ASTR-6000 Seminar
COLLAGE: Coronal Heating, Solar Wind, & Space Weather

April 21, 2022

The solar/stellar connection: exo-coronae & exo-winds and impacts on exo-planets

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Outline

1. Is the Sun really mediocre, run-of-the-mill, unexceptional?
2. Observations of stellar activity
3. Models & simulations
4. Impacts on exoplanetary systems
5. …and beyond?

(1) *Motivation*

- The Sun is the closest star to the Earth, and for many years it has served as a template for our understanding of the physical processes that occur in other stars and astrophysical plasmas.

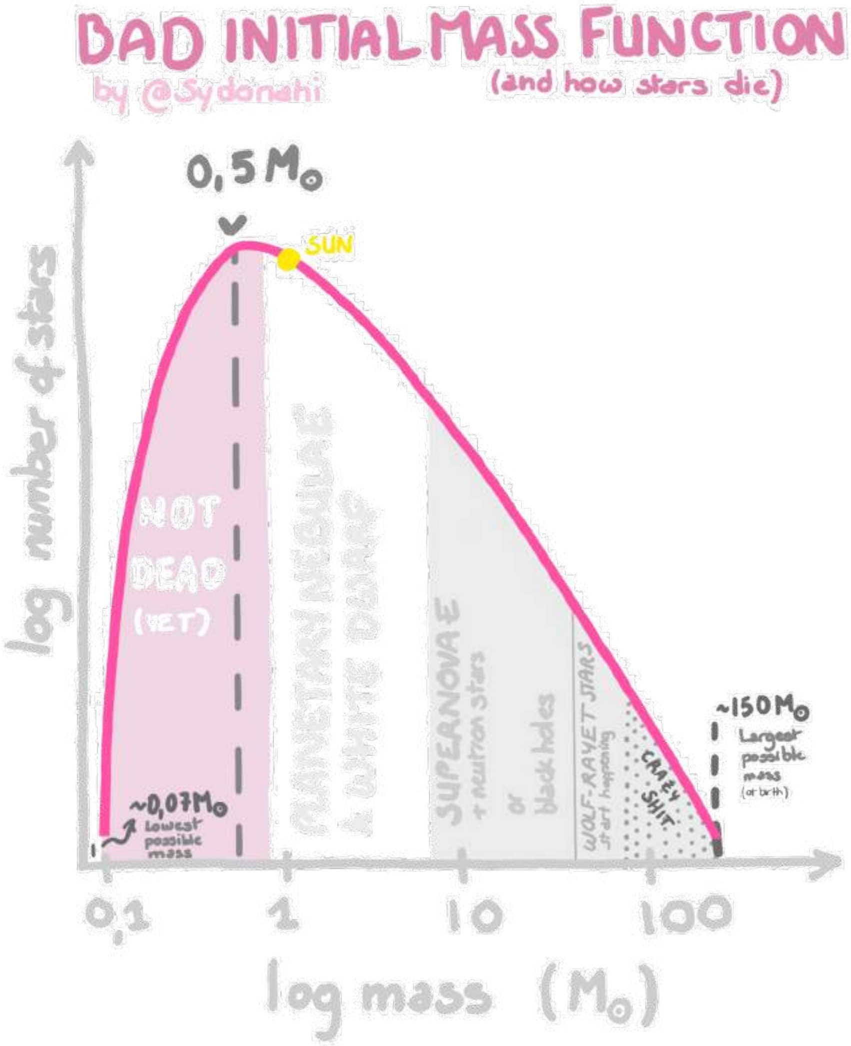
- An early summary of the motivation for studying the solar-stellar connection was given almost a century ago (1932), in a public radio address by Canadian astronomer Clarence Chant:

> *"Our sun is of superlative importance for two reasons,*
> *(1) because it is the central body and ruler of our system; and*
> *(2) because it is one of the stars, being the only one which is near enough for detailed study; and what we learn about it will help us to solve the problem of the universe around us."*

- Nevertheless, the fields of solar and heliospheric physics are often set apart from the rest of "nighttime" astronomy because of differences in measurement techniques and the nature of the available data.

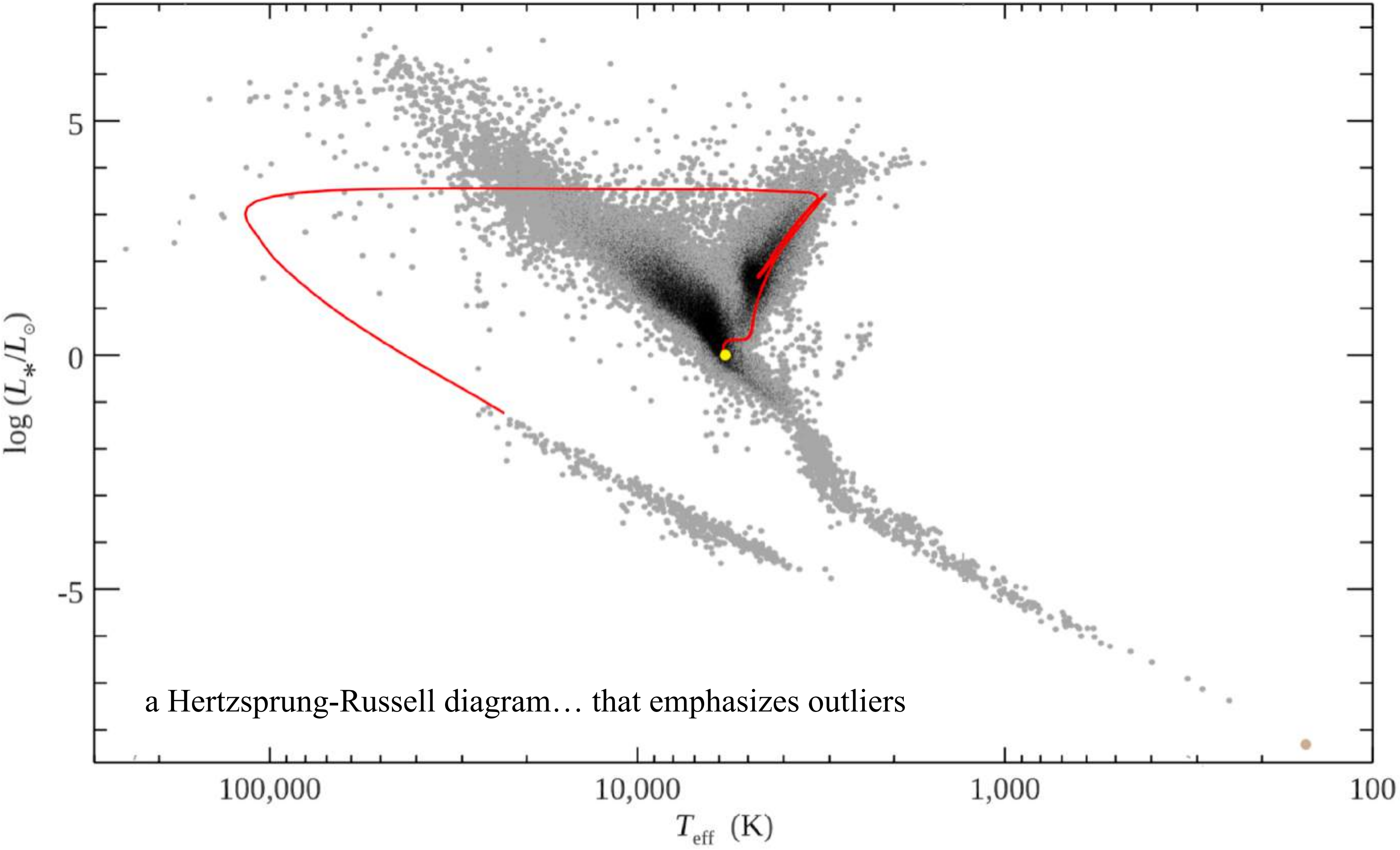
(1) *Motivation*

- The Sun *has* been called mediocre, unexceptional, and run-of-the-mill.
- Its **mass** is close to the most probable value that a random deity would sample from our Galaxy's initial mass function.
- Its current **age** falls close to the half-way point of its main-sequence lifespan (the Lindy effect?).
- Still, this is okay, because it lets us consider it as a **representative example** of a broad swath of other nearby stars.



https://twitter.com/sydonahi/status/1251815790648504320

(1) *Motivation*



a Hertzsprung-Russell diagram… that emphasizes outliers

(2) *Observations of stellar activity*

But maybe we shouldn’t emphasize outliers. Let’s survey ***typical:***

a. Rotation rates & star-spot coverage

b. Photospheric granulation patterns

c. Magnetic fields

d. Chromospheres & coronae (e.g., flares)

