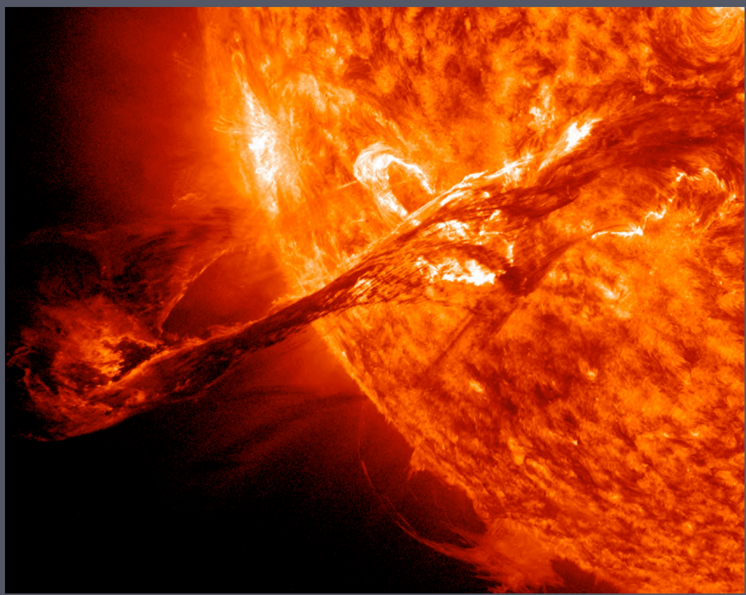
Effects of Stellar Eruptions Throughout Astrospheres



Credit: NASA

Ofer Cohen - Chapter 4 in Vol. IV

Heliophysics Summer School, Boulder CO, 2014

Outline

1. Astrospheres in Time:
    1. Astrospheric Structure and Evolution with Time.
    2. Astrospheric Evolution and Particle Transport.
    3. Stellar Activity and Disk Evolution.
2. Coronal Mass Ejections in Time:
    1. Initiation, Propagation and Evolution of CMEs Through Different Astrospheres.
    2. The Role of CMEs in Stellar Mass-loss and Stellar Spindown.
    3. Coronal Mass Ejections and Close-in Exoplanets.

Relevant book chapters:

Vol. I Ch. 9

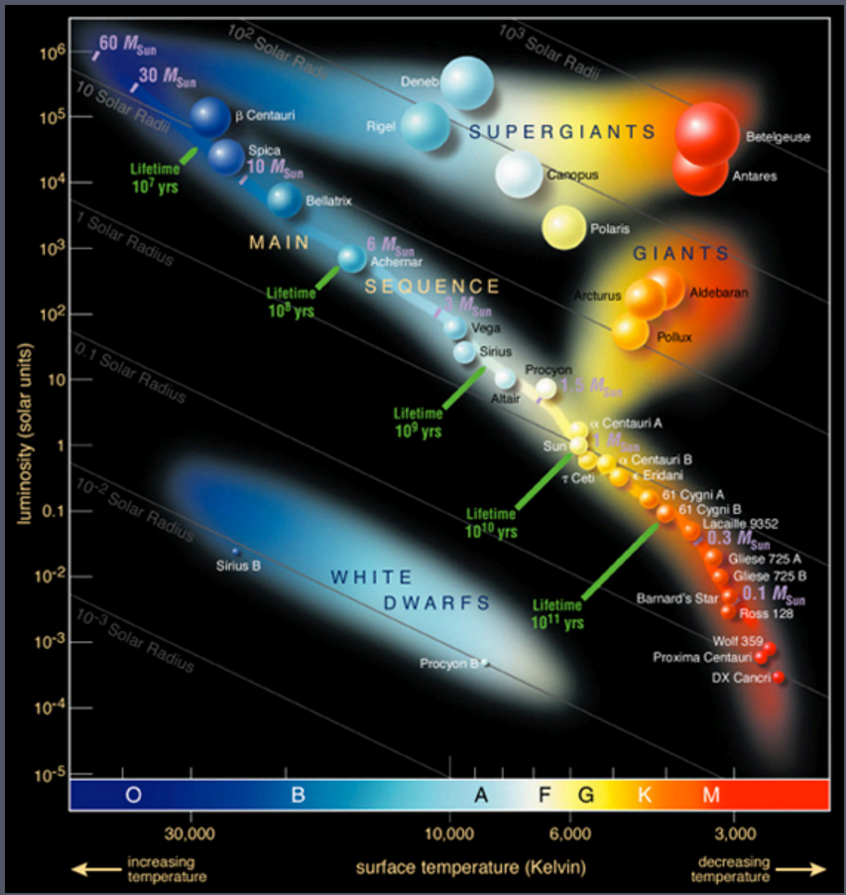
Vol. II Ch. 6

Vol III Ch. 2,3,4,8,9,11

Part I
Astrospheres in Time

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

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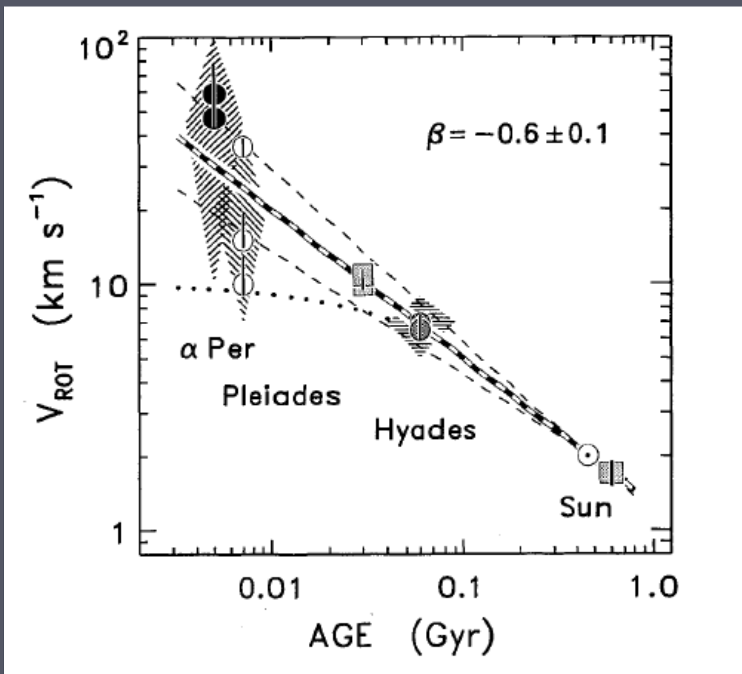
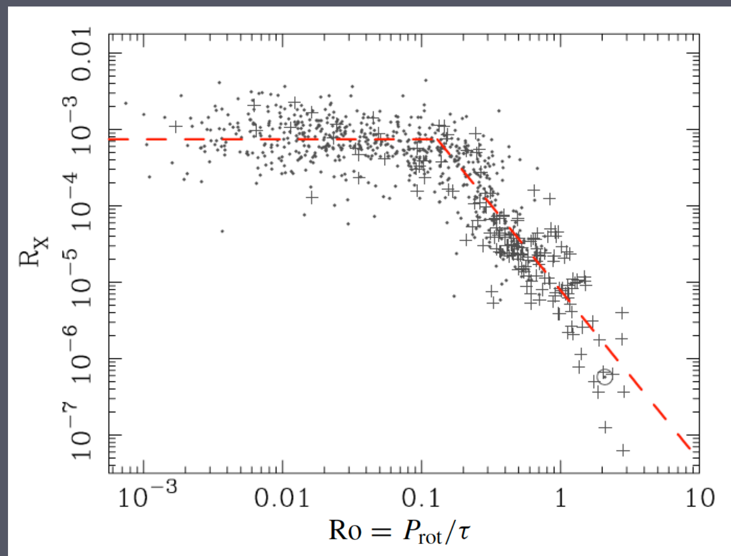
Ch. 2 Vol III



Ayres 1997



Wright et. al 2011

Skumanich Law:

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

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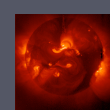
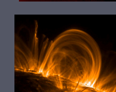
Ch. 2 Vol III

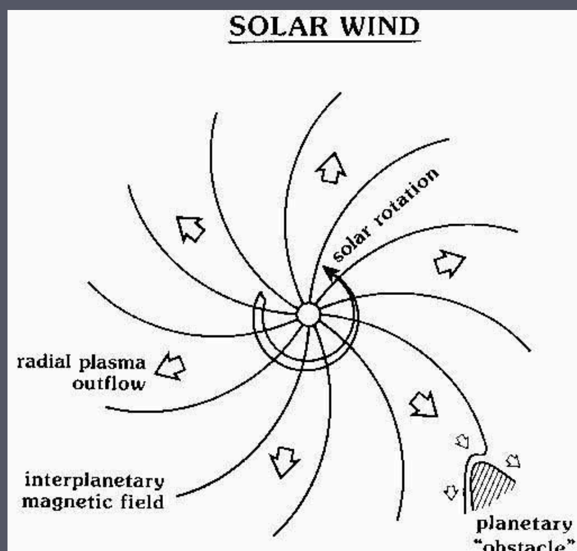
Rotation 

Age 

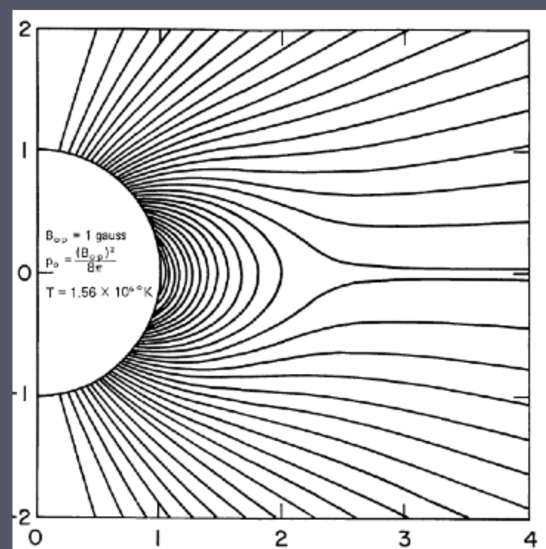
Stellar activity 

Magnetic field 

The structure of the Astrospheric Magnetic Field (AMF):



By J. Luhmann



Pneumann & Kopp 1971
HAO!!!

Assuming that at some distance, r_0, both B and u are purely radial:

$$\frac{B_\phi}{B_r} = \frac{u_\phi}{u_r} = \frac{-(r - r_0)\Omega_\odot \sin\theta}{u_{sw}}$$

$$\mathbf{B} = B_r\hat{r} - B_r\frac{(r - r_0)\Omega_\odot \sin\theta}{u_{sw}}\hat{\phi}$$

