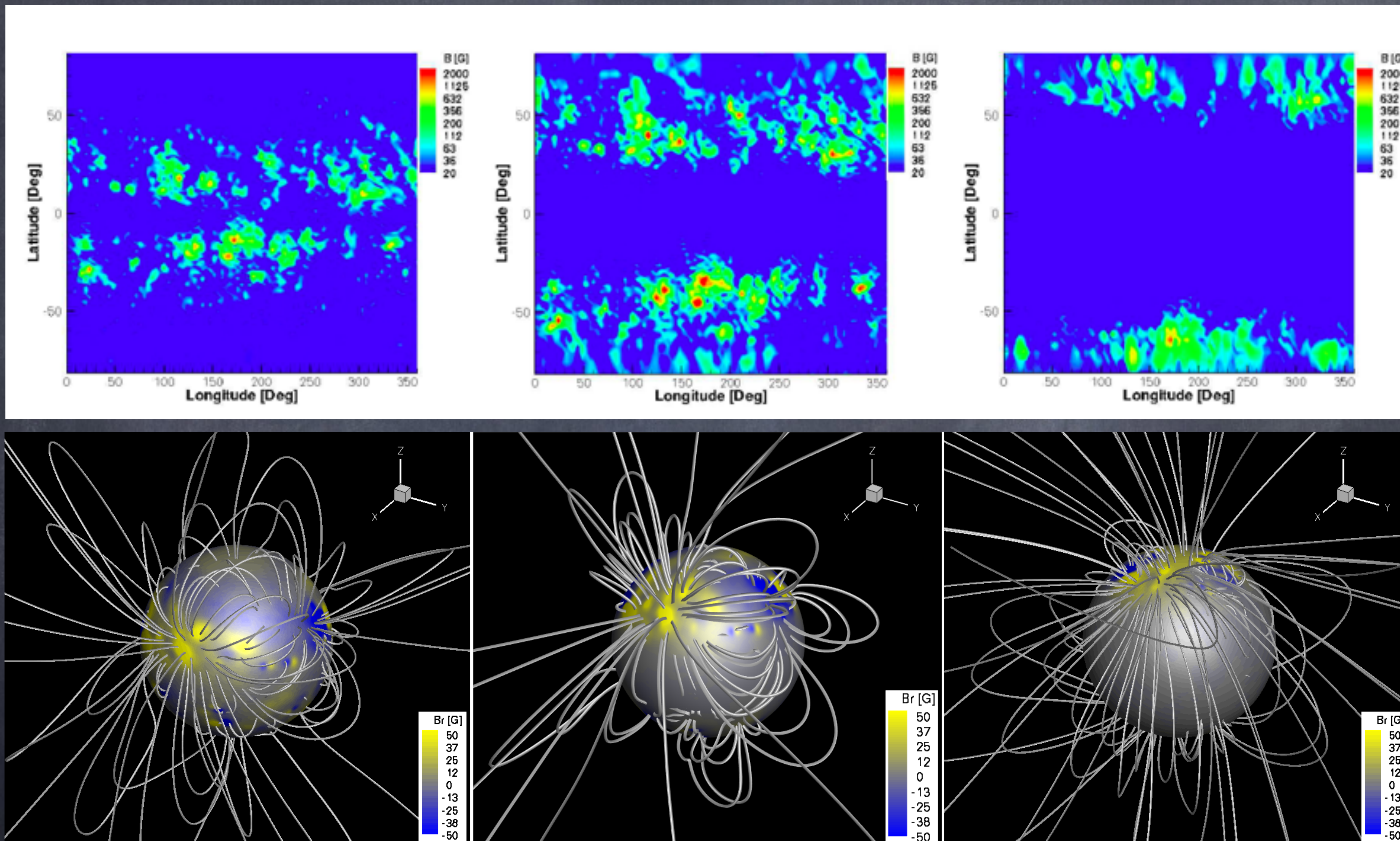
•Expected higher activity level.

Active Sun (CR1958, Jan. 2000):