e. Stellar wind mass-loss rates

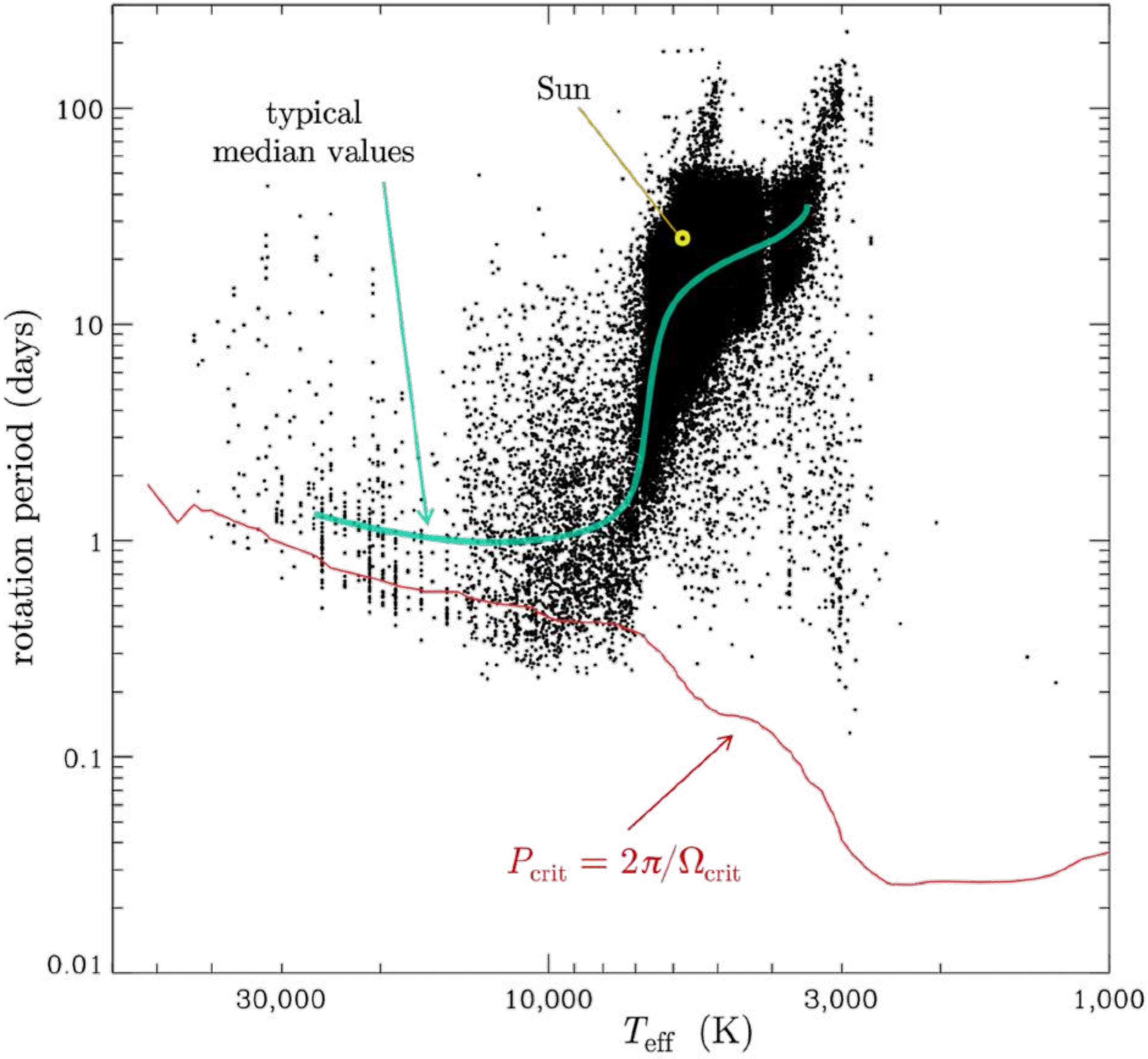
(2a) *Stellar rotation rates*

Note the "Kraft break" around $T_{\mathrm{eff}} \sim 7{,}000$ K.

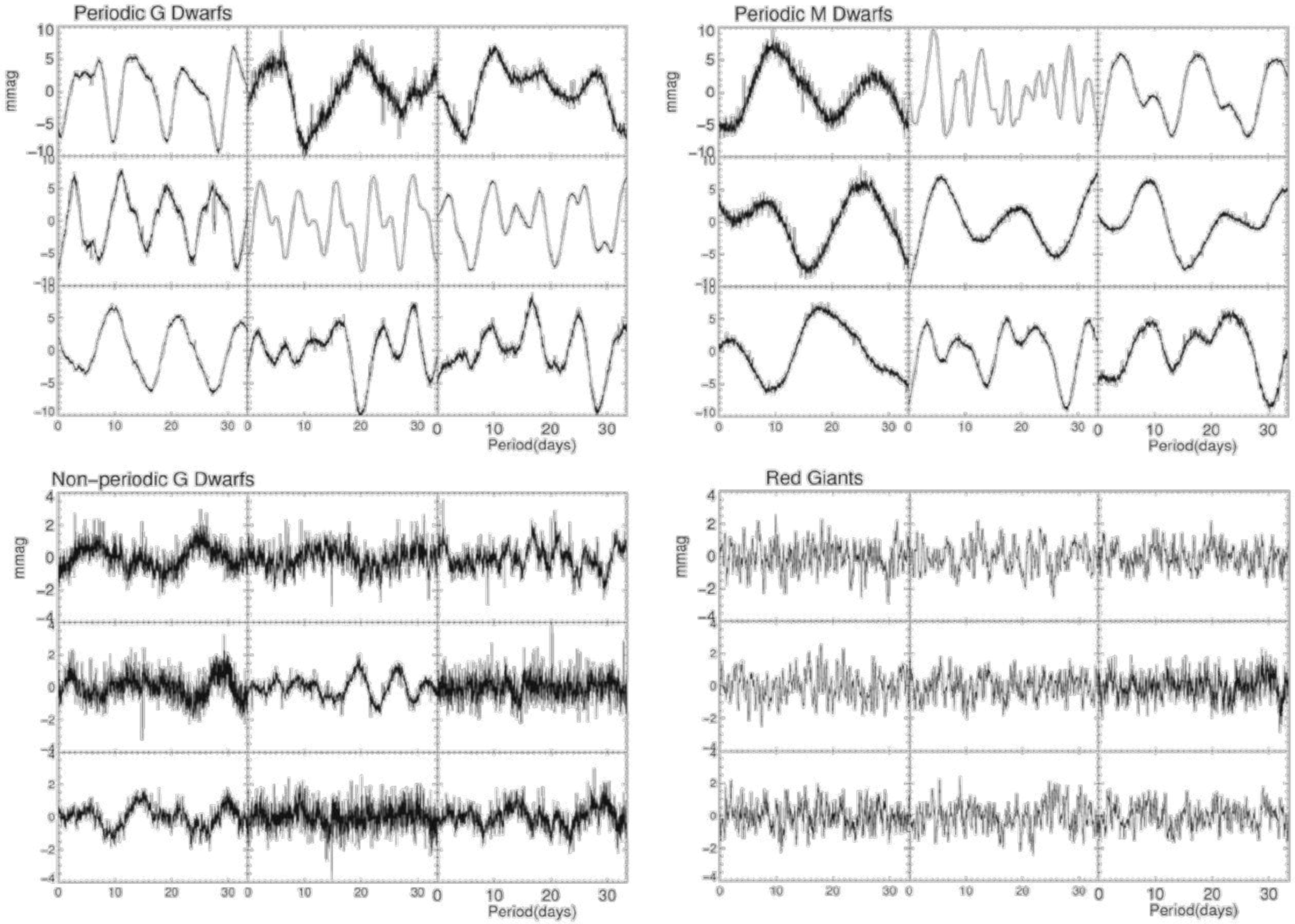
Most measured periods come from star-spot modulated light curves.

For the hottest stars, they tend to come from rotational broadening of spectral lines (sensitive to $V_{\mathrm{eq}} \sin i$, and the inclination angle i is usually not known).

The **"critical"** rotation rate occurs when gravity balances the centrifugal force at the equator ("breakup speed").