Assuming $\nabla \cdot \mathbf{B} = 0$

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

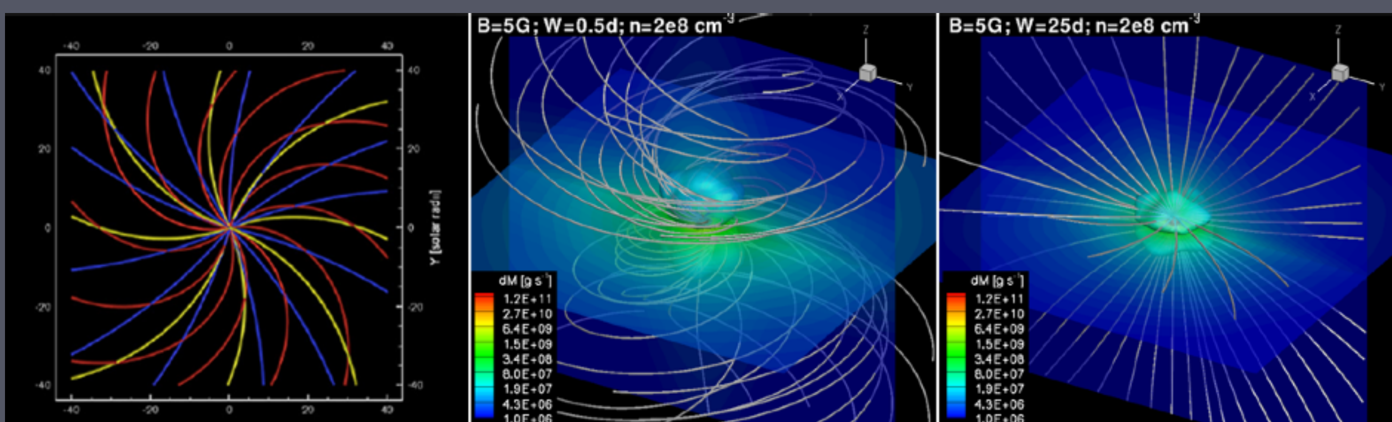
for $r \gg r_0$

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

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

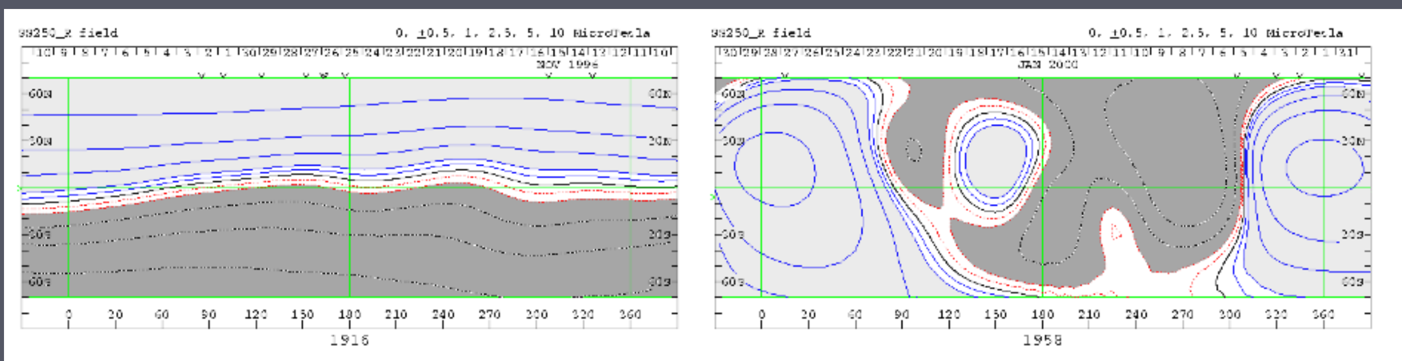
The effect of B_s:

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

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

Solar Minimum

Solar Maximum

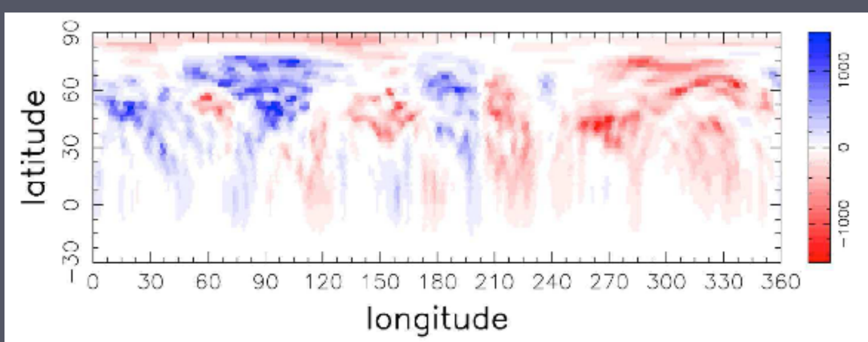


Wilcox Solar Observatory data

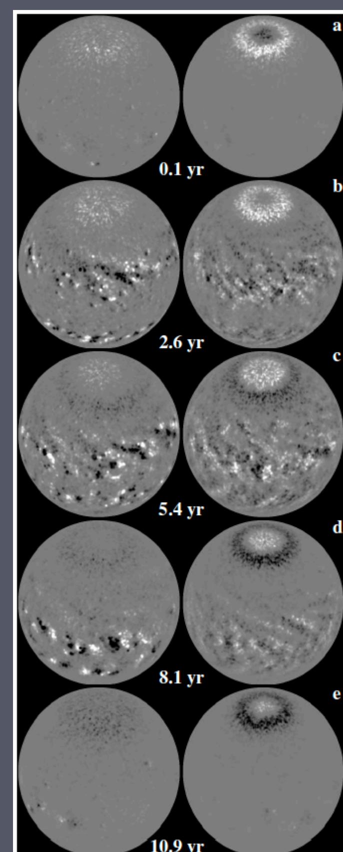
For stellar time-scales, let's consider only changes in the rotation rate, Ω, and the general field distribution .

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

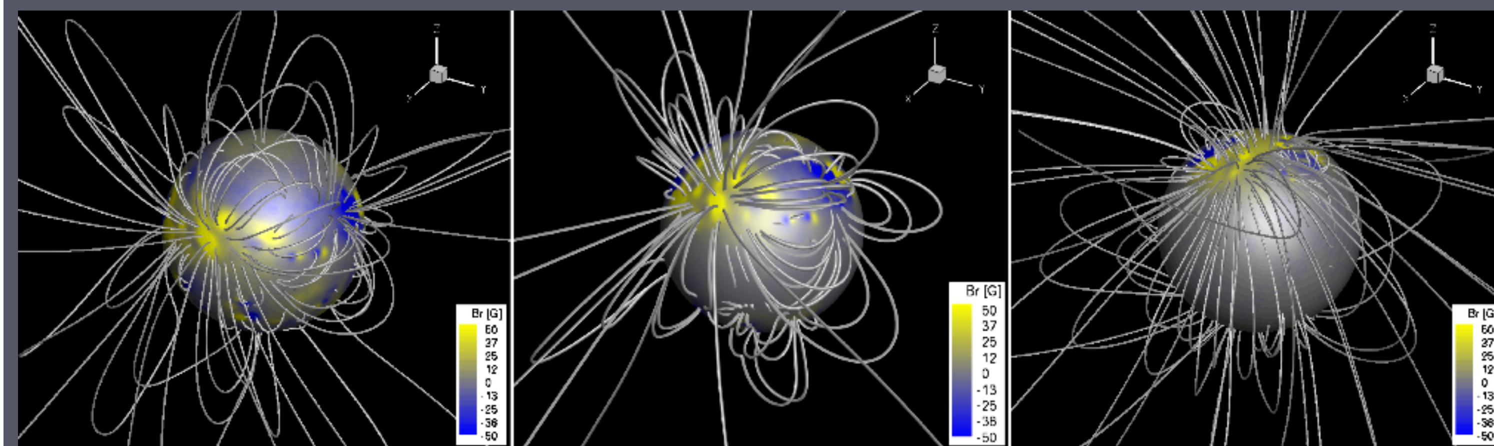
AB Doradus - young active Sun (P=0.5 days):



Hussain et. al 2007



Schrijver & Title 2001



Cohen, Drake & Kota, 2012

Astrospheric Evolution and Particle Transport

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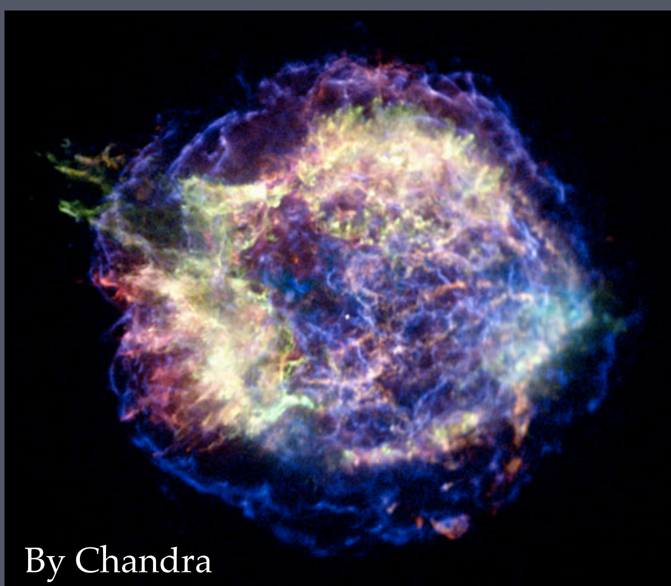
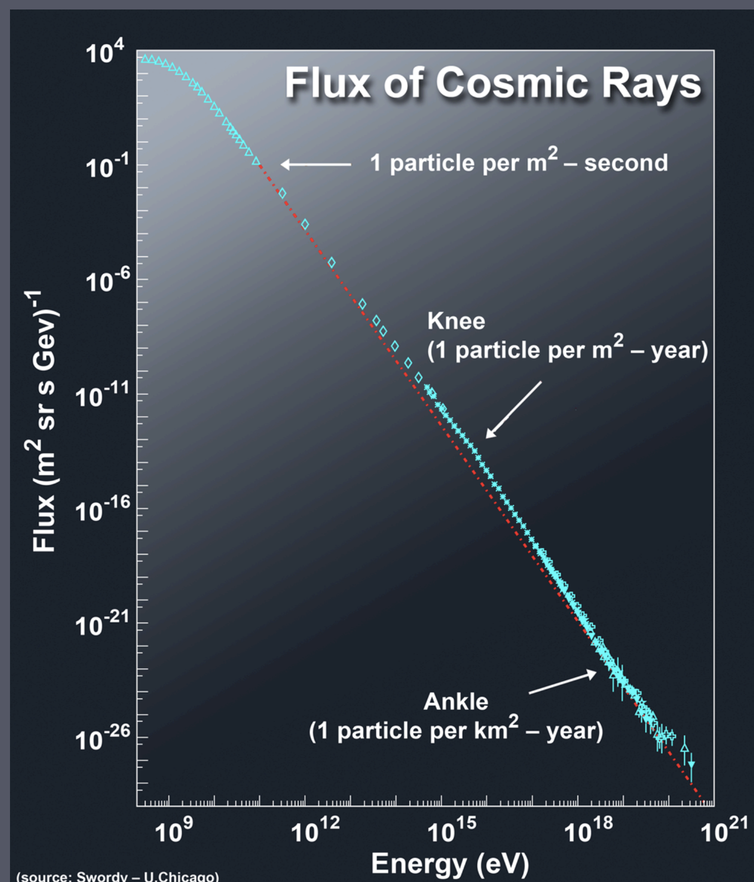
Galactic Cosmic Rays (GCR):





Transport of GCR (Parker 1965):

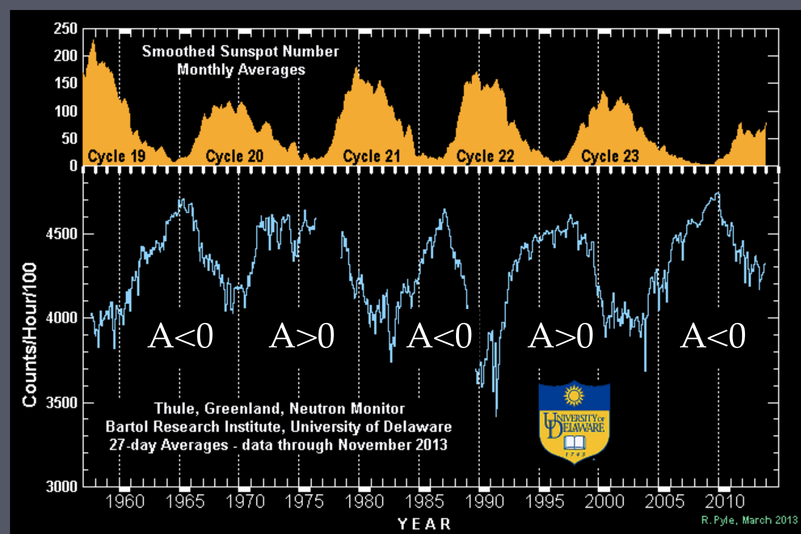
$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_i}\right] - v_i\frac{\partial f}{\partial x_i} - V_{di}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial v_i}{\partial x_i}\left[\frac{\partial f}{\partial \ln p}\right] + Q + L$$

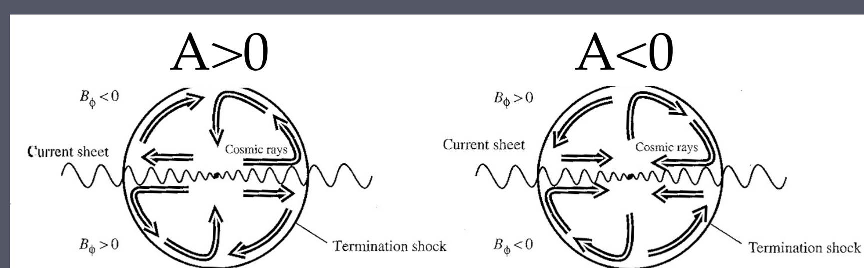
diffusion | advection | guiding center drift | energy change | sources and losses

Present day modulation of GCR (Ch. 9 Vol II):

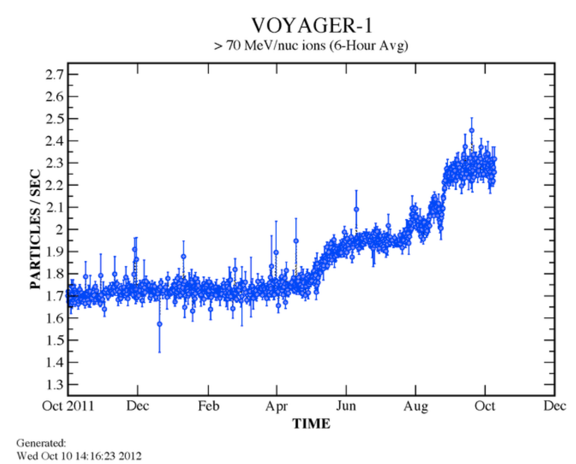
GCR intensity reduction due to:

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

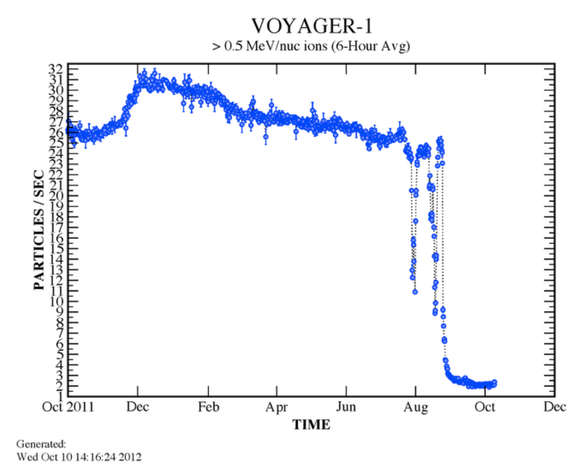




GCR flux



SW particle flux



GCR 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).