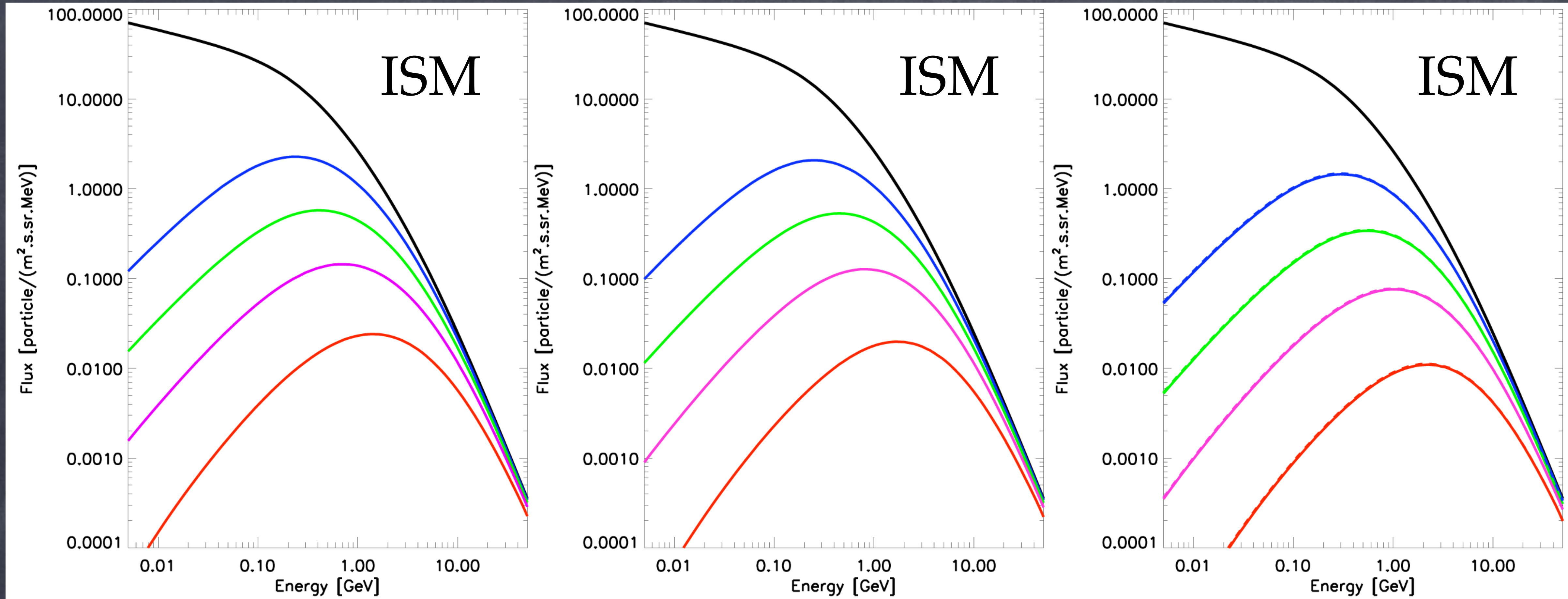
Decompose the map into weak, dipole component and strong, active region (spots) component.



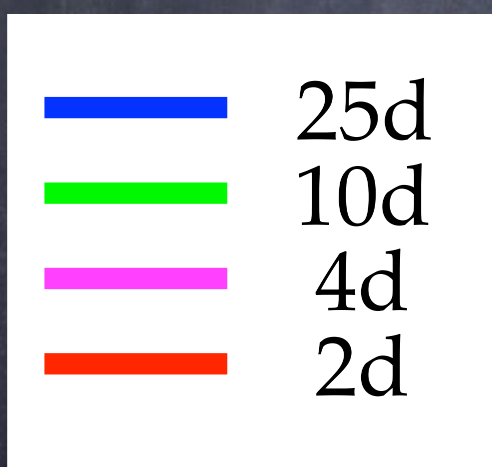
Manipulate the two components in location and magnitude:

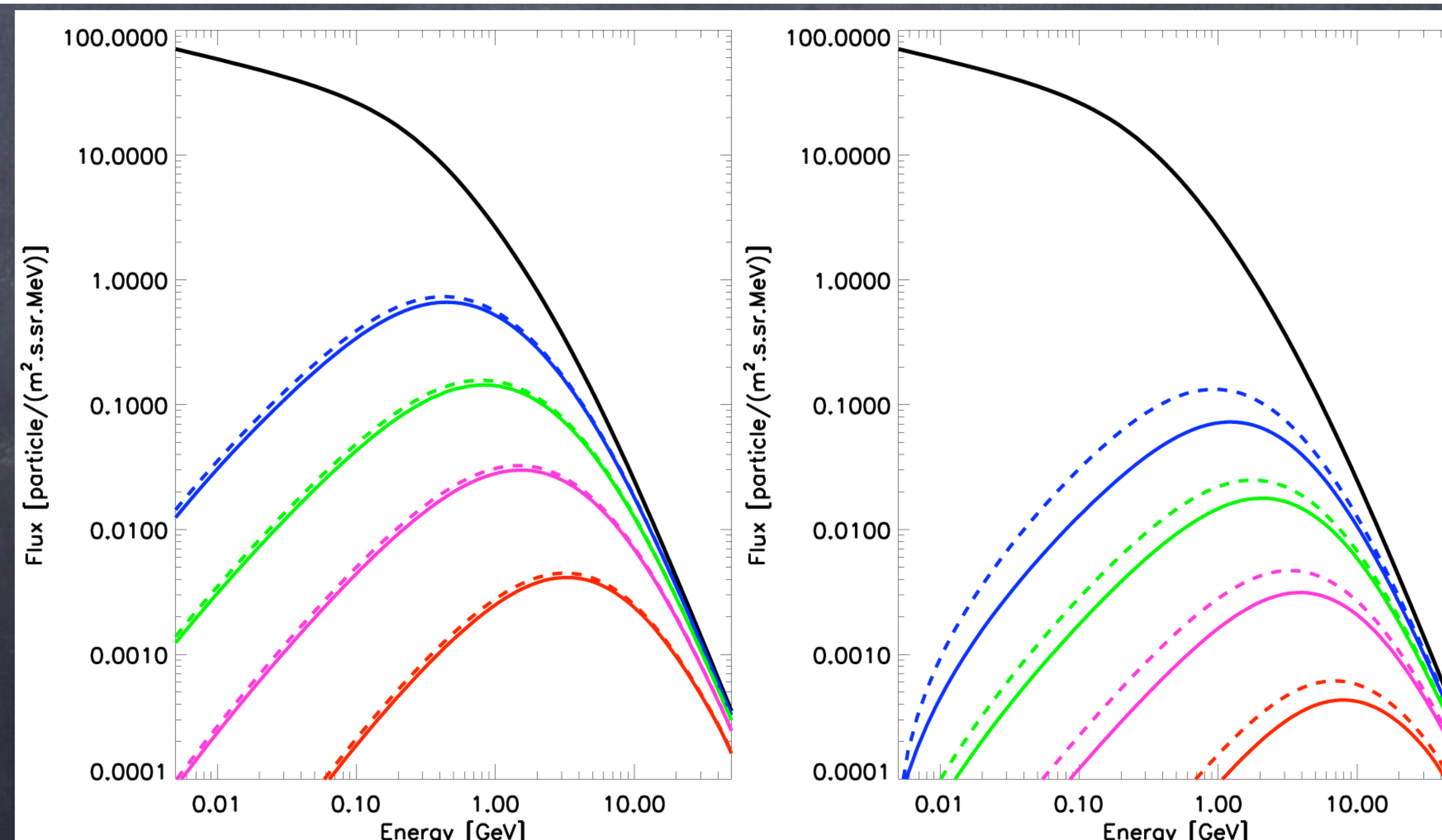


Cohen, Drake & Kota, 2012



Cohen, Drake & Kota, 2012

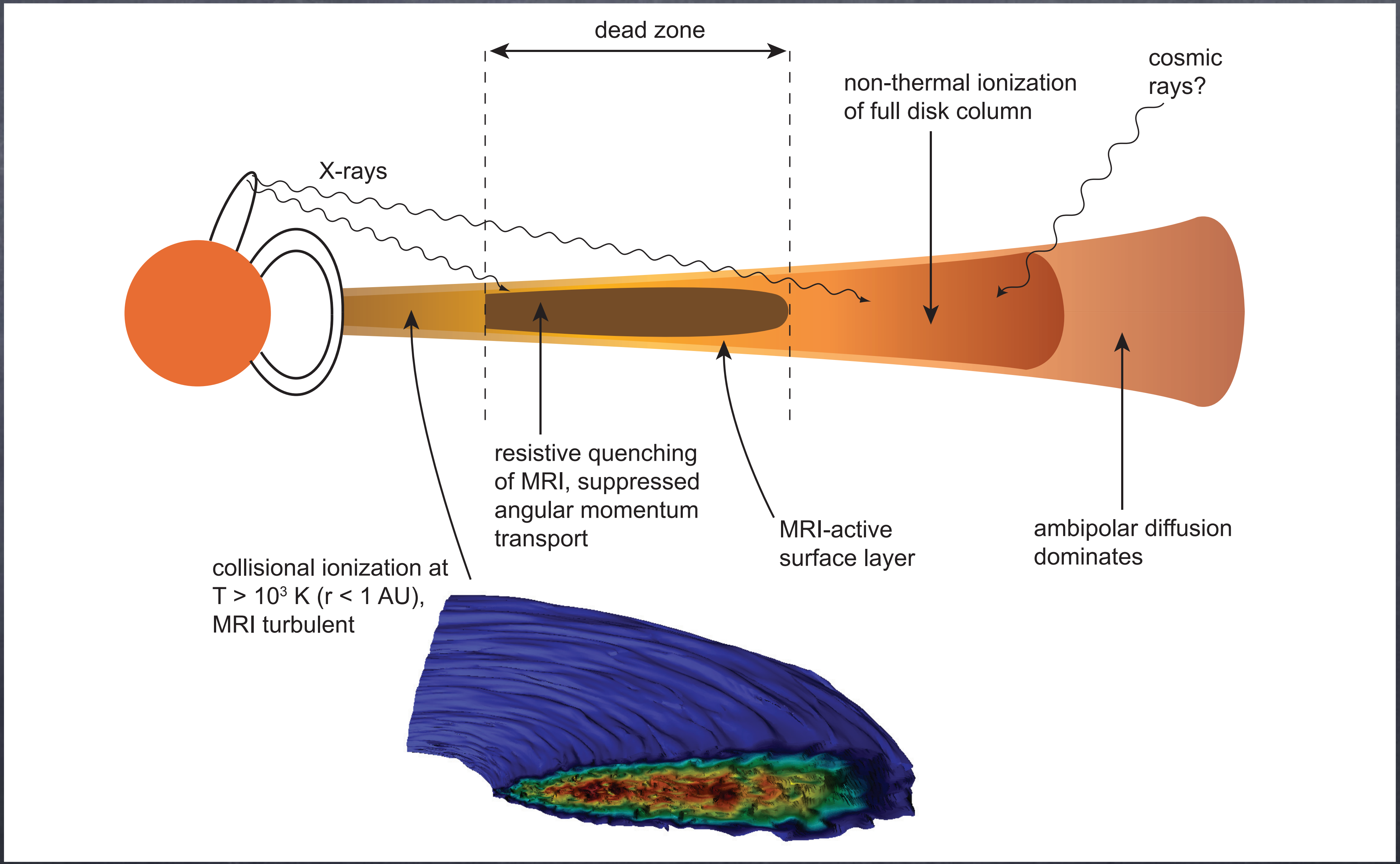




Habitability on Earth During the Early Sun (1)