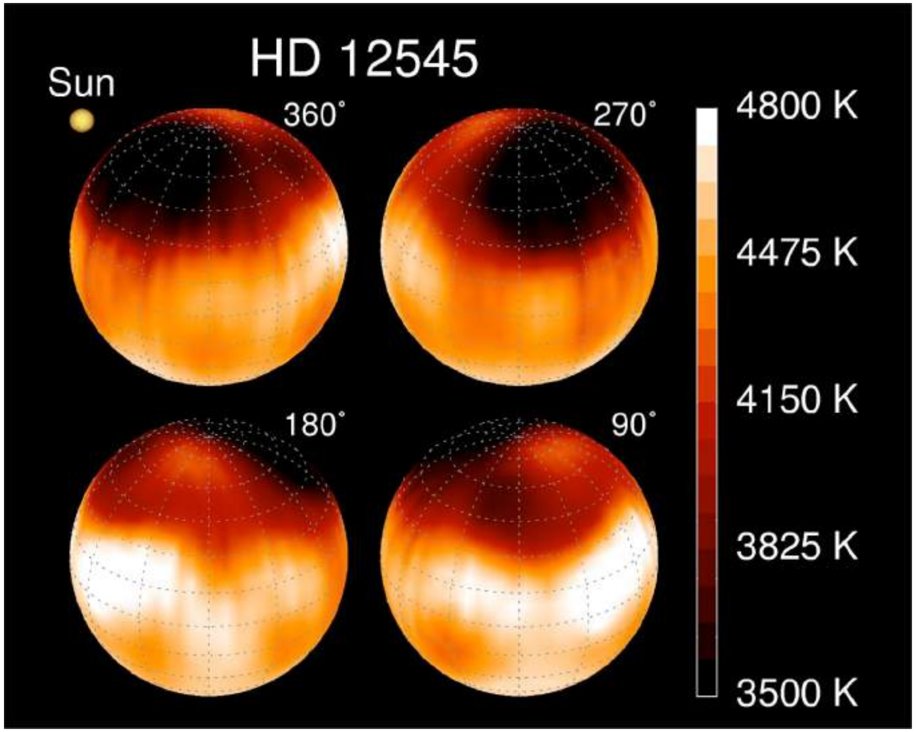


(2a) *Stellar rotation rates*

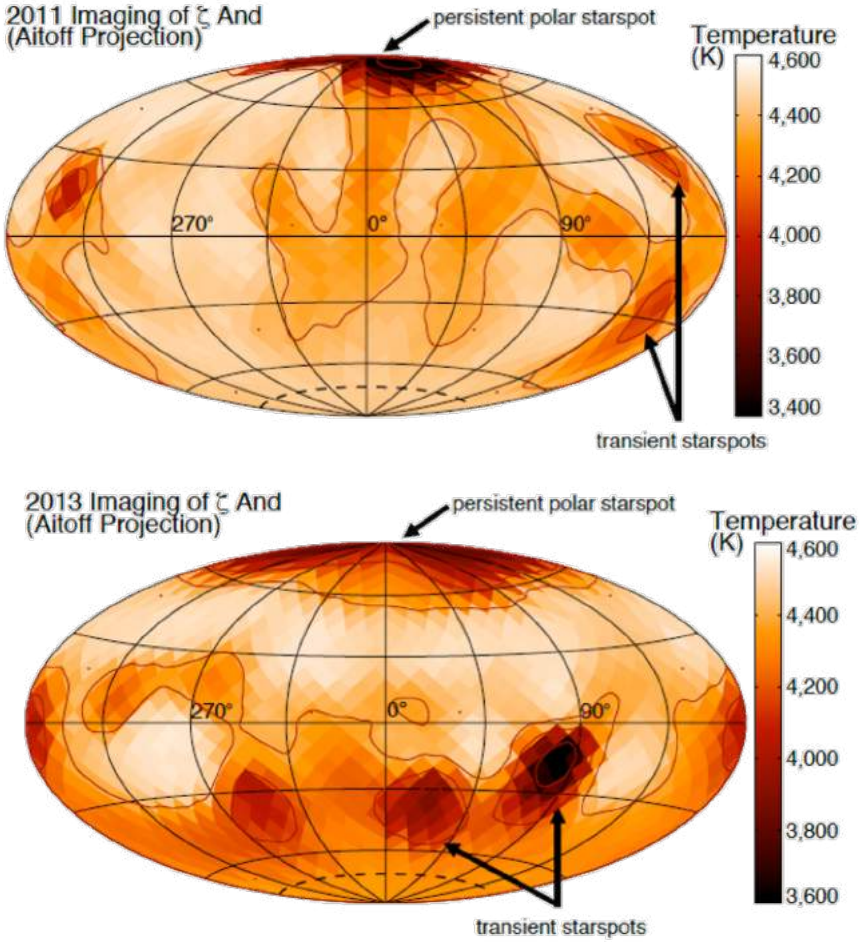


(Basri
et al.
2011)

(2a) *Stellar rotation rates*



If the spots are stable over multiple rotations, **Doppler tomography** can be used to reconstruct maps…

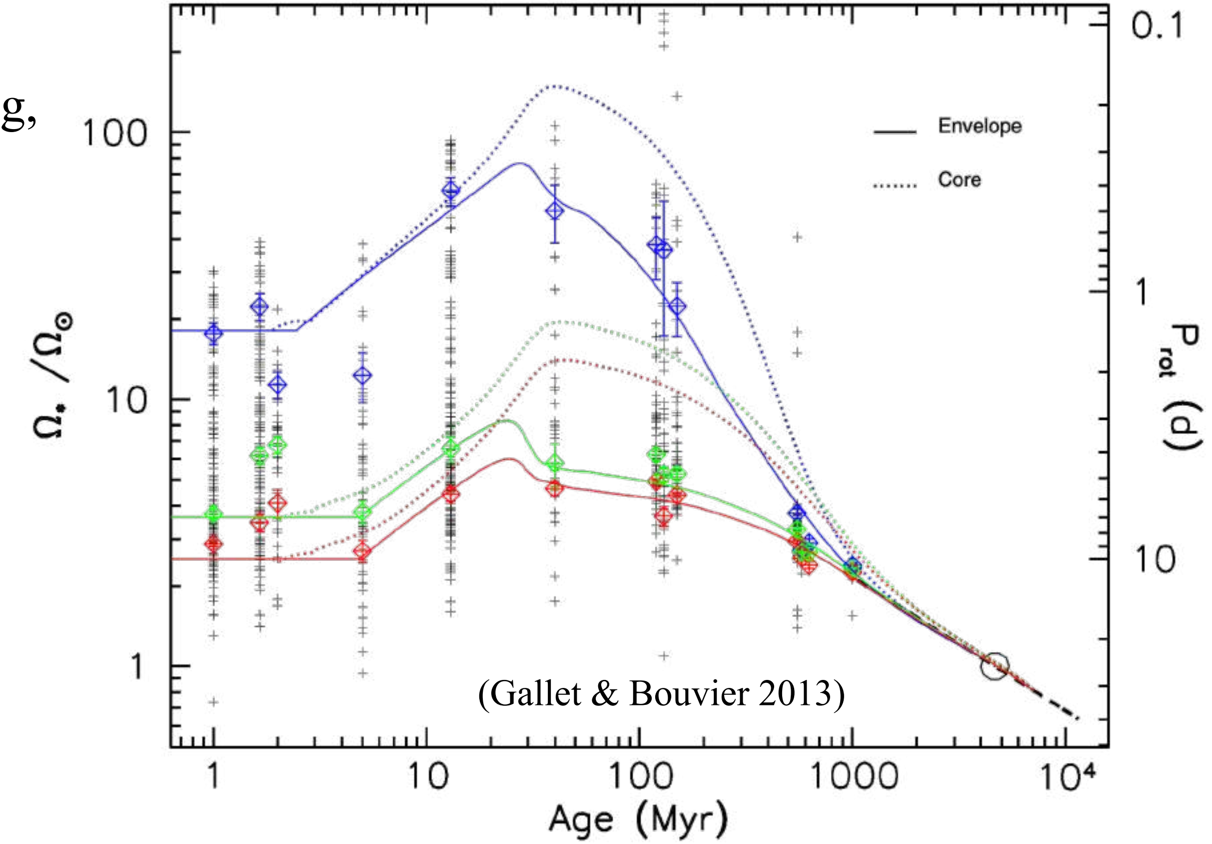


(2a) “*Gyrochronology*”

- Andy Skumanich (1972) started with a small sample of stars in young clusters and found a general spindown trend: $\Omega(t) \propto t^{-1/2}$.

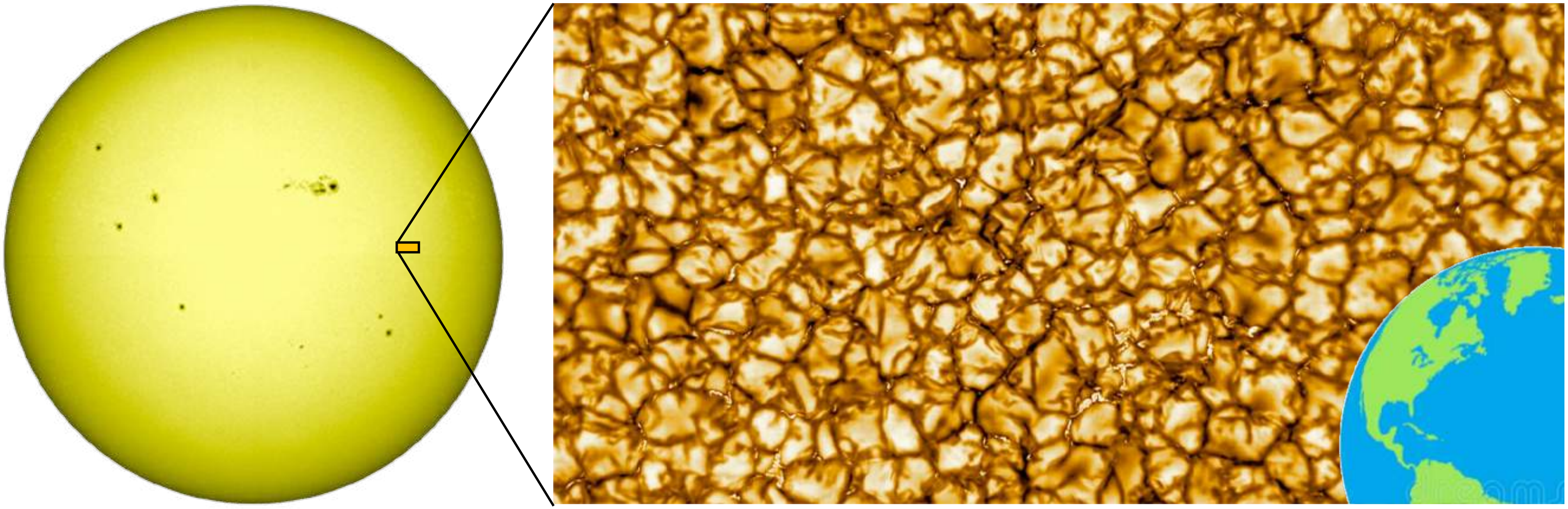
- More recent data upholds this law for main sequence (old) stars, but when they’re young, there’s much more diversity.

- One *expects* young stars to be rapid rotators, since their parent molecular clouds had ~100 times the angular momentum of even the fastest rotating star. (This is why young stars have **accretion disks**)



(Gallet & Bouvier 2013)

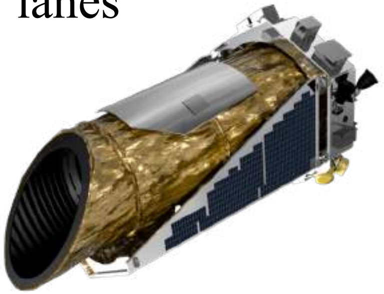
(2b) *Photospheric granulation*



Do we really expect to be able to see the effects of granulation on other stars?