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.

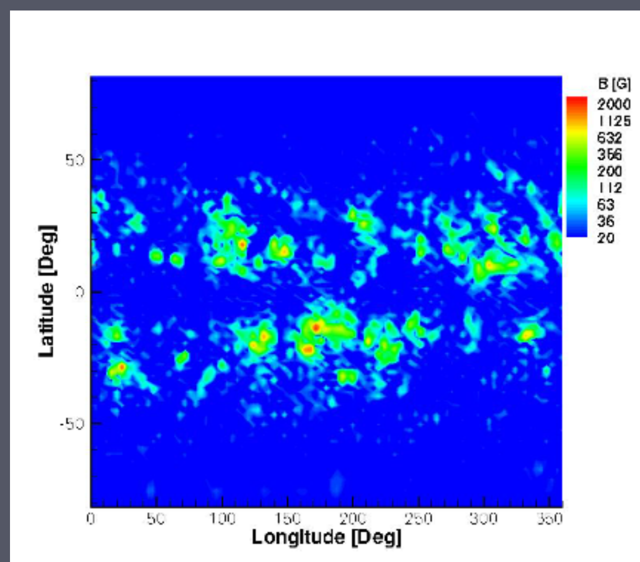
The young Sun during the Archean eon:

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

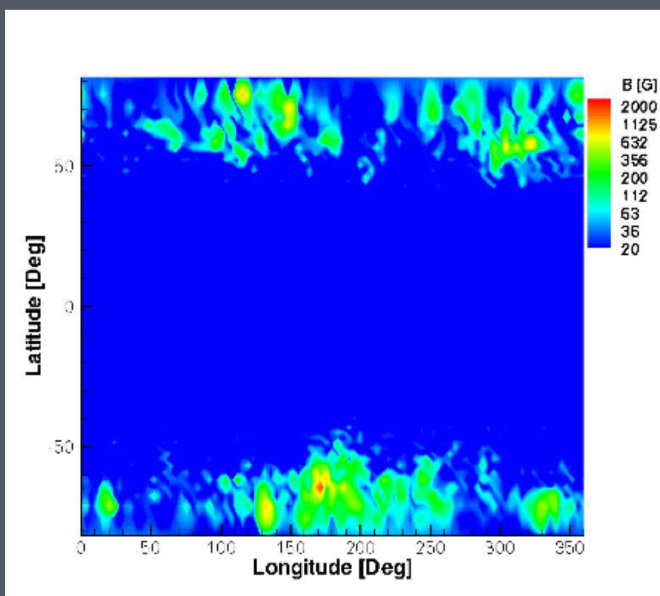
•Expected higher activity level.

Active Sun (CR1958, Jan. 2000):

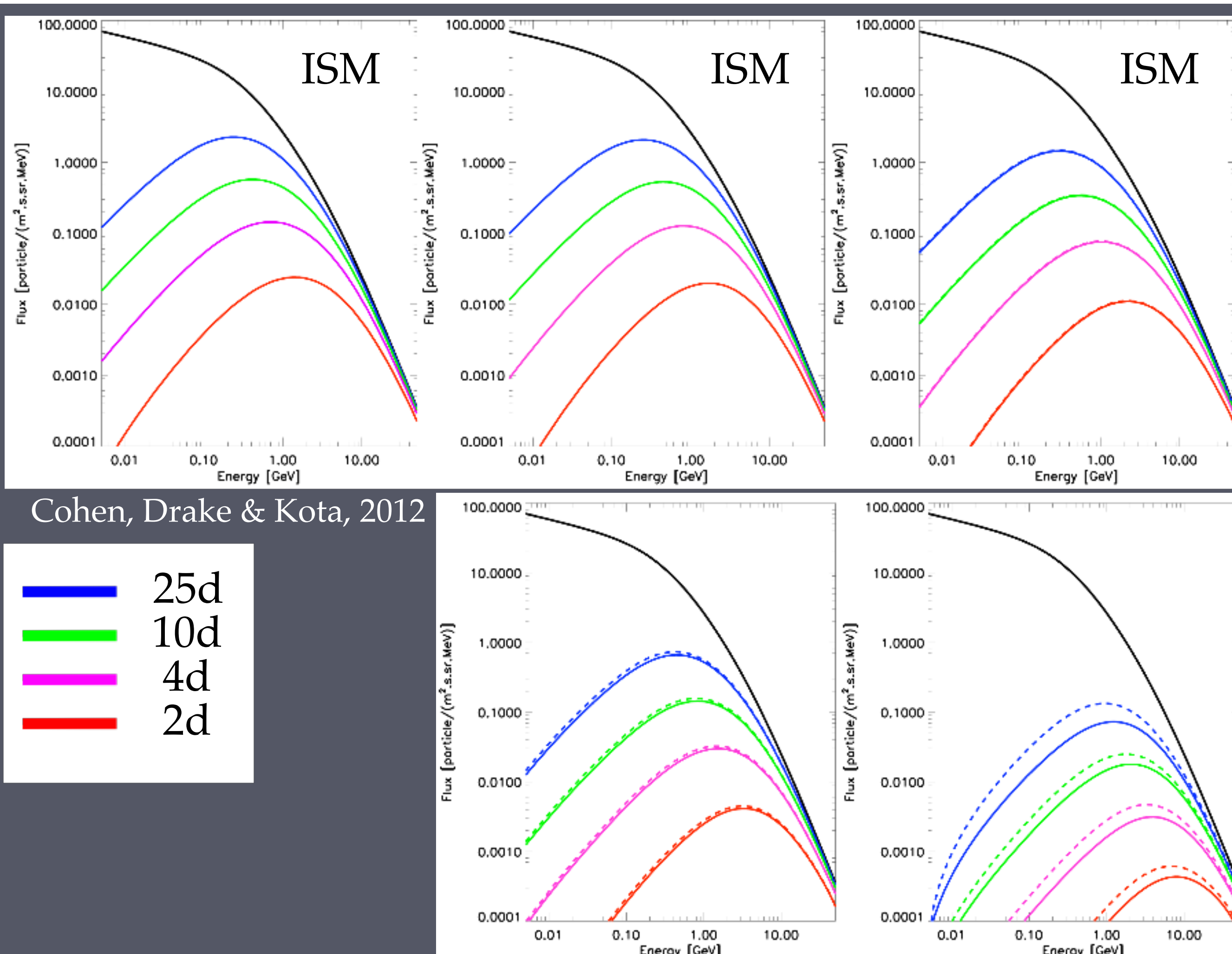
Decompose the map into weak, dipole component and strong, active region (spots) component.



Manipulate the map and its two components in location and magnitude:



For each solution, calculate the GCR intensity at Earth.



Cohen, Drake & Kota, 2012

Stellar Activity and Disk Evolution

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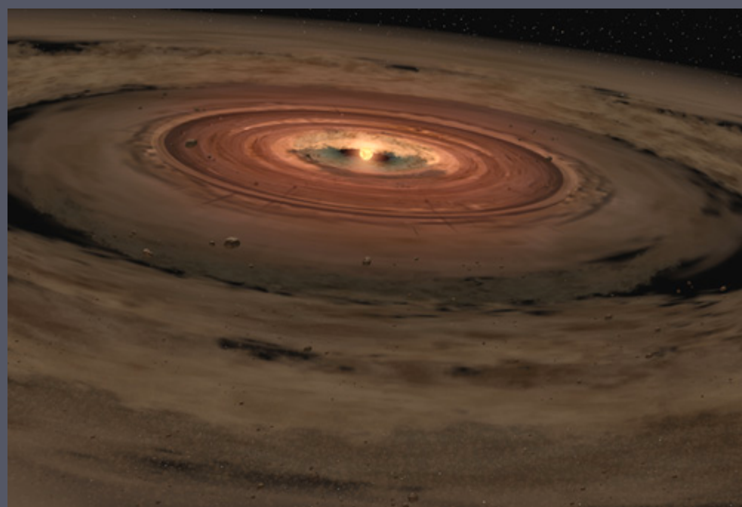
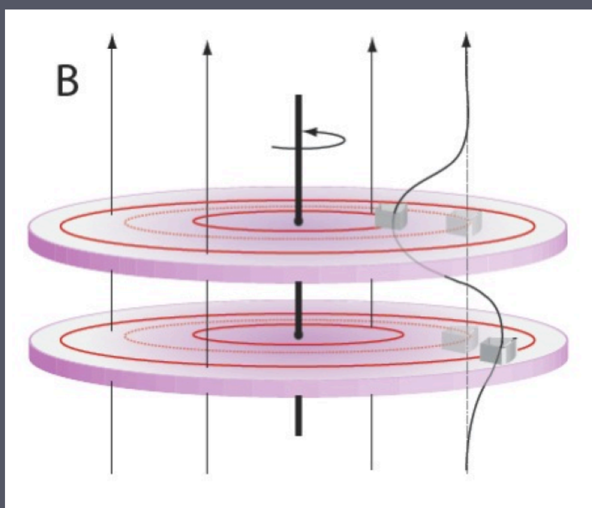


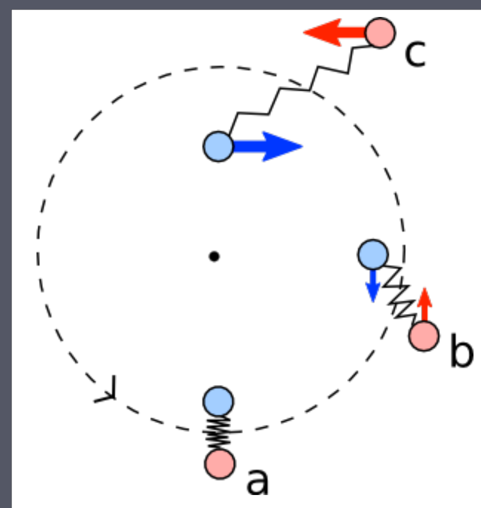
Credit: NASA

Angular momentum transport controls the transfer of material to and from different regions of the disk:

- Formation of planetary systems.
- Origin of planets.