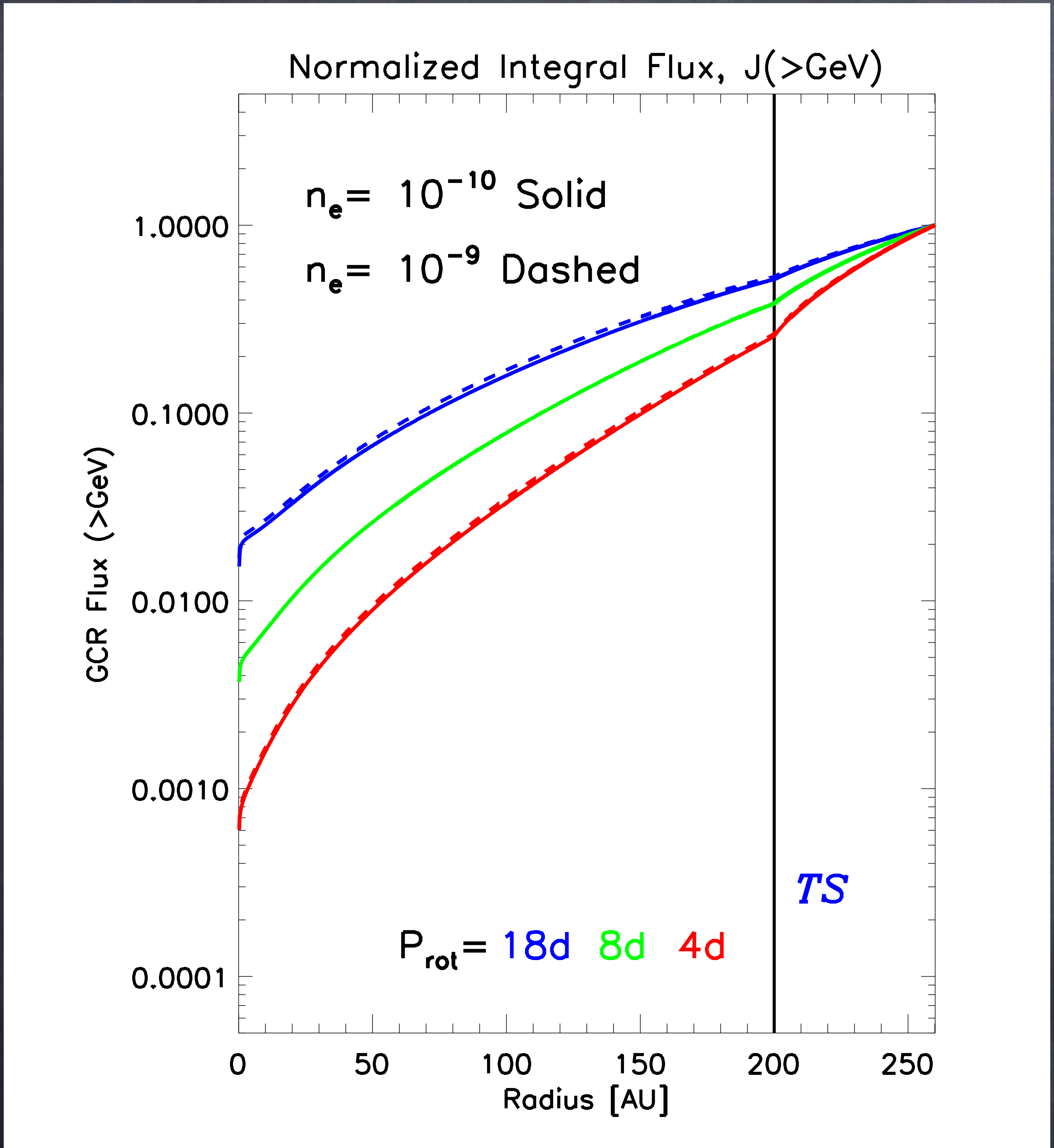
Planet formation in protoplanetary disks depends on angular momentum transfer.