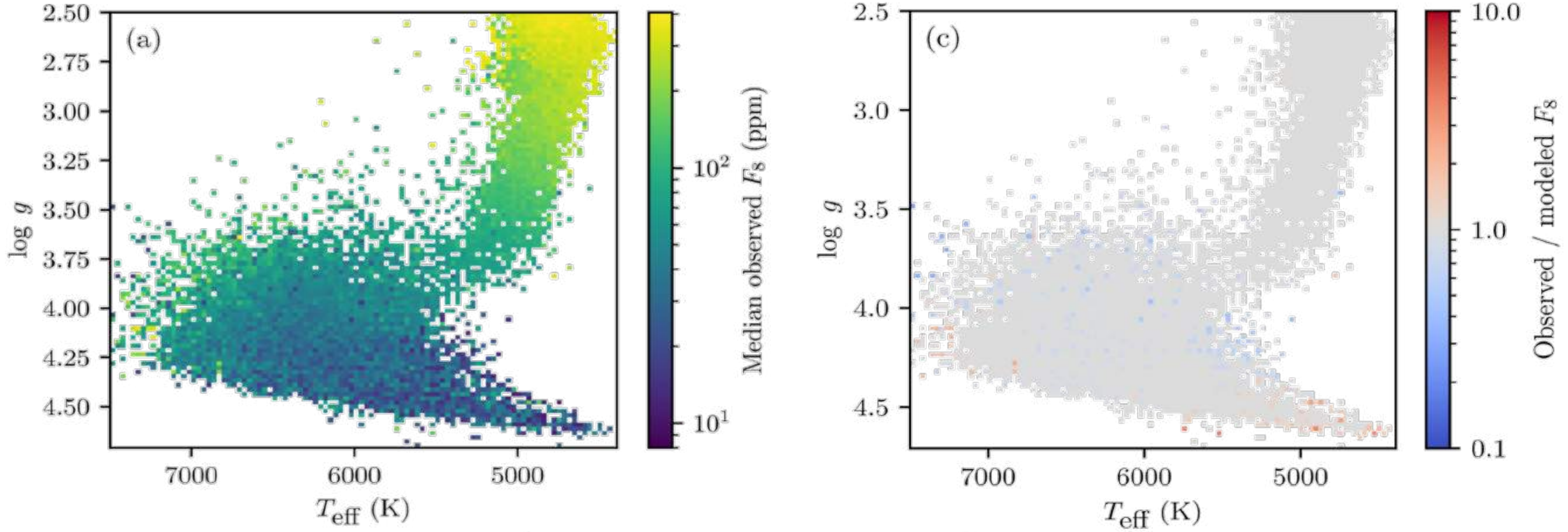
- Number of granules on the solar disk: $N = (\pi R_s^2)/A_{\text{gran}} \approx 2$ million
- Intensity contrast: cell-centers are ~2% brighter than intergranular lanes
- If cells vary incoherently, the full-Sun r.m.s. variability $\approx 0.02/N^{1/2} \approx 15$ ppm.

Yes!
Kepler
did it!

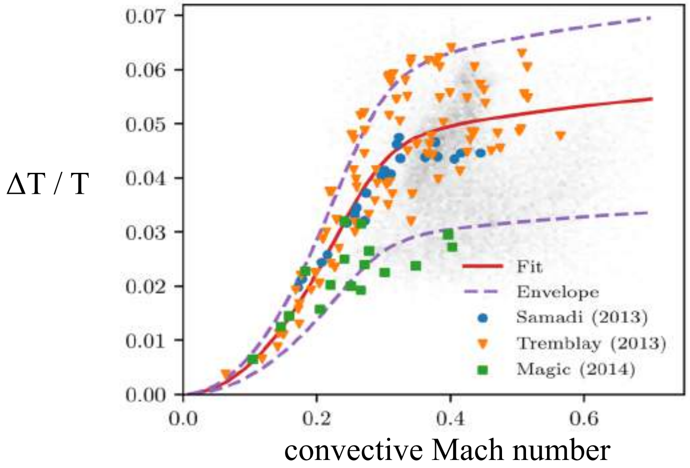


(2b) *Photospheric granulation*

- *Kepler* measured “flicker” amplitudes for ~17,000 stars (Bastien et al. 2013).
- Van Kooten et al. (2021) modeled what we see using convection simulations…



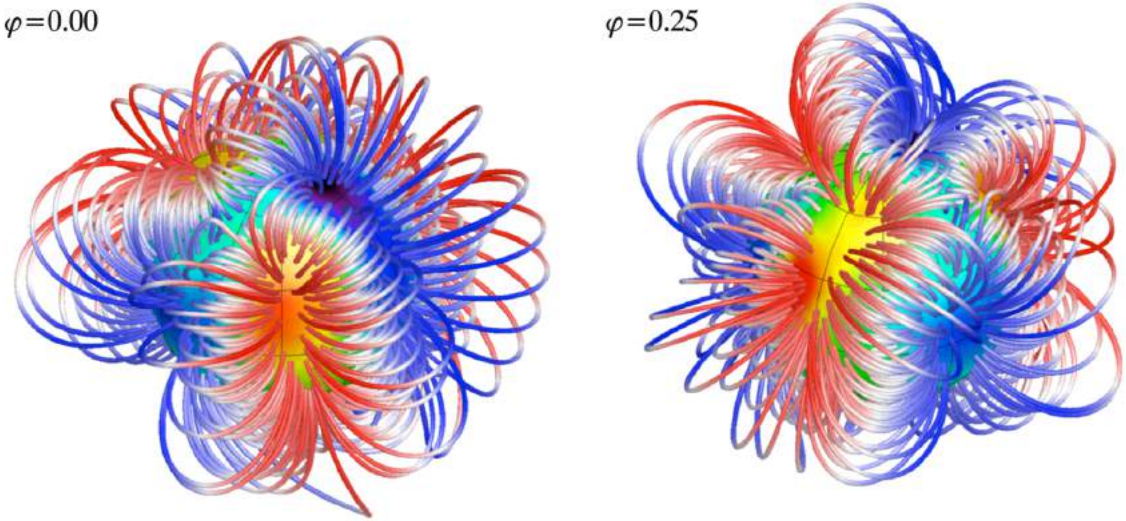
Caveat emptor:



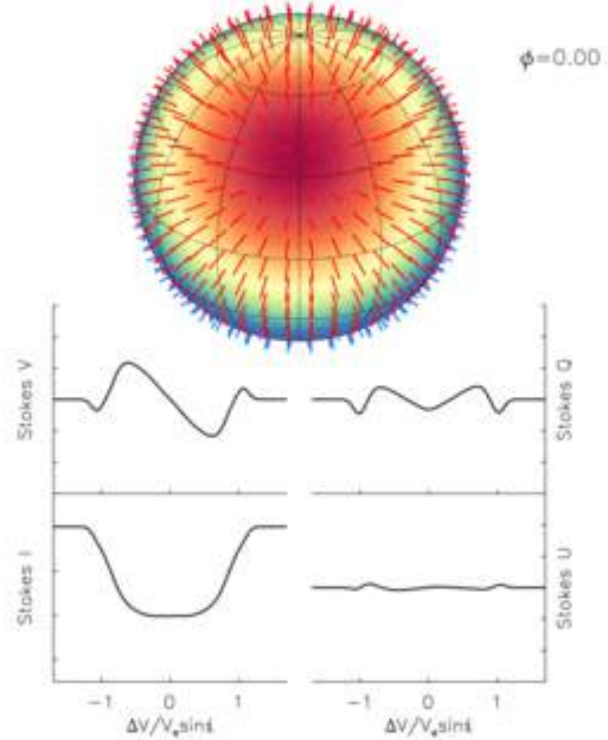
Model predictions have substantial *spread*…

(2c) *Stellar magnetic fields*

- Like on the Sun, spectropolarimetry can utilize both the Zeeman & Hanle effects to measure magnetic fields on distant stars.
- Like with star-spots, rapid rotation can be used to make tomographic maps of the 3D field geometries (ZDI: “Zeeman Doppler Imaging”)



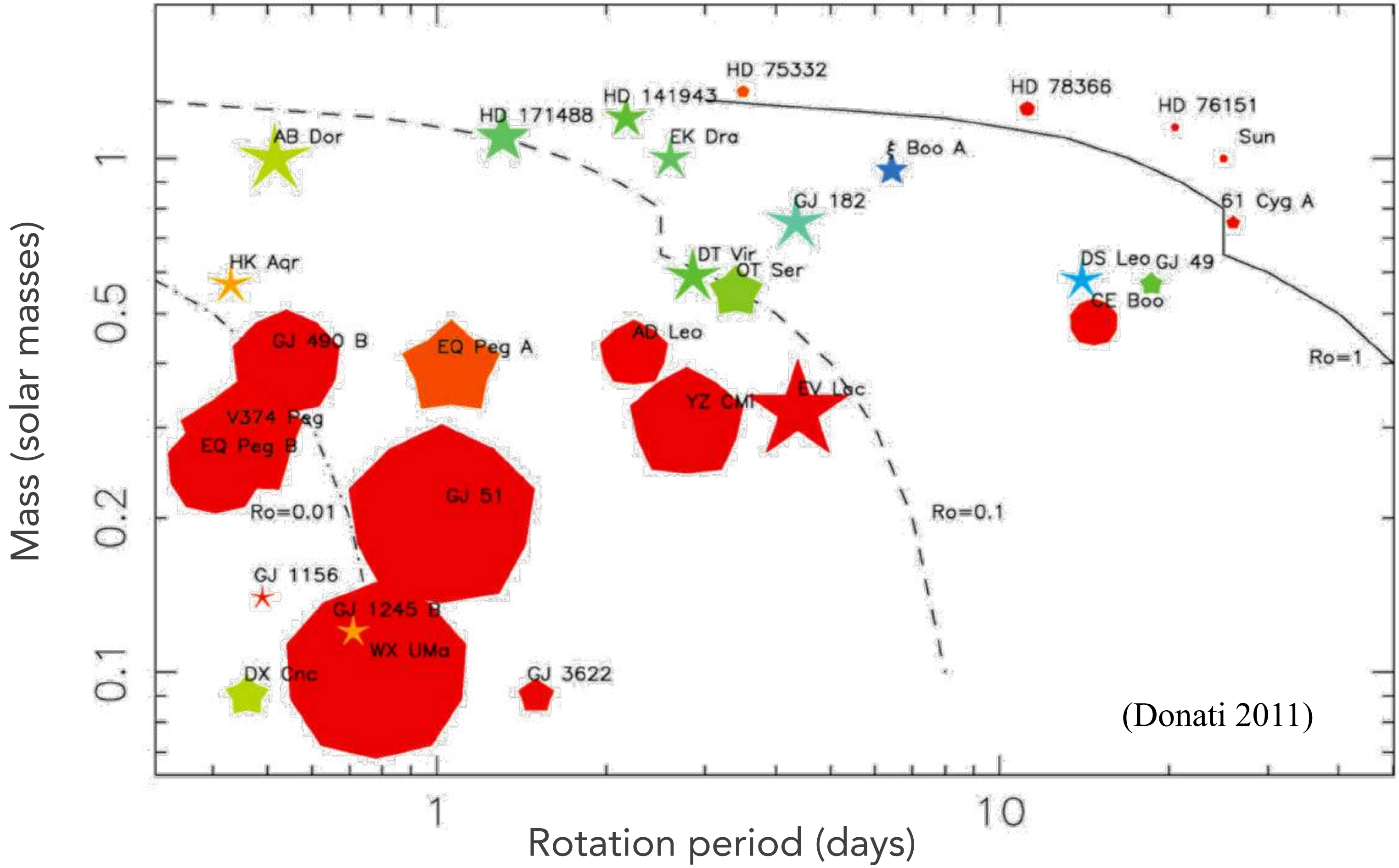
(U. Uppsala)