Magneto-rotational Instability (MRI)

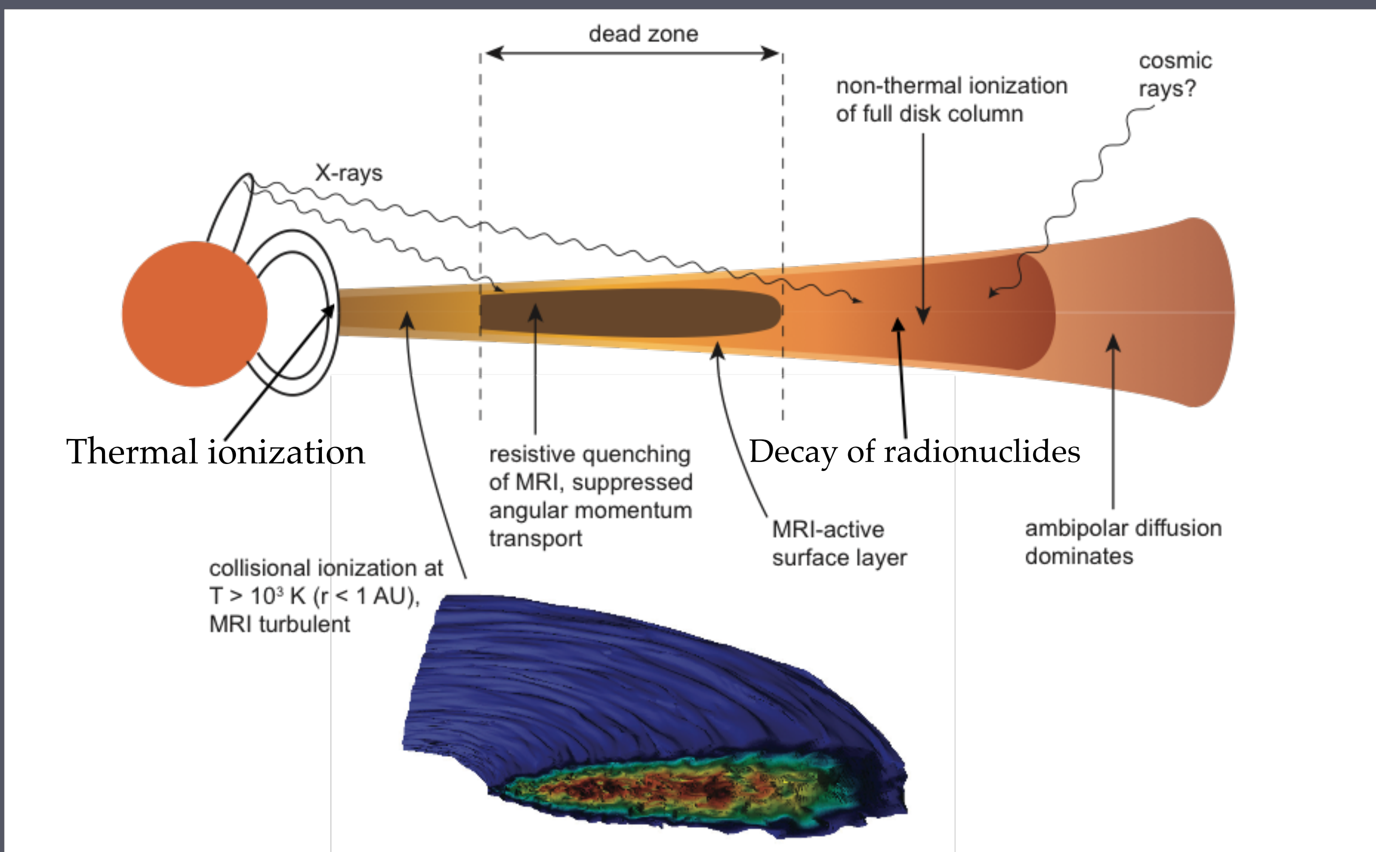




wordpress.com

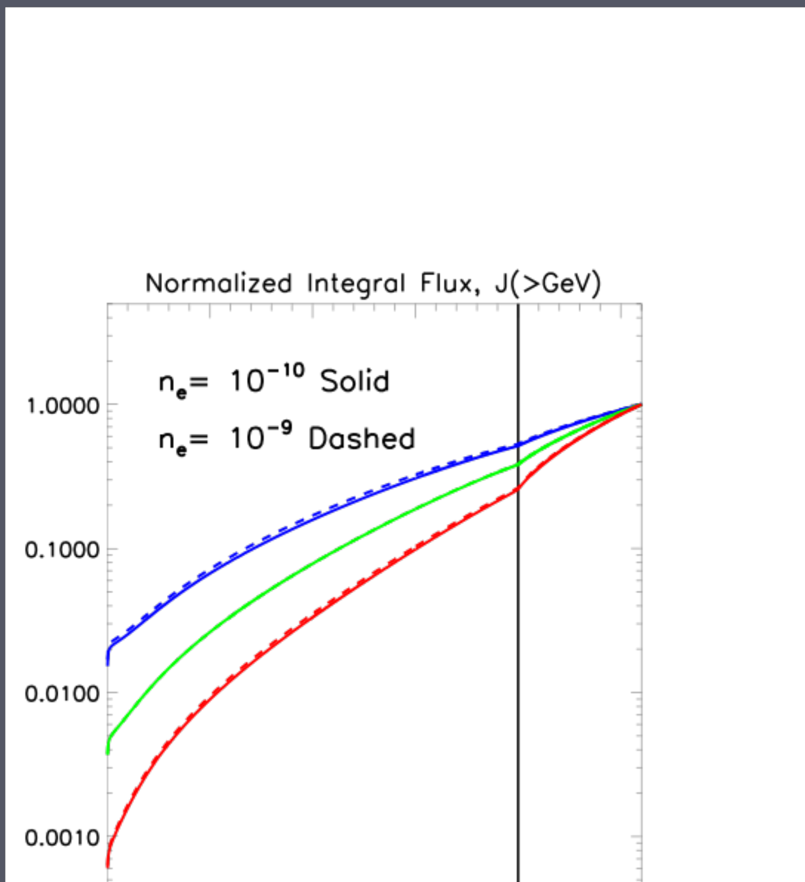
MHD formulation to explain angular momentum transfer in disks.
The disk's gas must be sufficiently ionized!!!

Possible ionization mechanisms:



Credit: jila.colorado.edu (Phil Armitage)

Possible ionization mechanisms:



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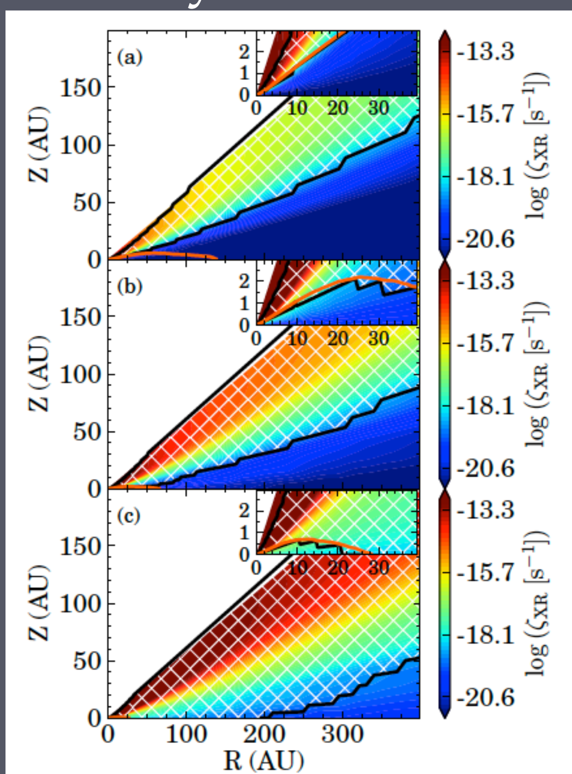
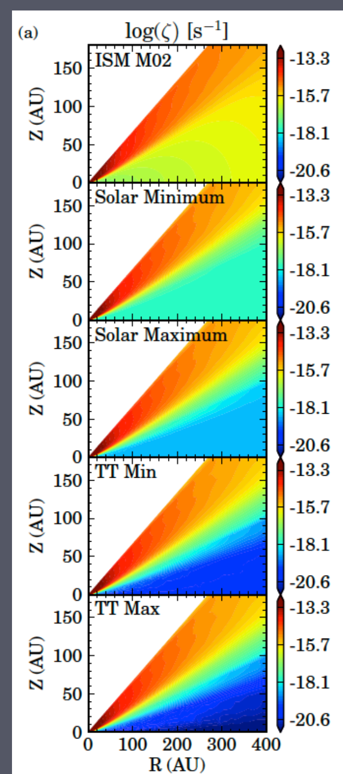
Can the disk be sufficiently ionized?

X-ray ionization



Cleeves et al., 2013

GCR ionization



It is not clear yet whether the center of the disk can be sufficiently ionized.

Part II
Coronal Mass Ejections in Time

1969 1984 2014

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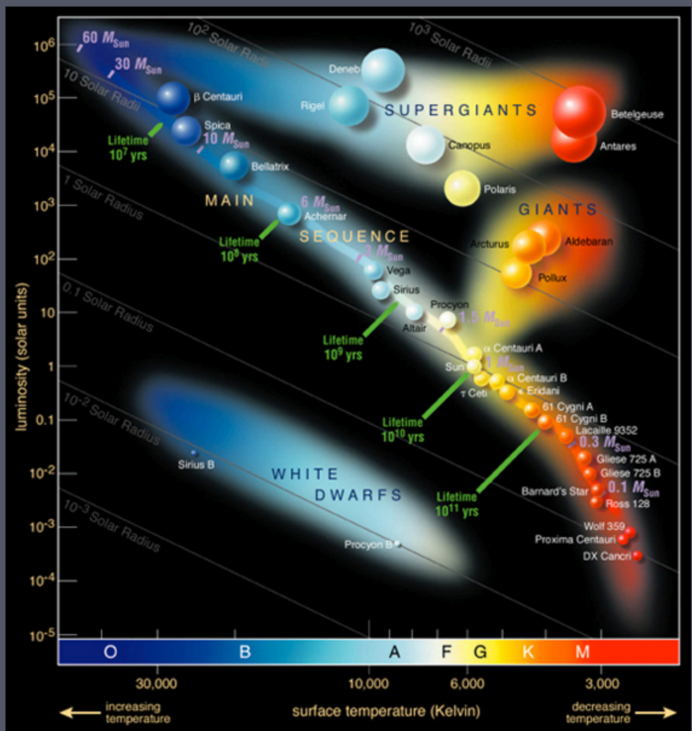
Part II
Coronal Mass Ejections in Time



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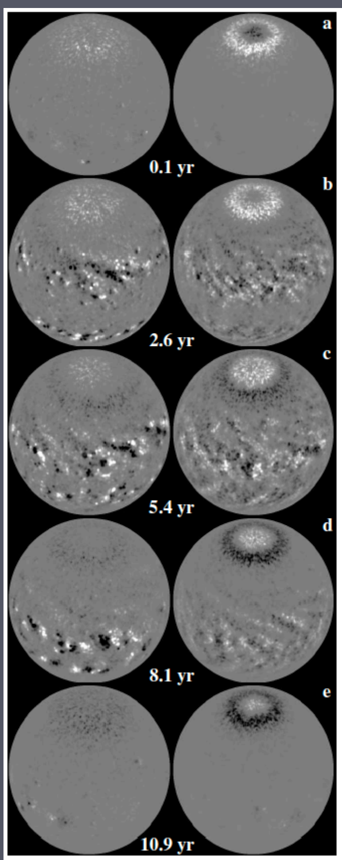
How do CMEs change with stellar evolution and change in activity level?

- Impact on CME initiation.
- Impact on propagation & evolution.

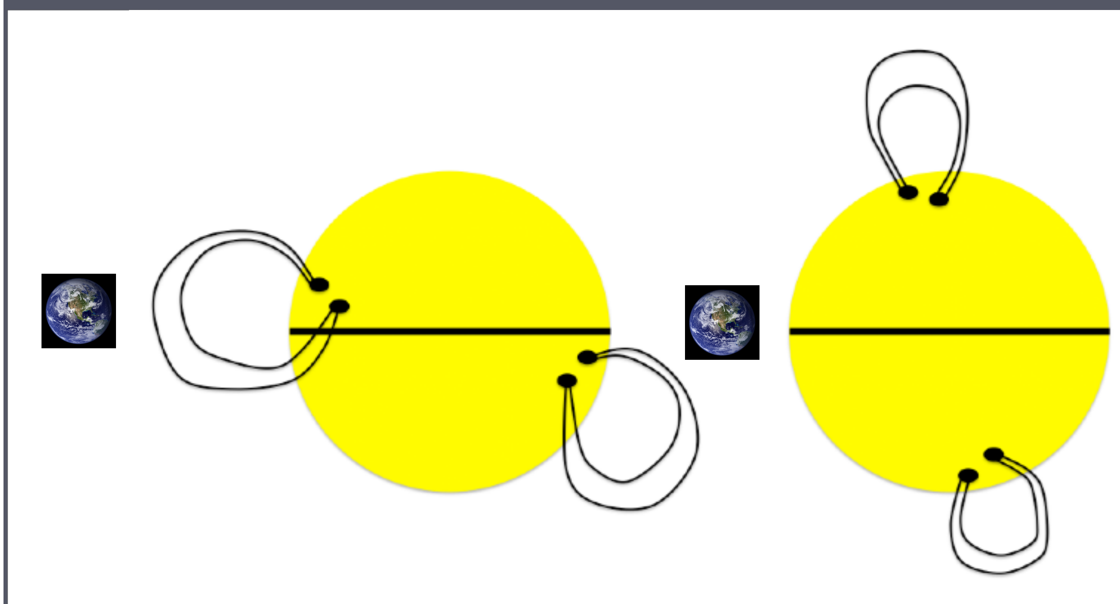
Observations:

Stellar flares...