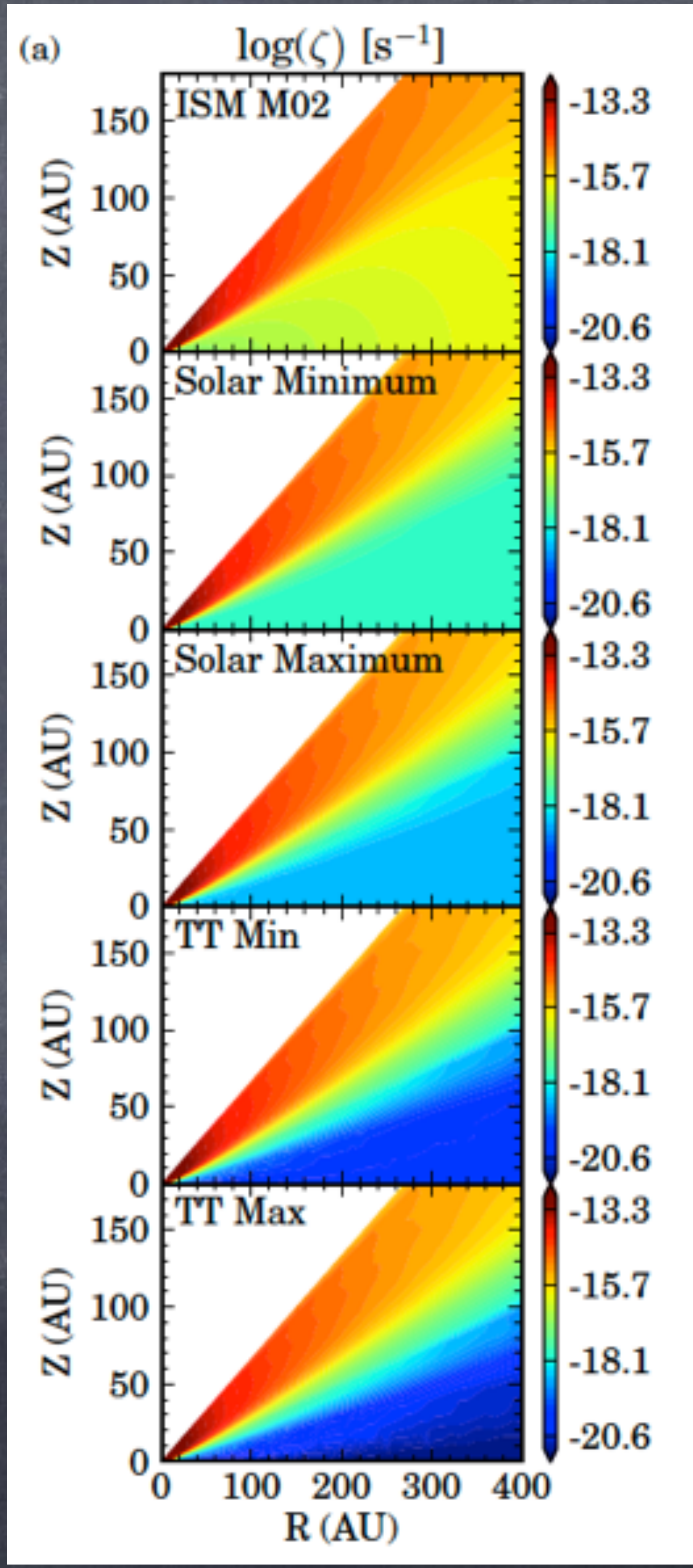
For MRI instability the disk should be sufficiently ionized:



Credit: jila.colorado.edu (Phil Armitage)