- After decades of monitoring some stars, we’ve seen hints of decadal activity cycles & polarity flips…

(2c) *Stellar magnetic fields*

- In general, more rapidly rotating stars have stronger magnetic field strengths…



(Donati 2011)

Symbol size: field strength, color: toroidal → poloidal, shape: axisym ○ → non-axisymm ✶

(2c) *Stellar magnetic fields*

- Noyes et al. (1984) realized everything makes more sense if one plots activity versus **Rossby number** instead of just the rotation rate.

$$\mathrm{Ro} \;=\; \frac{\mathcal{P}_{\mathrm{rot}}}{\tau_{\mathrm{conv}}} \;=\; \frac{\text{rotation period}}{\text{convective overturning time}}$$

- Also, for different stars, the overall impact of the magnetic field in the photosphere depends on how the magnetic pressure compares to the gas pressure.
- For a given photospheric pressure P_{gas} we can compute an **equipartition** field strength:

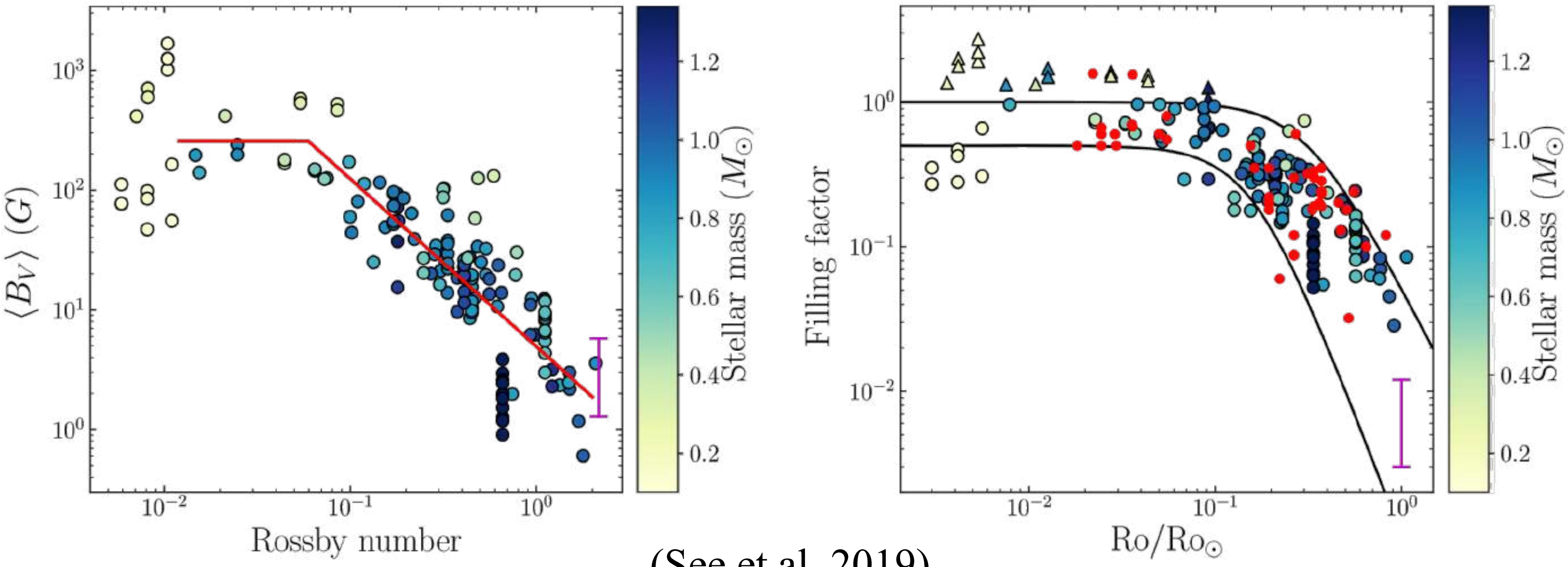
$$P_{\mathrm{gas}} \;=\; P_{\mathrm{mag}} \;=\; \frac{B^2}{8\pi} \qquad \longrightarrow \qquad B_{\mathrm{equi}} \;=\; \sqrt{8\pi P_{\mathrm{gas}}}$$

- The ratio of the measured surface-averaged field strength to the equipartition field strength gives an effective **filling factor** of strong fields.

$$f_* \;=\; \frac{\langle B \rangle}{B_{\mathrm{equi}}}$$

- For Sun, f_* varies from about 0.003 (min) to 0.02 (max).

(2c) *Stellar magnetic fields*

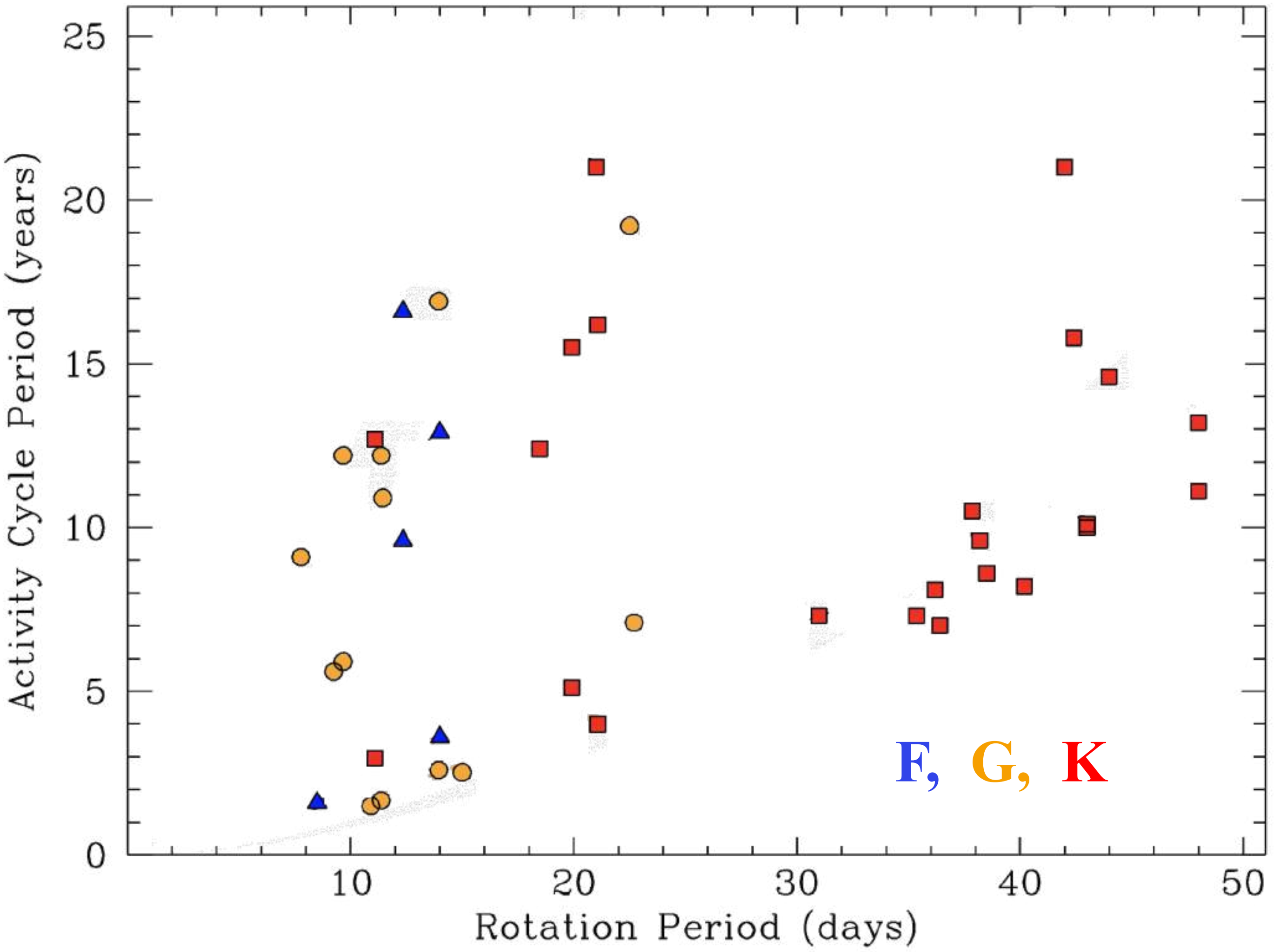


(See et al. 2019)