Impact on CME initiation:



Schrijver & Title 2001



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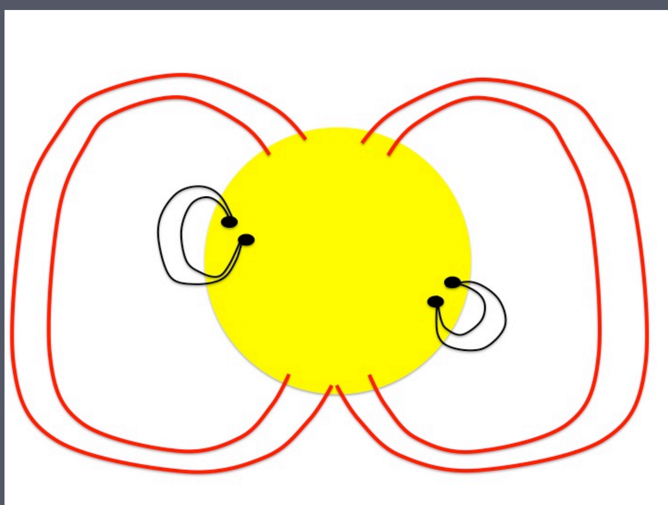
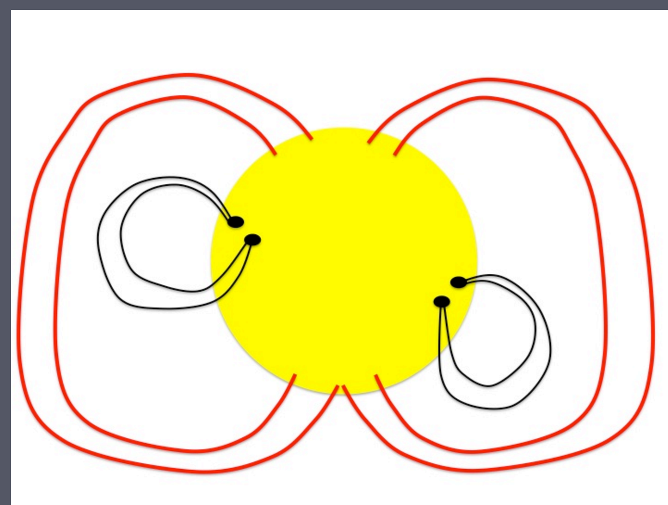
Do stellar CMEs scale with the overall increase in magnetic energy?

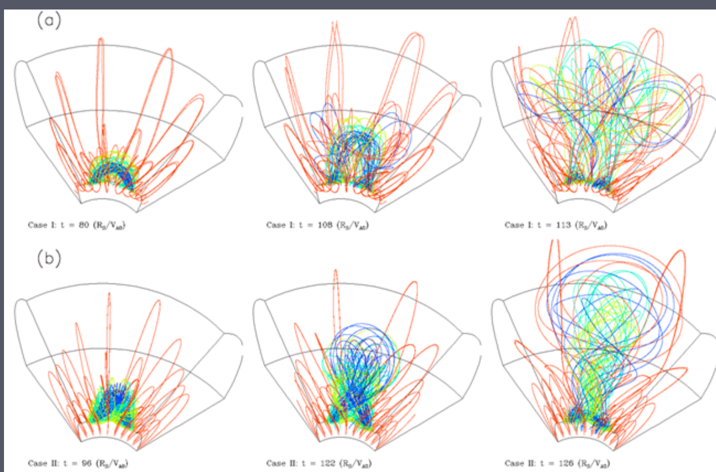




Open question...

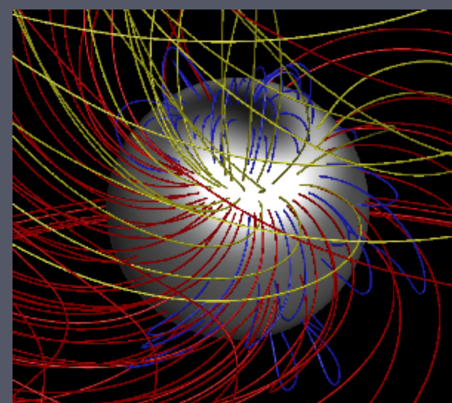
Different initiation mechanism?

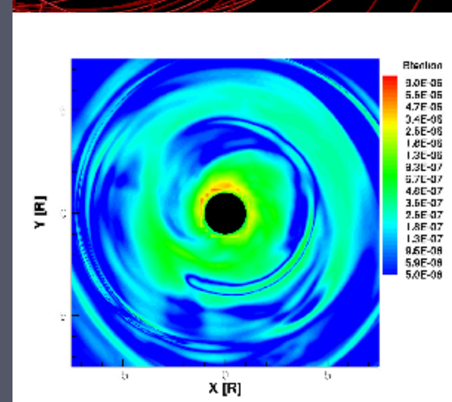
Solar CME



Fan & Gibson 2007

FK Comae

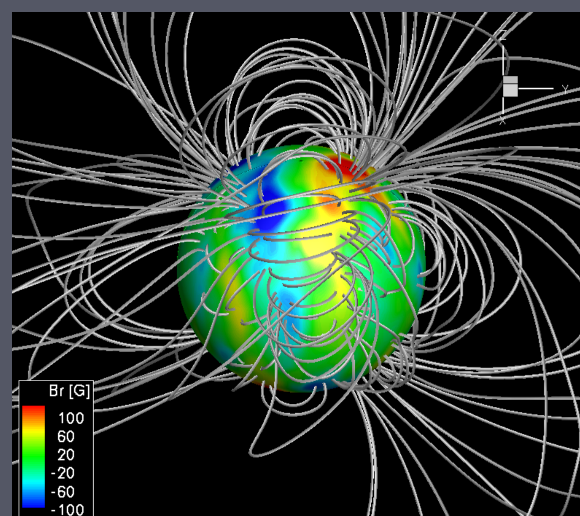




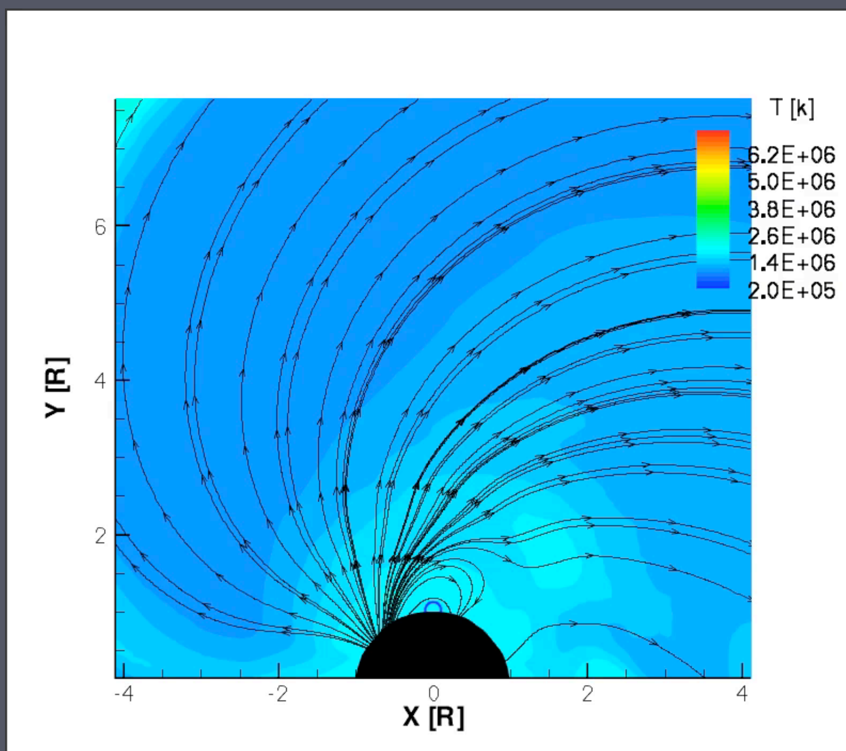
The propagation and evolution of CMEs depend on the Astrospheric field.

Strong azimuthal field close to the star

Strong field strength



A toy simulation of a CME on AB Doradus



Possible consequences:

- Slowdown CMEs?
- More/Less shocks?
- Increase/Decrease in SEPs and GCRs?

The Role of CMEs in Stellar Mass-loss and Stellar Spindown

Effects of Stellar Eruptions Throughout Astrospheres
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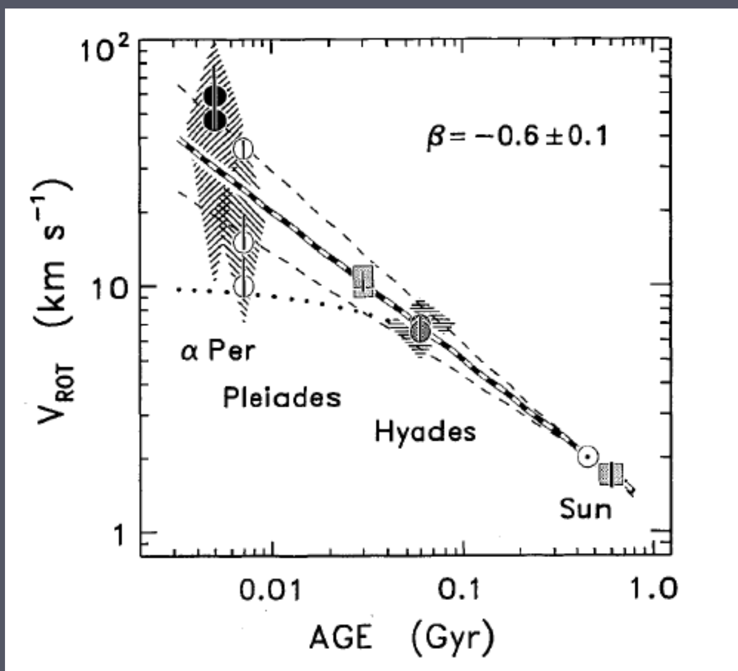


Ayres 1997

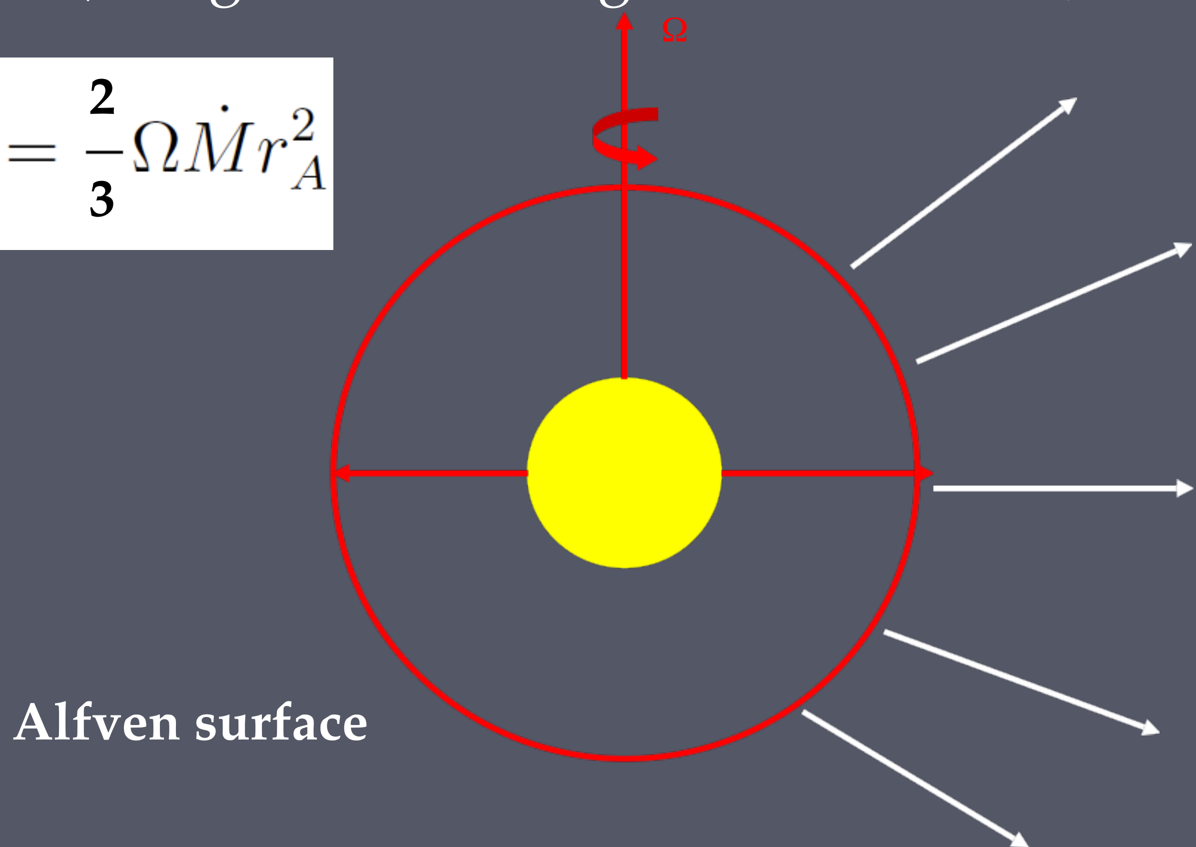
Skumanich Law:

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

We need a mechanism explain stellar loss of angular momentum over time.