GCR ionization

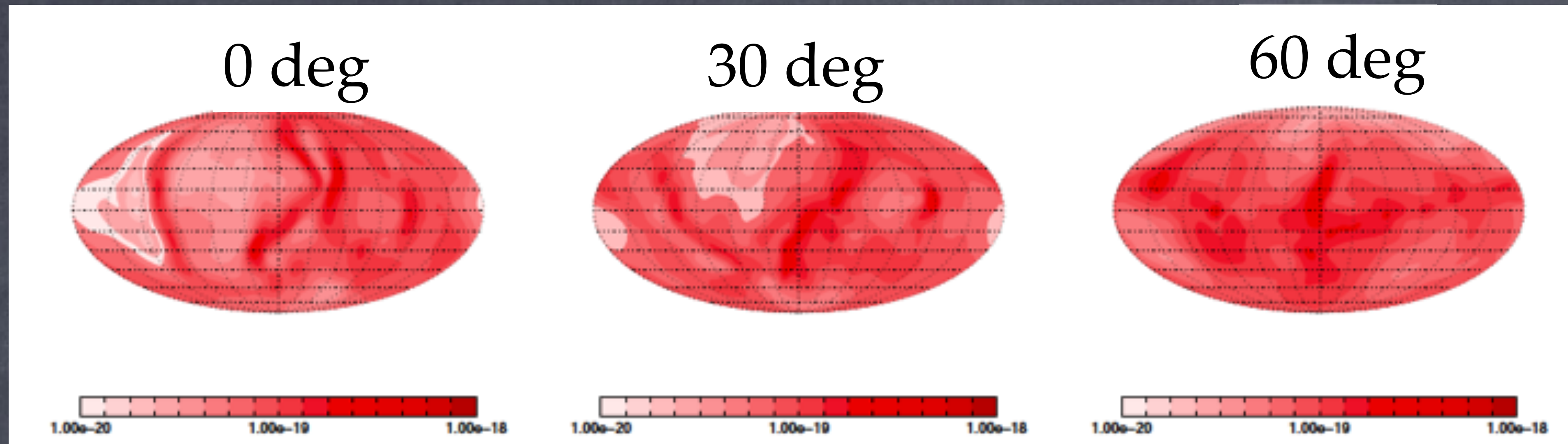




Cleeves et al., 2013

Mass flux distribution at 1AU

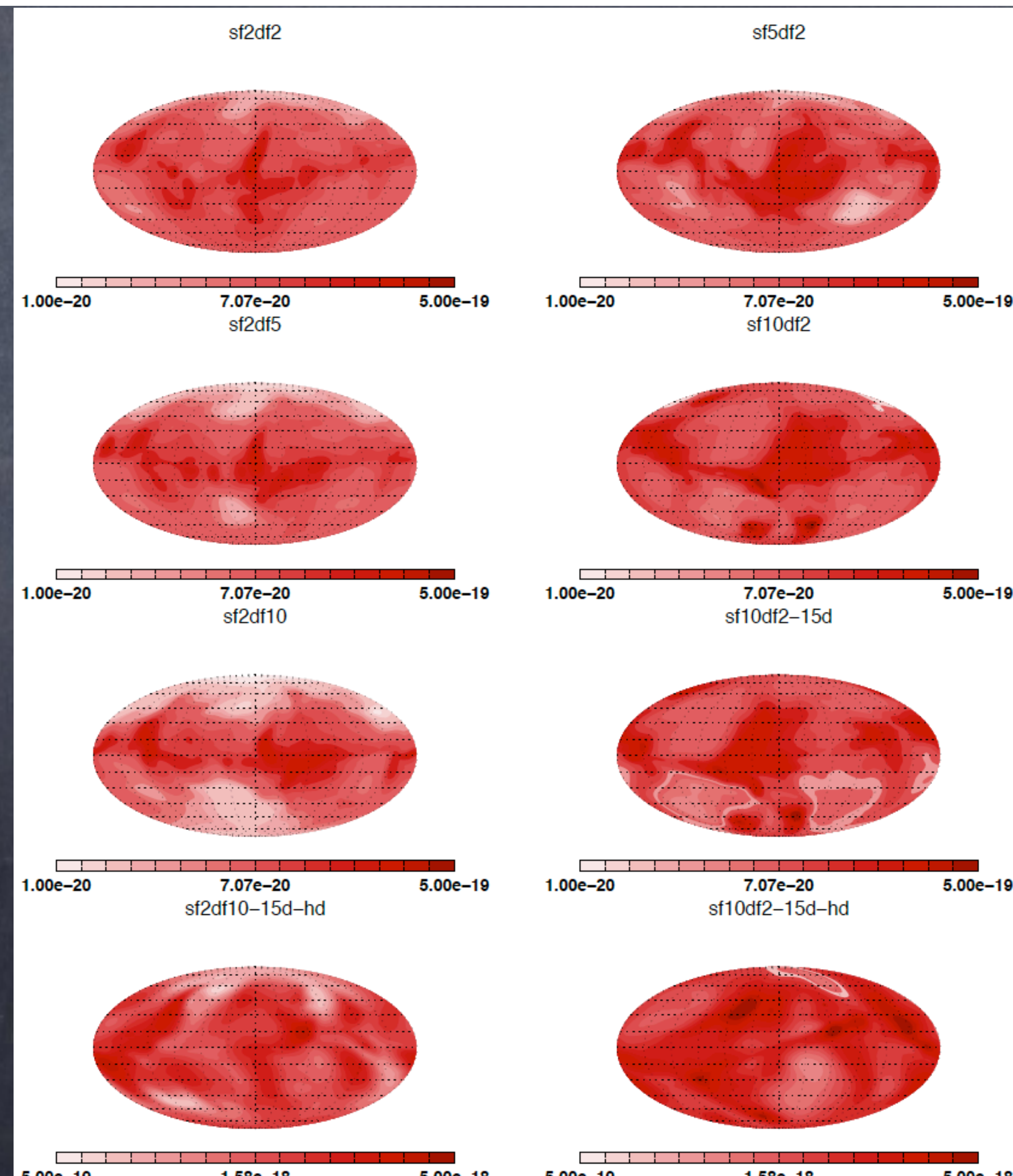
Shifting the spots in latitude



Changing dipole strength

Changing spots strength

High base density

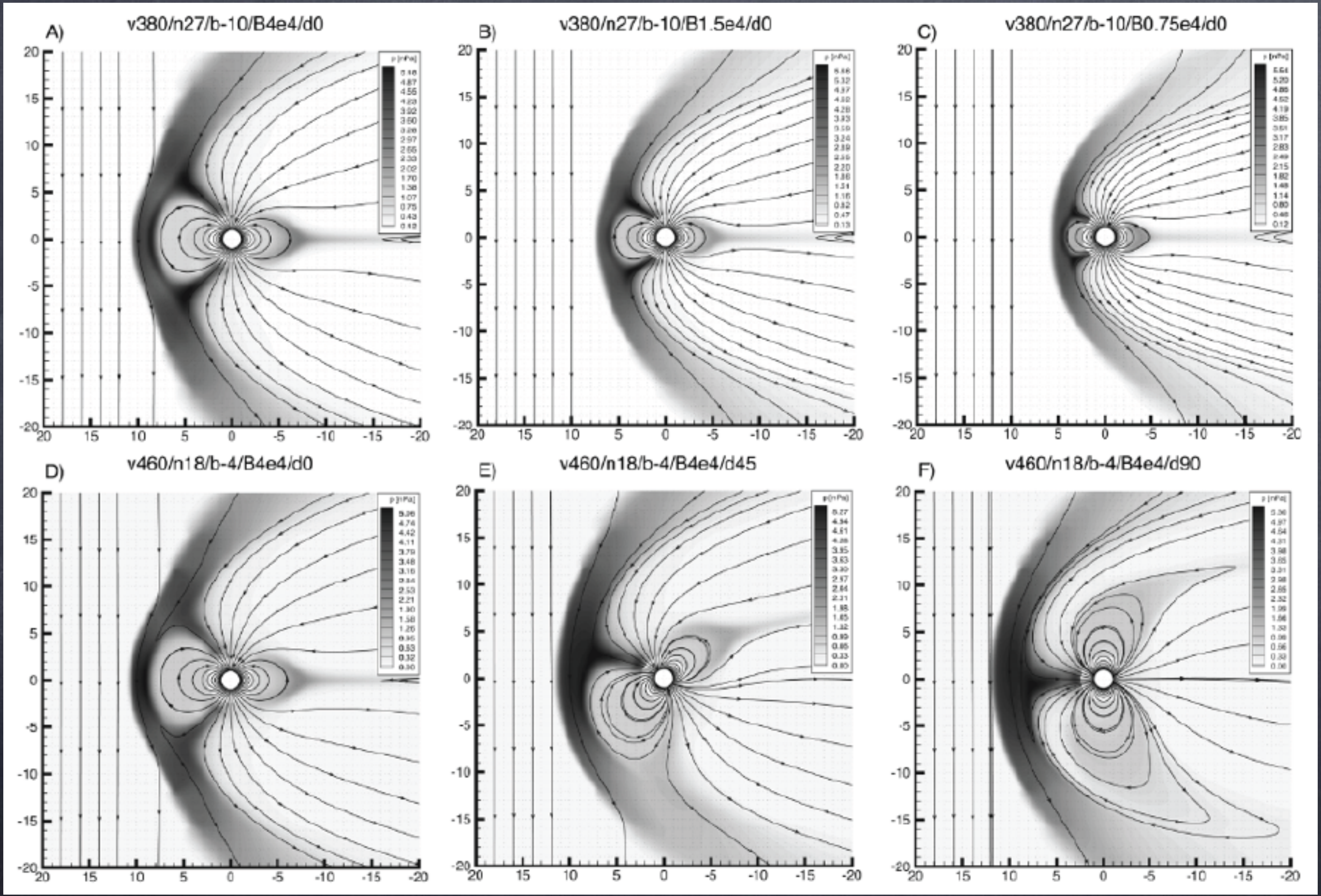


Habitability on Earth During the Early Sun (1)

Sterenborg et. al 2011

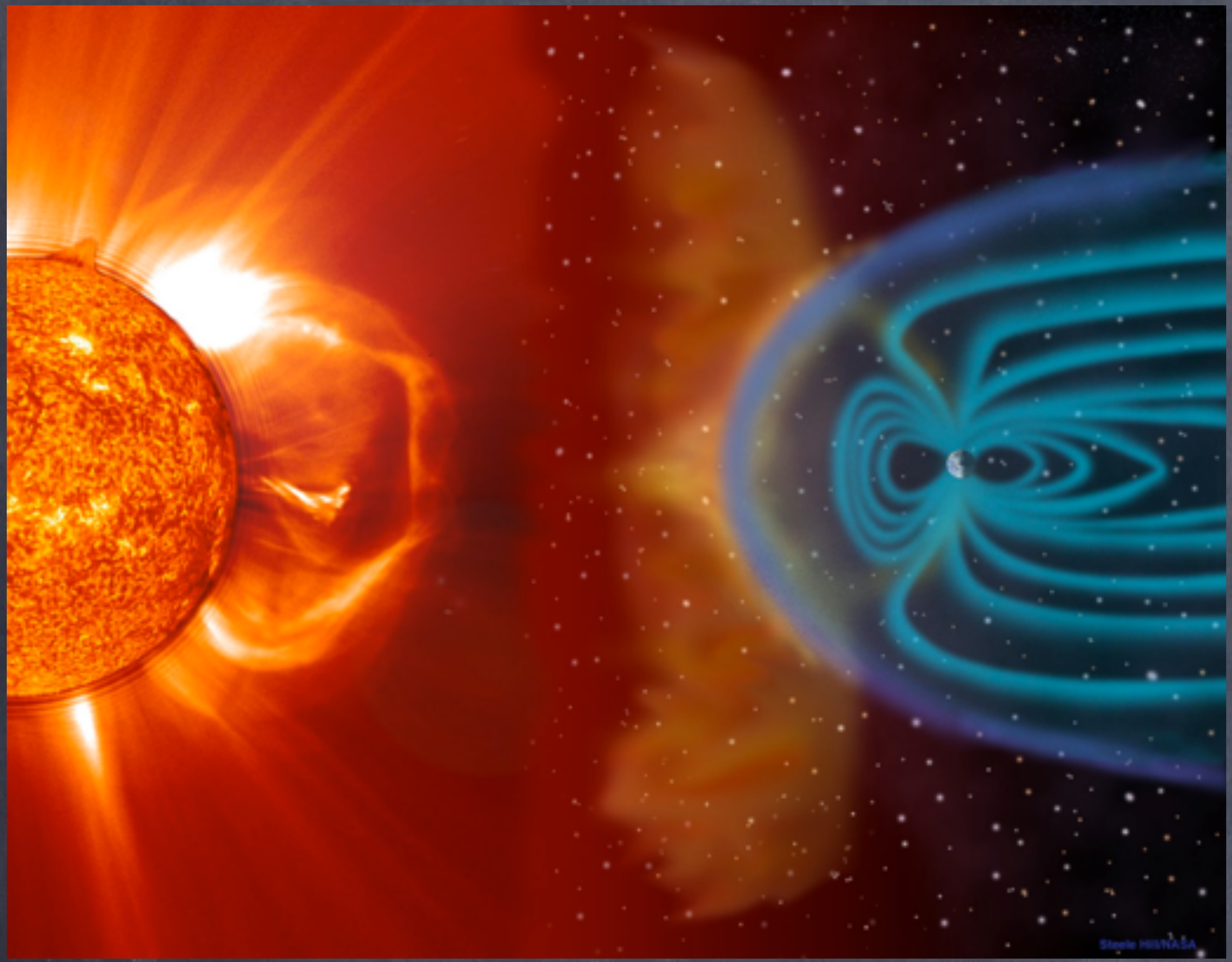
solar wind solution	u_{av} (km/s)	n_{av} (cm^{-3})	B_{av} (nT)	T_{av} (K)	mass flux (10^{-14} $M_{\odot}$/yr)
sf2df2	392.06	18.54	3.10	50542.81	5.55
sf2df5	413.26	20.41	3.44	53117.51	5.43
sf2df10	450.05	20.12	4.03	60625.57	5.01
sf2df10_15d_hd	280.43	441.17	11.90	34261.75	109.50
sf5df2	579.19	16.72	6.13	88623.79	6.30
sf10df2	388.56	27.08	7.86	49528.60	7.58
sf10df2_15d	381.95	27.05	9.20	50009.18	7.59
sf10df2_15d_hd	266.00	547.99	24.76	32020.56	142.06
shift00	444.57	10.67	2.41	62499.35	4.28
shift00_up	448.66	10.44	2.54	63477.22	-
shift00_down	440.13	10.81	2.29	60785.75	-
shift00_hd	287.34	373.98	8.01	34732.92	103.57
shift30	394.21	14.66	2.94	50702.75	4.93
shift60	392.06	18.54	3.10	50542.81	5.55
cr2074-shift00	307.59	22.31	2.01	39500.31	3.24