- The most rapidly rotating stars (Ro << 1) are “fully covered” in ~equipartition fields, so their activity appears saturated.
- Slower rotators (like the Sun) have weaker fields.
- These scaling relations are key constraints to models of **convective dynamos.**

(2c) *Stellar magnetic fields*

Earlier I mentioned decade-scale activity cycles. How do they behave as a function of rotation rate? Böhm-Vitense (2007); Metcalfe & van Saders (2017) found trends:



(2c) *Stellar magnetic fields*

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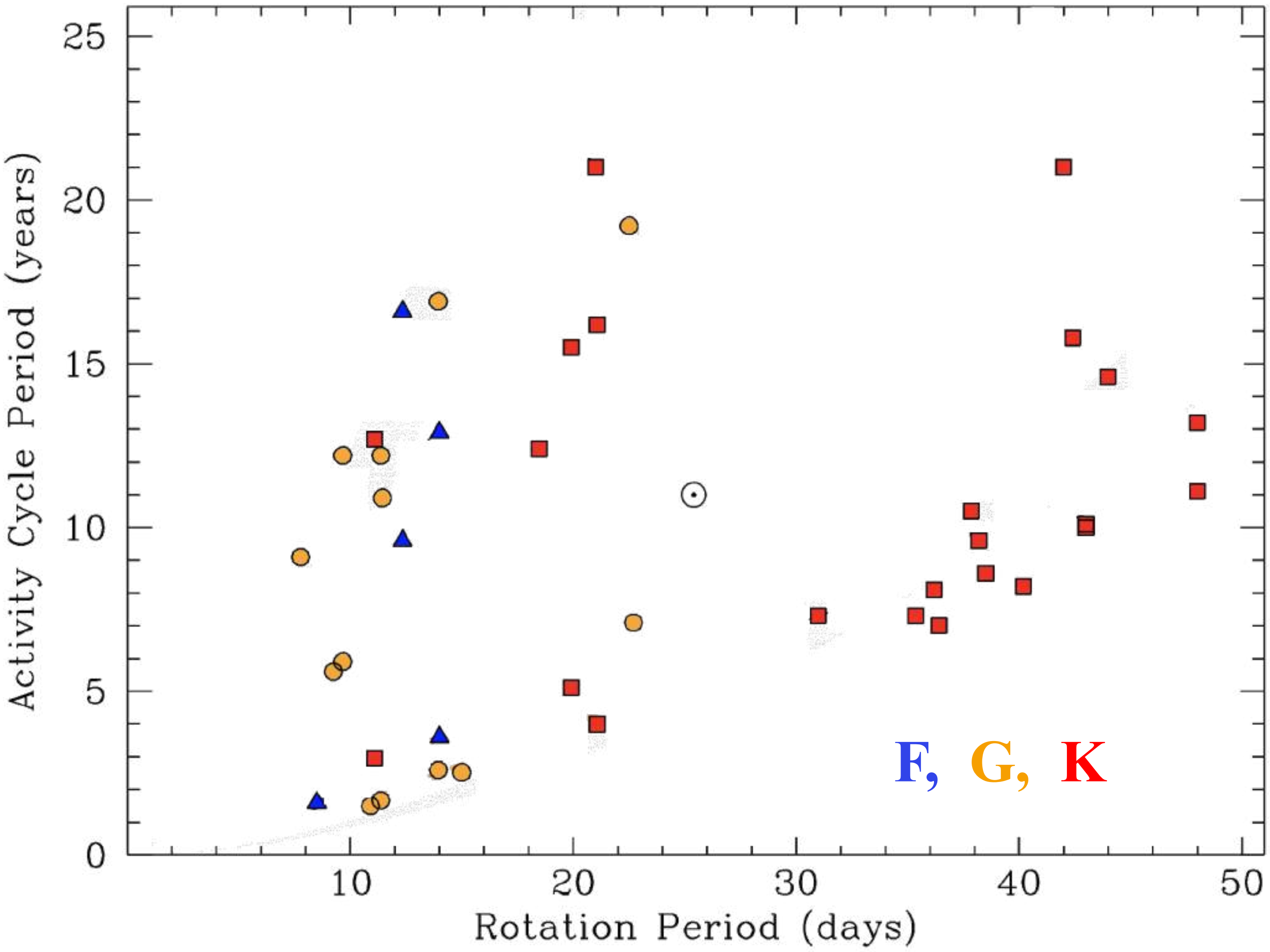

Is the Sun an oddball outlier?

(2c) *Stellar magnetic fields*

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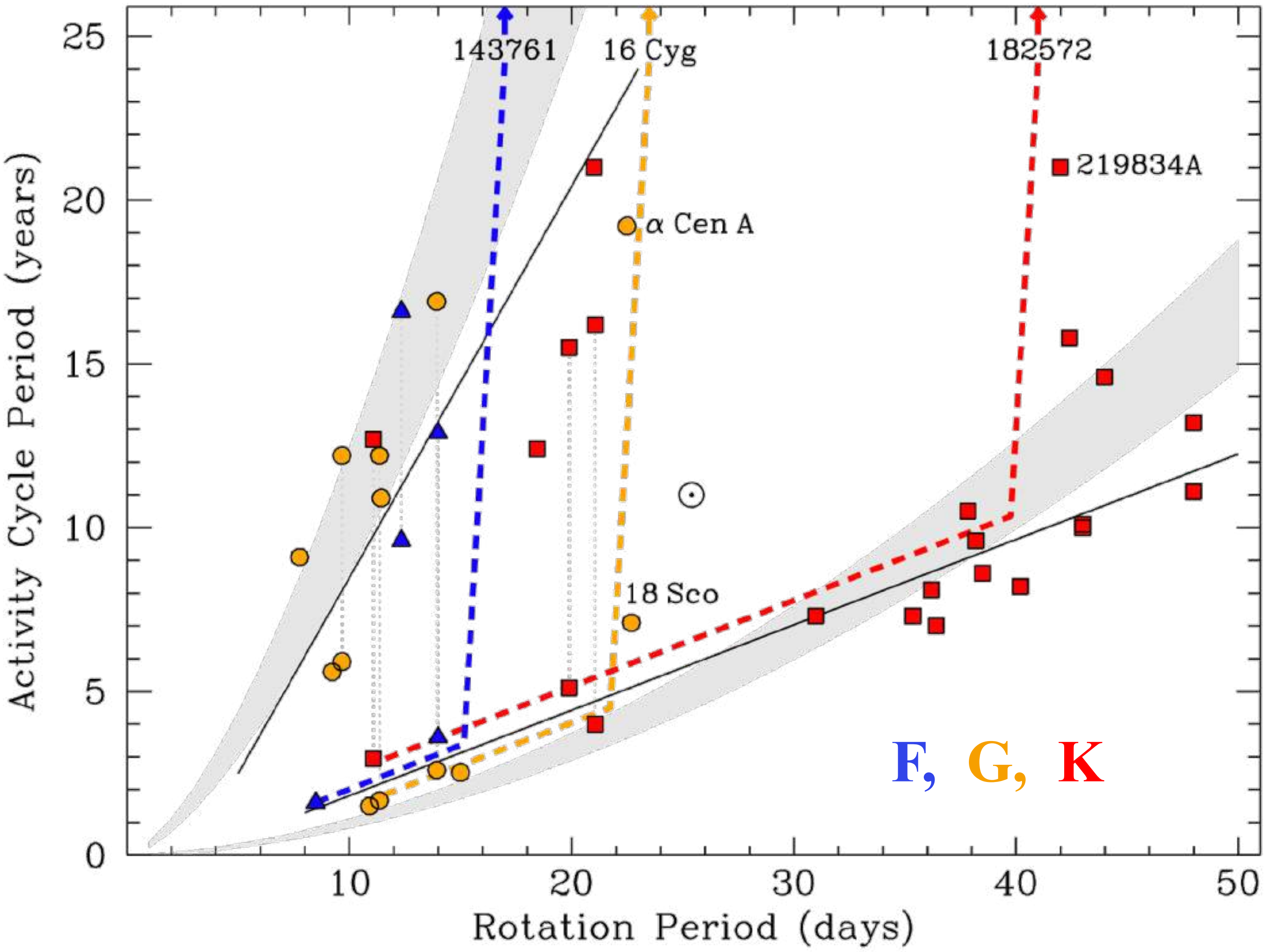
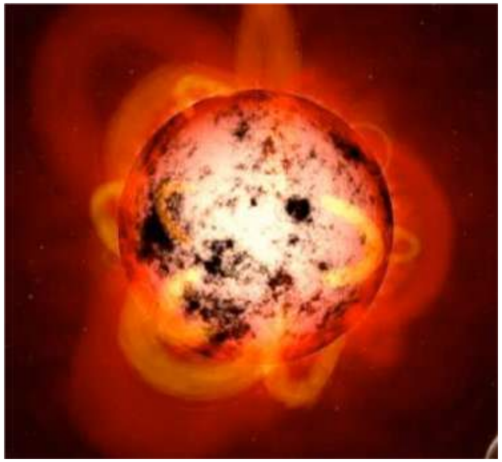


F, G, K

Is the Sun an oddball outlier?

Or is it in a time of transition from one sequence to another?

(2d) *Stellar chromospheres & coronae*



Many low-mass stars exhibit **correlations** between

- Age (*t*)
- Rotation rate
- Magnetic field strength
- X-ray & radio emission (corona)
- Emission in Ca II H,K lines & Balmer Hα (chromosphere)

Many of these correlations resemble the previous plots vs. Rossby number.