Stellar angular momentum loss to the magnetized wind (“magnetic breaking” - Weber-Davis, 1967):

$$\dot{J} = \frac{2}{3}\Omega \dot{M} r_A^2$$

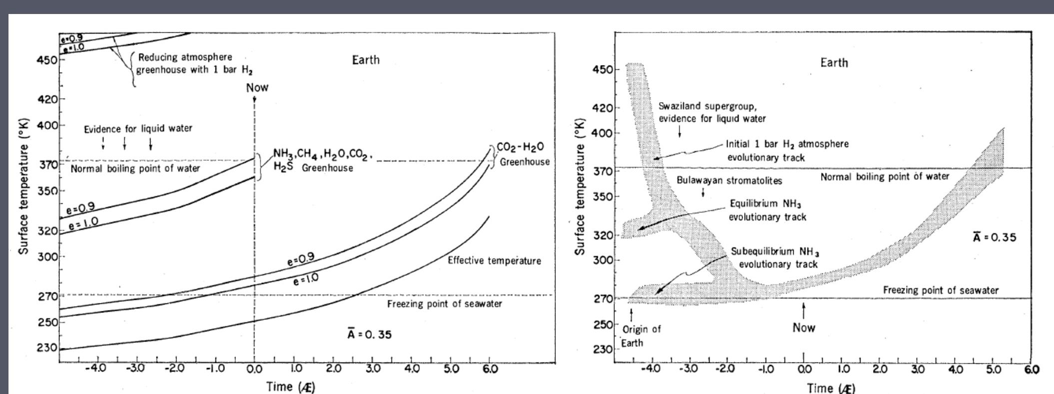


$$\frac{\dot{\Omega}}{\Omega} \propto \frac{\dot{M}}{M} \left(\frac{R_{\mathrm{A}}}{R_{\odot}} \right)^{m}$$

Defining stellar mass-loss rates is a key for understanding stellar evolution!!!

The faint young Sun paradox:

• The young Sun's luminosity was about 30% lower than current days.
• The surface temperature on the Earth should have been below freezing.
• Geological evidences for liquid water on the surface.
A paradox...



Sagan & Mullen 1972

Solutions:

- Greenhouse gases - global warming.
- GCR impact on cloud condensation and albedo (probably not).
- More massive young Sun - higher luminosity.

Winds mass-loss rates of cool stars -

10^{-15}-10^{-12} Msun/yr.

Solar wind mass-loss rate:

$rho_{SW} * u_{SW} * 4\pi(1AU)^2 = 2 * 10^{-14}$ Msun/yr.

Mass-loss rate due to CME:

CMEs carry 10^{13}-10^{17} g

Over the solar cycle - 0.5-4 CMEs per day,

Average of 2-3 CMEs per day.

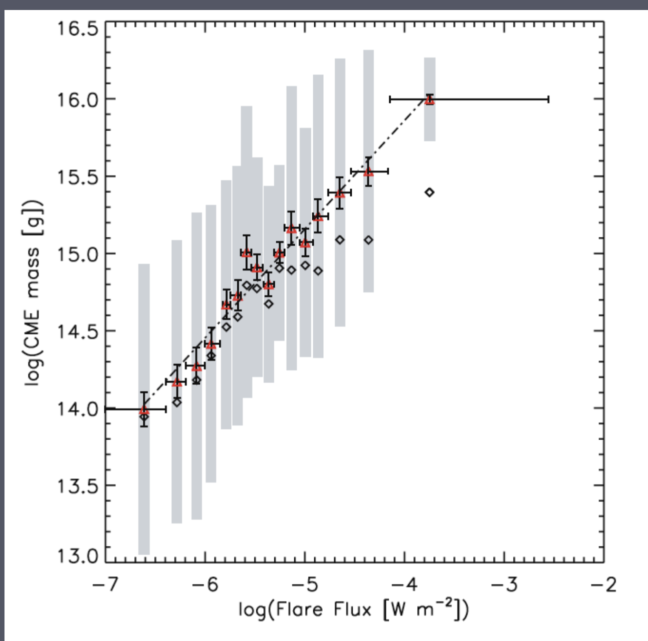
2-3*10^{15} g / 86400 sec (per day) = 2-3*10^{10} g/s

Mass-loss rate of about 5*10^{-16} Msun/yr

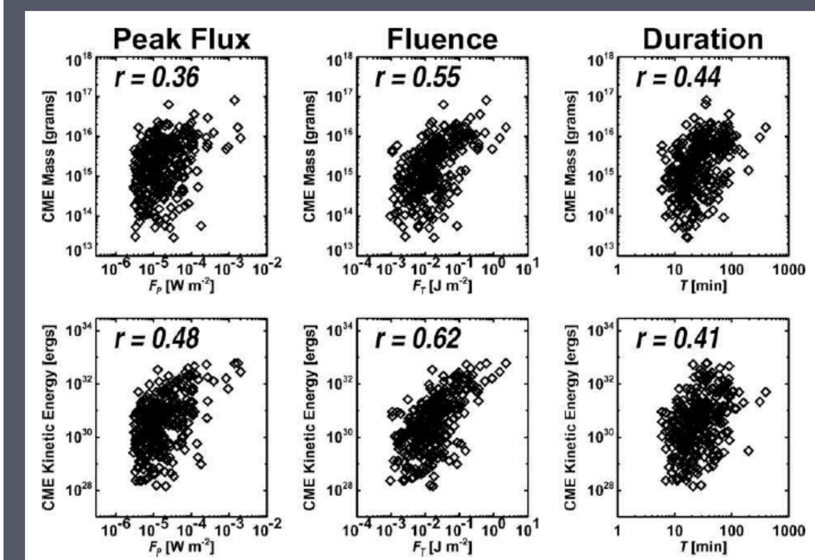
Few percents of the SW mass-loss rate

What if the CME rate is much higher?
How to scale CMEs to other stars?

Scaling solar CMEs with solar flares (LASCO & GOES 1-8A):



Aarnio et. al 2012



Yashiro & Gopalswamy 2009

$$\log(\text{CME mass}) = (18.67 \pm 0.27) + (0.70 \pm 0.05) \times \log(\text{flare flux})$$

Extrapolating the mass-flux relation to other stars (Drake et. al 2013):

$$m_c(E) = \mu E^{\beta}$$

$$\mu \approx 0.002 - 0.02 \text{ and } \beta \approx 0.6$$

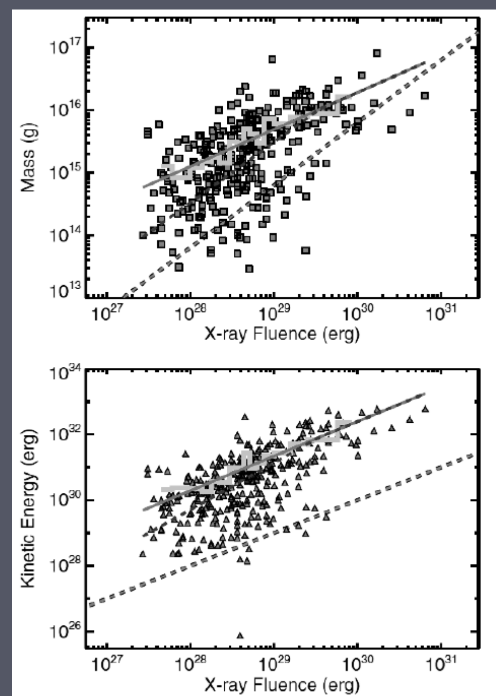
m_c - CME mass

E - flare energy

$$E_k(E) = \eta E^{\gamma}$$

$$\eta \approx 10 - 30 \text{ and } \gamma \approx 1$$

E_k - CME kinetic energy



The occurrence rate of CMEs can also be scaled with E:

$$\frac{dn}{dE} = kE^{-\alpha}$$

α is found to be between 1.5-2.5

The total flare power is given by:

$$P = \int E dn = \int E \frac{dn}{dE} dE = \int_{E_min}^{E_{max}} E k E^{-\alpha} dE = \frac{k}{2-\alpha}\left[E_{max}^{2-\alpha} - E_{min}^{2-\alpha}\right].$$

$$k = \frac{L_x(2-\alpha)}{E_{max}^{2-\alpha} - E_{min}^{2-\alpha}}$$

Yashiro & Gopalswamy (2009) also defined the association fraction as a function of X-ray fluence, f(E).

This function tells us what is the likelihood that a CME actually erupts for a given are energy (not every solar are is associated with a CME).

This likelihood increases as we move to higher are energies.

The association fraction is:

$$f(E) = \zeta E^{\delta}$$

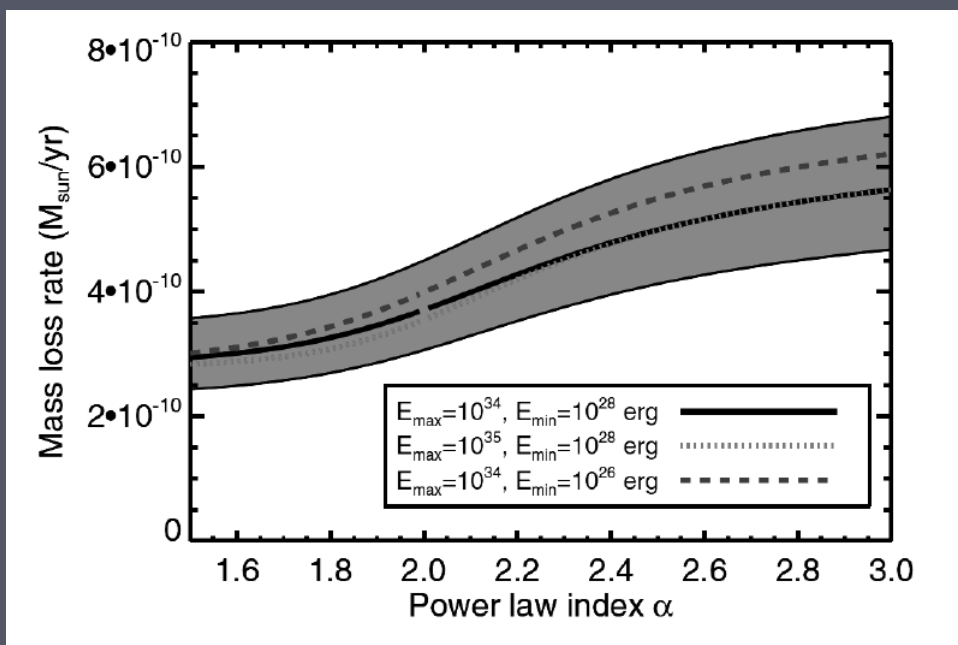
$\zeta = 7.9 \times 10^{-12}$, and $\delta = 0.37$ for $E \leq 3.5 \times 10^{29}$ egrs