Sterenborg et. al 2011

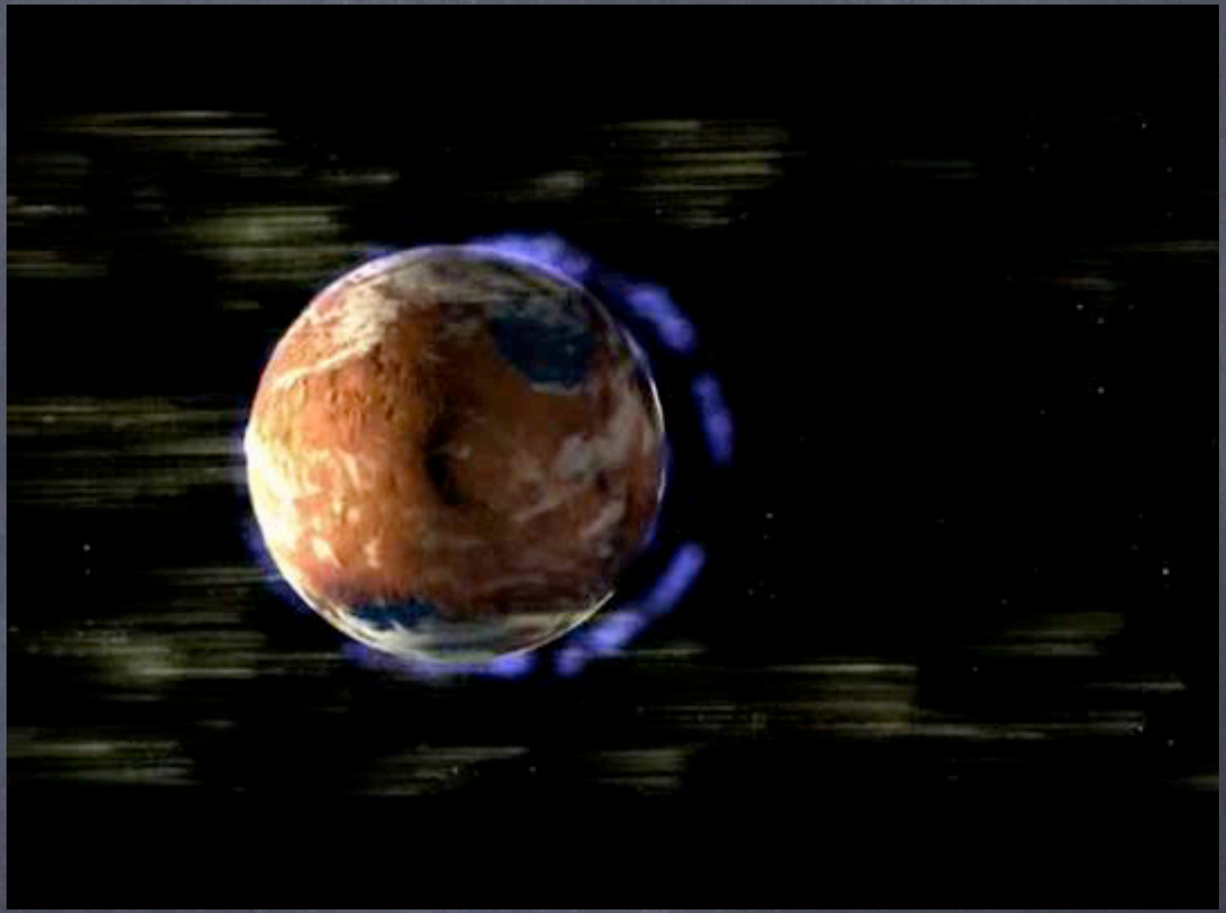


Habitability on Earth During the Early Sun (1)

Sterenborg et. al 2011



Credit: NASA



Habitability on Earth During the Early Sun (1)

To wrap things up...

1. The young Sun was more active, rotated faster, and emitted higher EUV/Xray radiation.

2. As a result, the IMF was more compressed and overall stronger.

3. The cosmic-ray flux near Earth was significantly lower, with all the consequences for life.

4. It is not clear whether the solar wind's mass flux was much higher (x100 times).