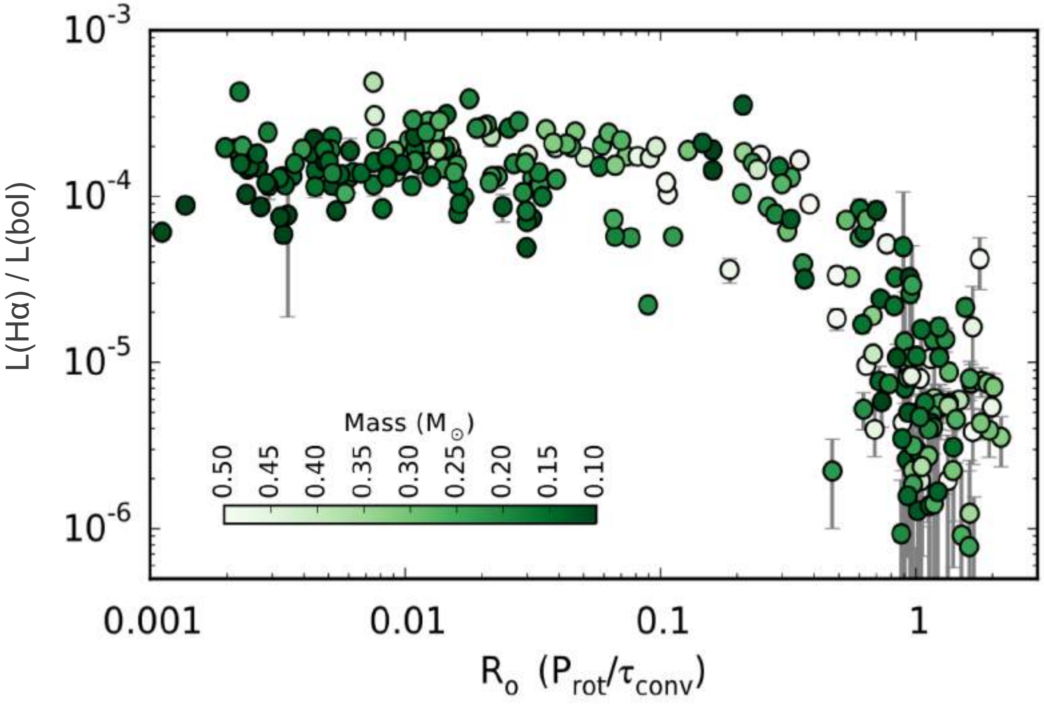
In the unsaturated regions, some power-law relations are often used…

$$\Omega \propto t^{-1/2}$$ (Skumanich 1972)

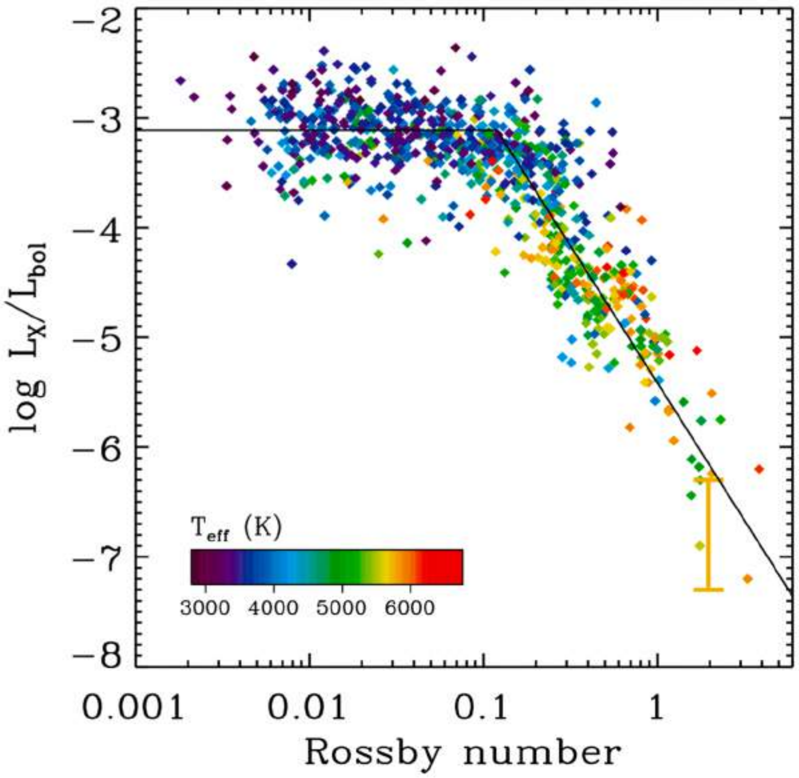
$$\Phi_* = 4\pi R_*^2 \langle B \rangle \propto \Omega^{2.8}$$ (Schrijver et al. 2003)

$$L_X \propto \Phi_*^{1.13}$$ (Pevtsov et al. 2003)

(2d) *Stellar chromospheres & coronae*



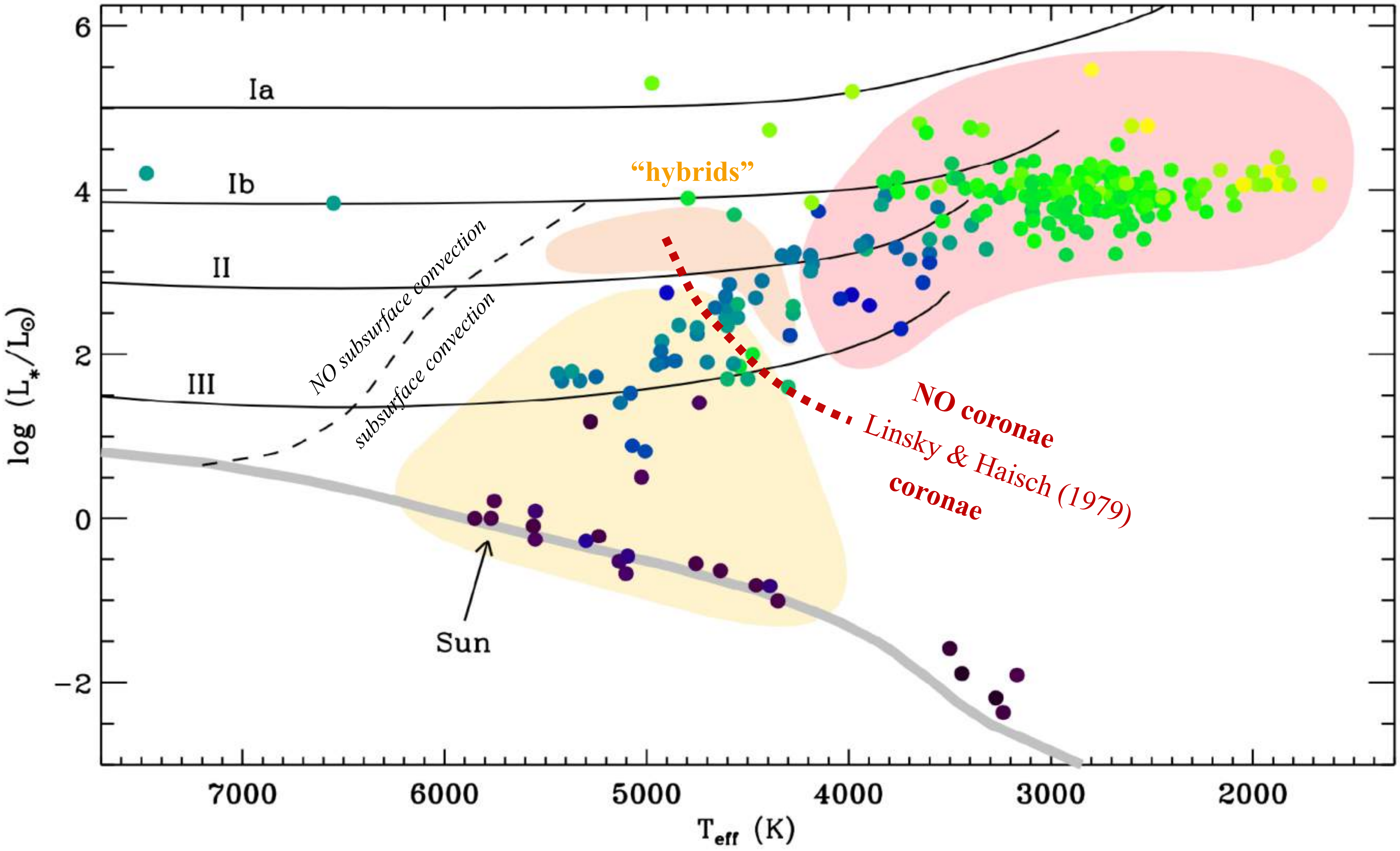
(Newton et al. 2017)



(Wright et al. 2011)