We now can estimate the mass-loss rate due to CMEs:

$$\dot{M}_{CME} = \int_{E_{min}}^{E_{max}} m_c(E) f(E) \frac{dn}{dE} dE$$

$$\dot{M}_{CME} = \mu \zeta L_x \left(\frac{2-\alpha}{1+\beta+\delta-\alpha} \right) \left[\frac{E_{max}^{1+\beta+\delta-\alpha} - E_{min}^{1+\beta+\delta-\alpha}}{E_{max}^{2-\alpha} - E_{min}^{2-\alpha}} \right]$$

CME mass-loss rate:



Drake et. al 2013

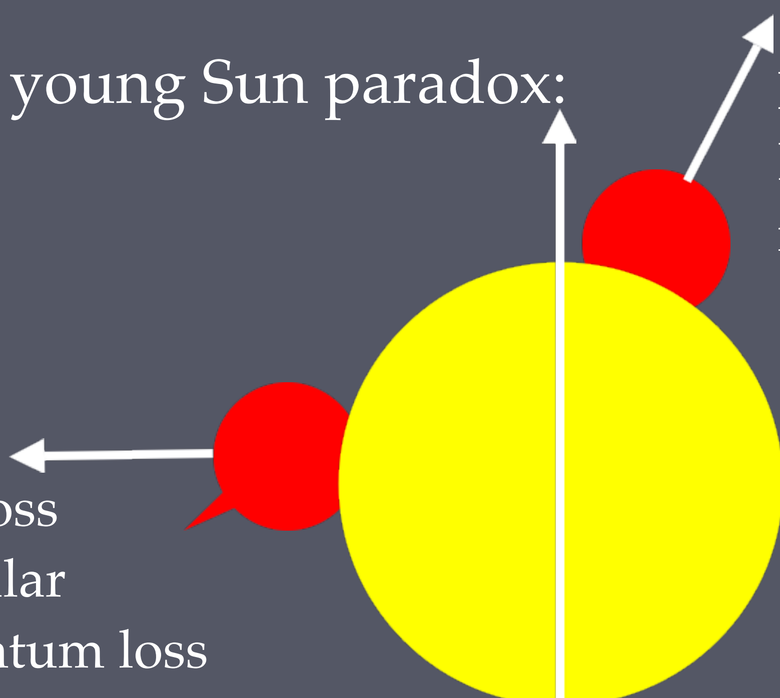
Drake et. al 2013: 10^{-11} - 10^{-10} Msun/yr (1% - 10% L_{bol})

Aarnio et. al 2012: 10^{-11} - 10^{-9} Msun/yr

Impact on stellar spindown (Aarnio et. al 2012):

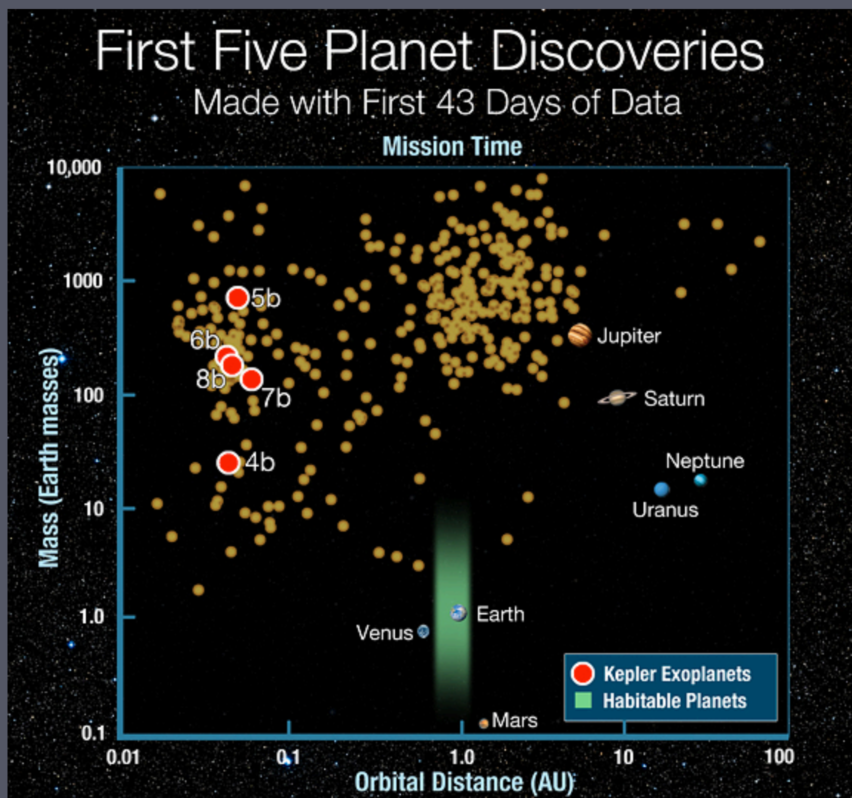
$$\tau = k^2 \left(\frac{M_\star}{\dot{M}_{CME}}\right) \left(\frac{R_\star}{r_A}\right)$$

Faint young Sun paradox:



The Impact of CMEs on Close-in Exoplanets

Effects of Stellar Eruptions Throughout Astrospheres
Heliophysics Summer School, Boulder, CO 2014



NASA Kepler mission

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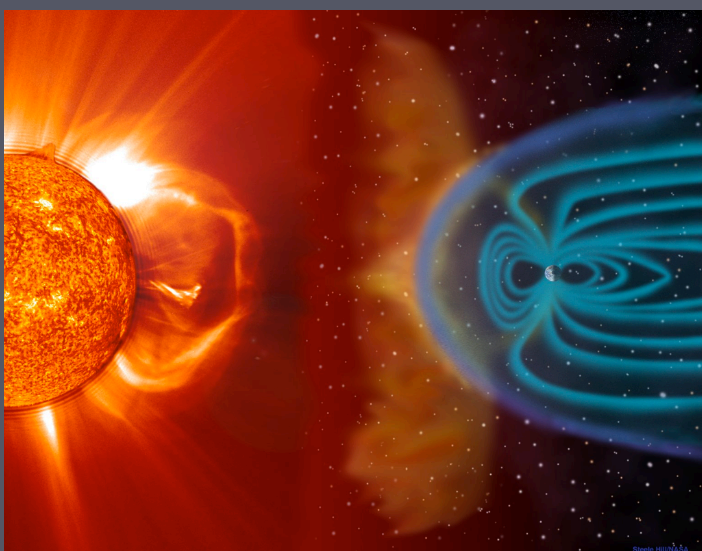


Credit:
NASA

Scaling the CMEs density to close-in orbits (Khodachenko et al. 2007):

$$n_{eject}^{min} = n_0^{min} \left(\frac{d}{d_0}\right)^{-2.3}$$

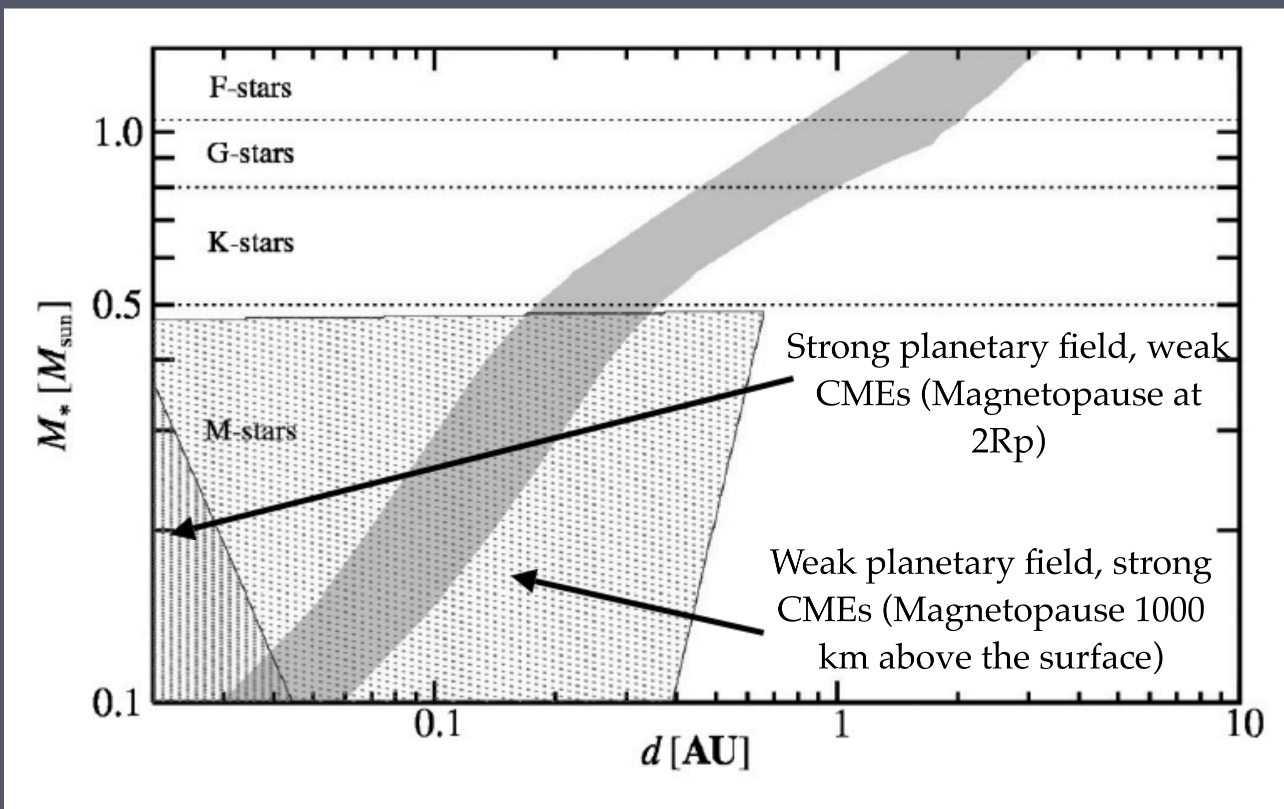
$$n_{eject}^{max} = n_0^{max} \left(\frac{d}{d_0}\right)^{-3.0}$$

$$n_0^{min} = 4.88\ cm^{-3},\ \text{and}\ n_0^{max} = 7.0\ cm^{-3}$$

The size of the magnetosphere:

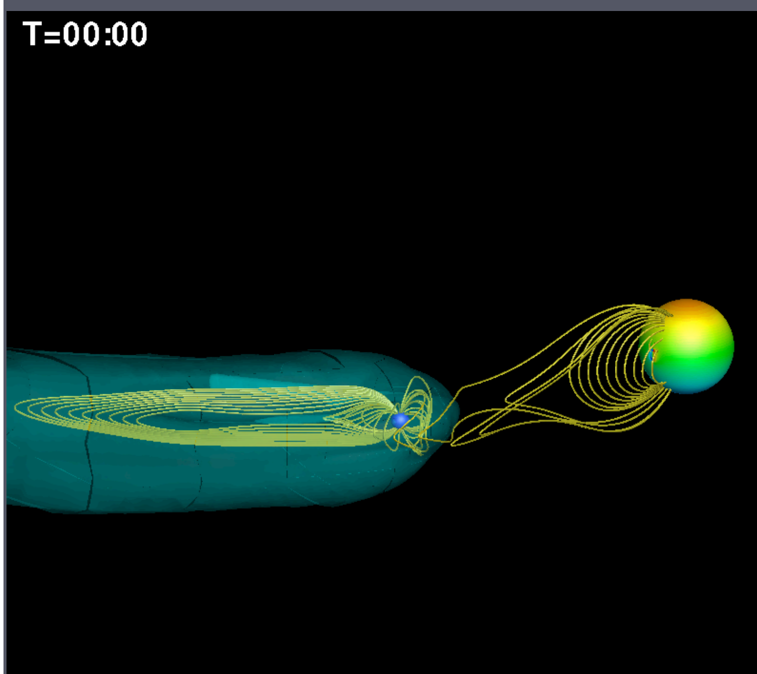
$$P_{CME} = n_{CME}\ m v_{CME}^2 \quad v_{CME} = 500\ km\ s^{-1}$$

$$R_M = \left(\frac{\mu_0 f_0^2 M^2}{8\pi^2 P_{CME}}\right)^{1/6}$$

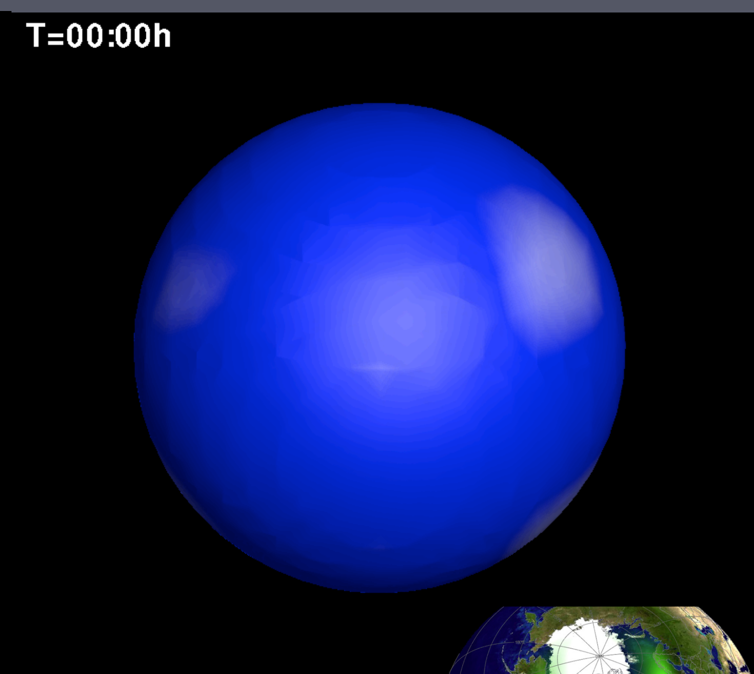


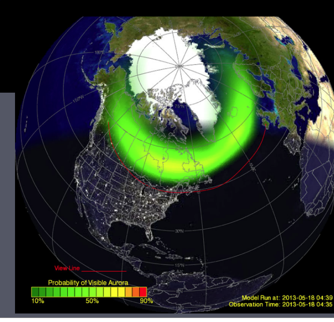
Khodachenko et al. 2007

3D view



Predicted Auroral structure





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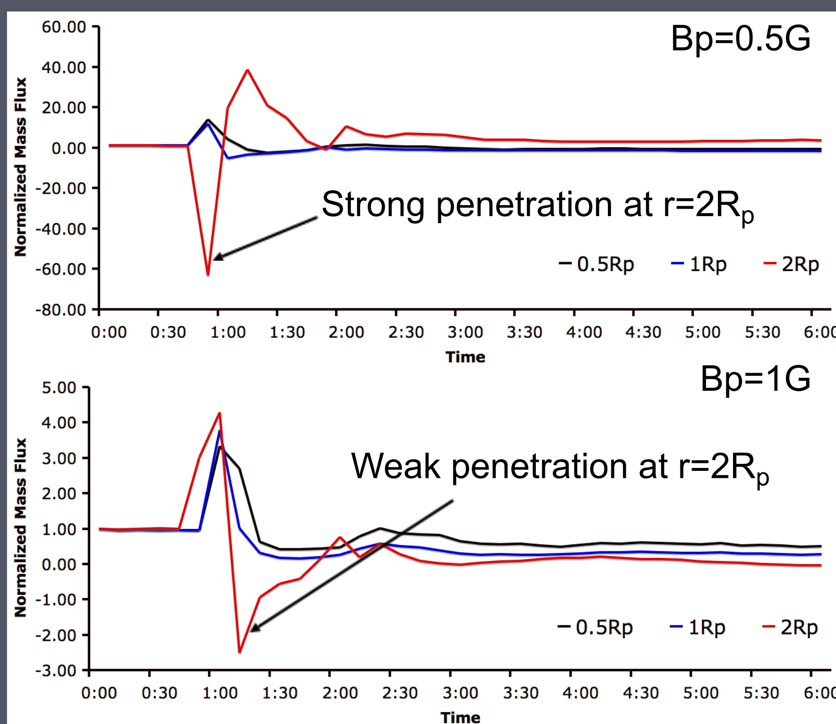
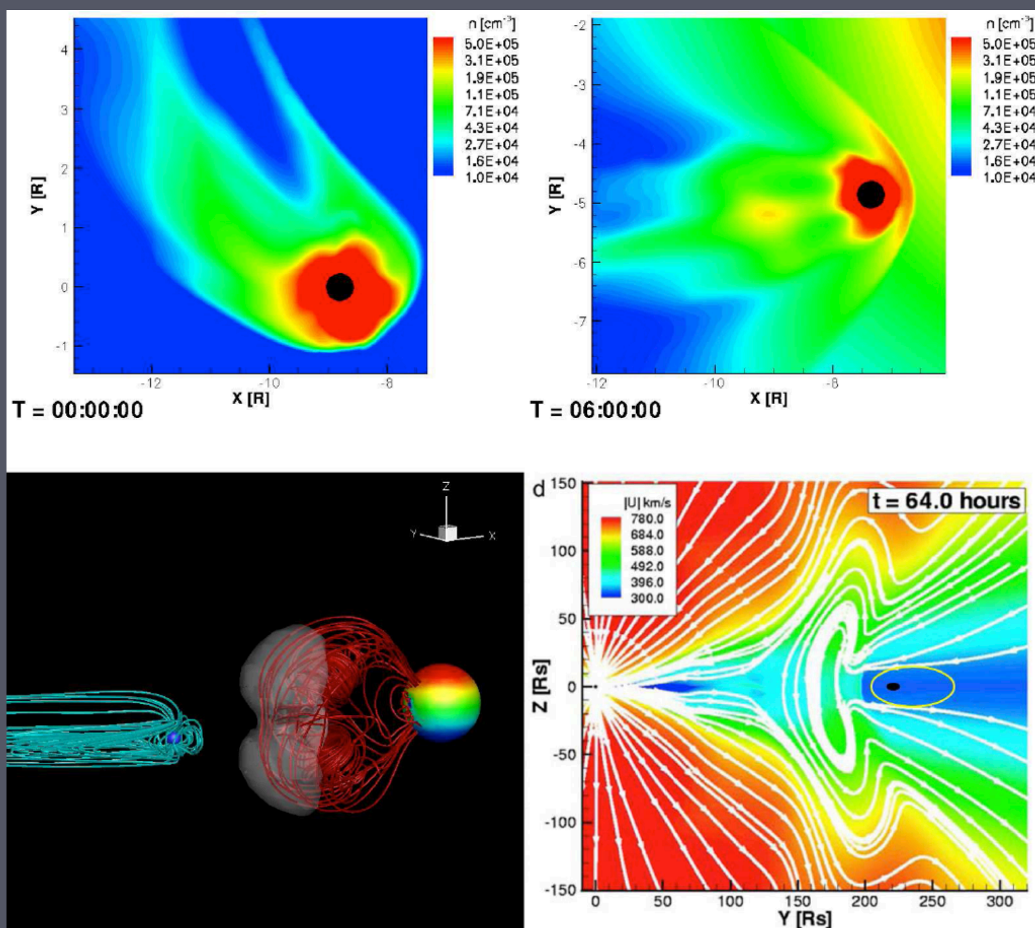
Radial mass flux in the planetary frame of reference - negative values indicate a CME penetration at a particular height above the surface:



Cohen et al. 2011



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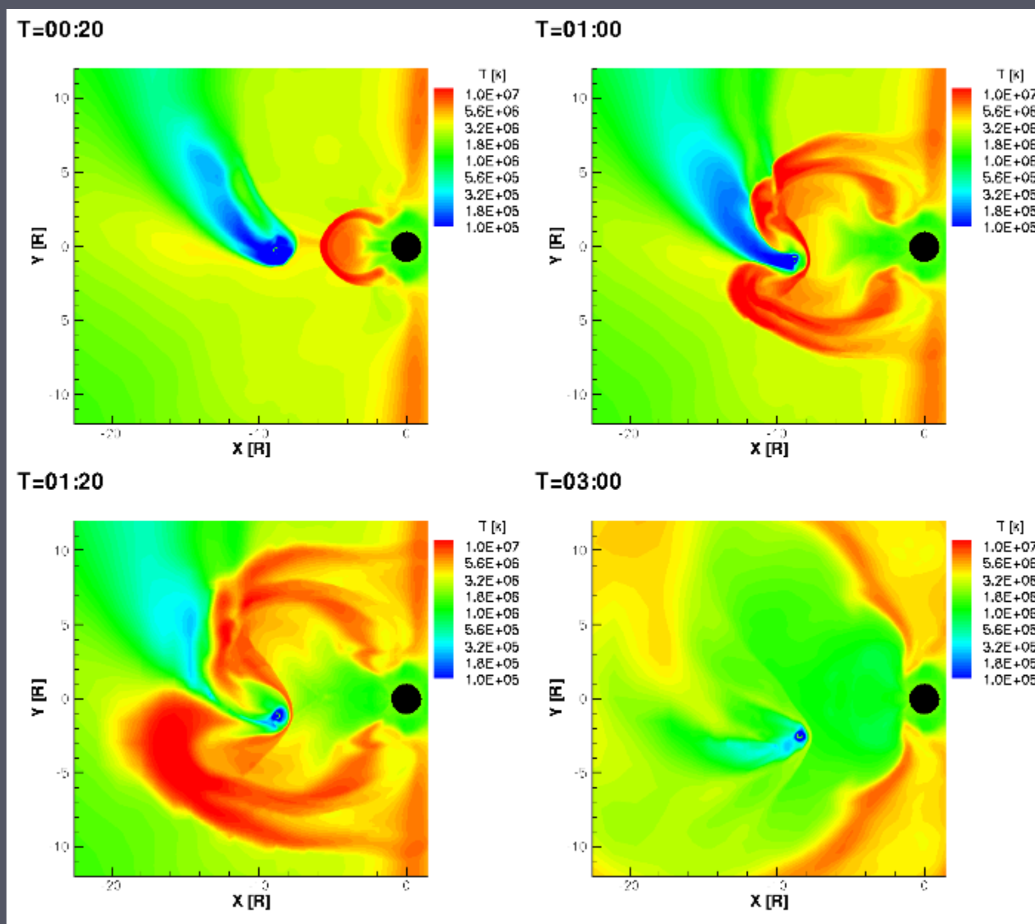
Cohen et al. 2011



Cohen et al. 2011

To wrap things up...

Cohen et al. 2011

This is Astrophysics... data is limited

Stellar magnetic fields - Zeeman Doppler Imaging (ZDI) - stellar synoptic magnetic maps.

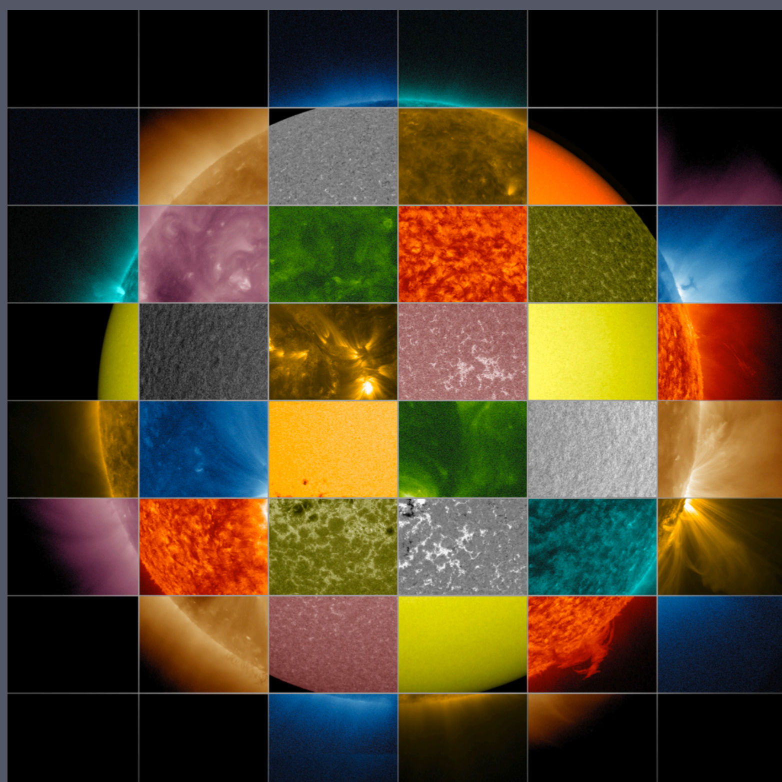
Stellar winds from cool stars - more observations and modeling work.

Stellar CMEs - flaring data, observations of radio bursts.

Magnetic fields of exoplanets - a key to determine atmospheric protection.

Cohen et al. 2011

The only good proxy for stars is:
Our own Sun



NASA SDO

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