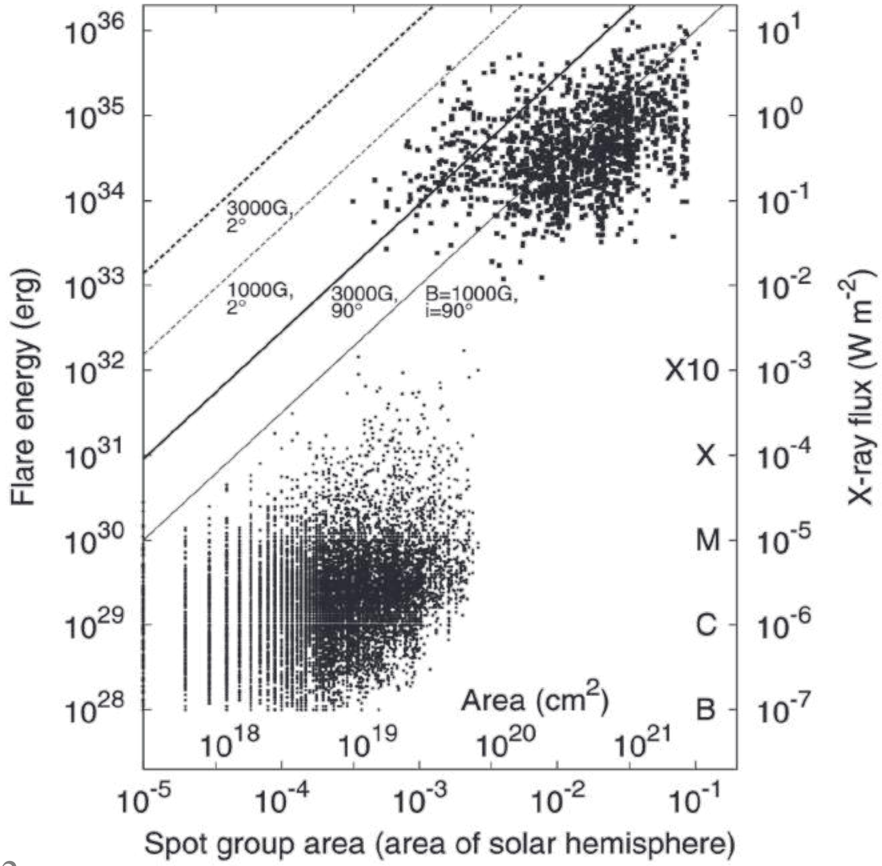
(2d) *Evolved chromospheres & coronae*

Ignore the symbol colors for a moment…

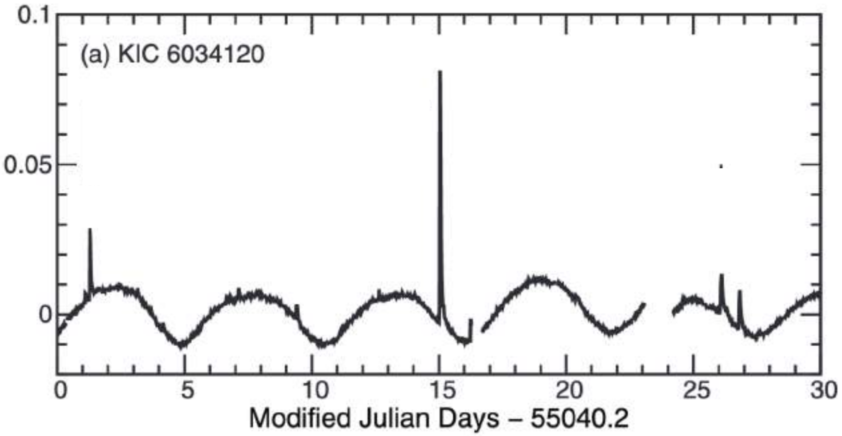


(2d) *Stellar chromospheres & coronae*

- We can’t forget **superflares!**
- There may be some detection bias going on, since the weakest solar flares may not be detectable on other stars. Still, we see energies so much higher than ever seen on the Sun…

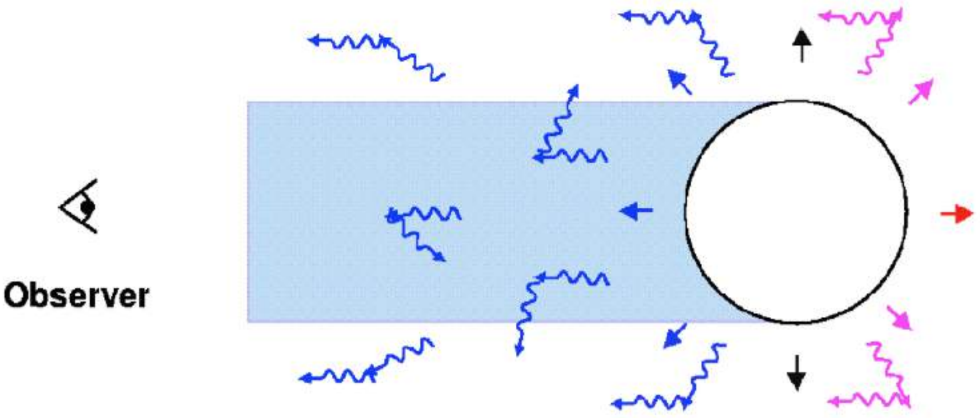


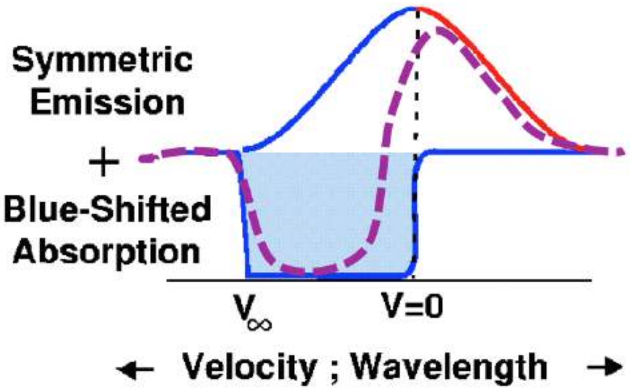
- Examples & energy distributions from Notsu et al. (2013).
- Note: $L_{\odot} \times (10\ \mathrm{min}) = 2 \times 10^{36}$ erg



(2e) *Stellar mass loss*

- It’s often stated that the only reason we know there’s a solar wind is because we’re inside it!
- How can winds of other stars be detected?
- If the outflow is dense enough, its signature can be imprinted on strong scattering lines (e.g., UV resonance lines of abundant ions).
- The accelerating gas in front of the star produces blue-shifted absorption, and scattering from the ”off-limb” regions produces both red- and blue-shifted emission.



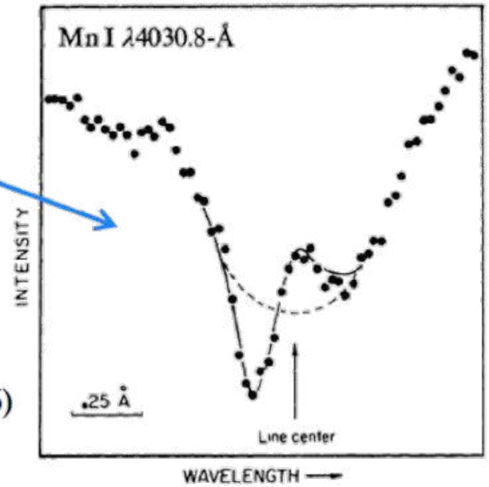


- **“P Cygni lines”** – named after **luminous blue variable** where first detected.

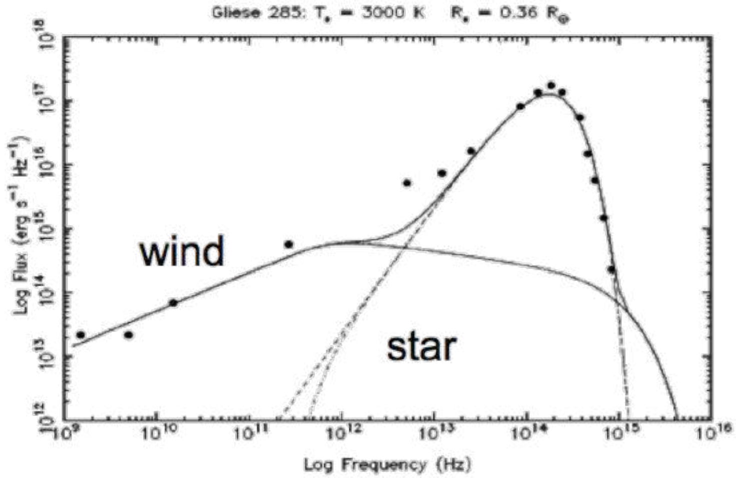
(2e) *Other detection methods*

- **Optical/UV spectroscopy:** either blueshifted absorption or full "P Cygni" profiles.
- **IR continuum:** circumstellar dust causes SED excess.
- **Molecular lines (mm, sub-mm):** CO, OH masers.
- **Radio:** free-free emission from (partially ionized?) components of the wind.

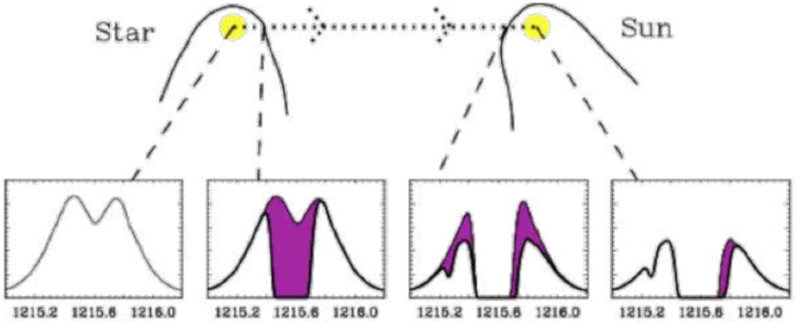
- Continuum methods need V_∞ from another diagnostic to get mass loss rate.
- $\dot{M}_{\text{(dust, molec, ion)}} < \dot{M}_{\text{total}}$ Clumping?

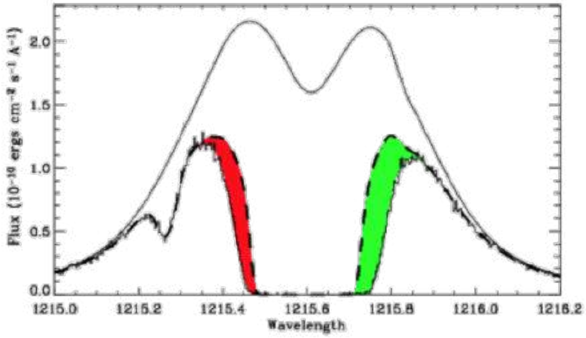


(Bernat 1976)



(van den Oord & Doyle 1997)

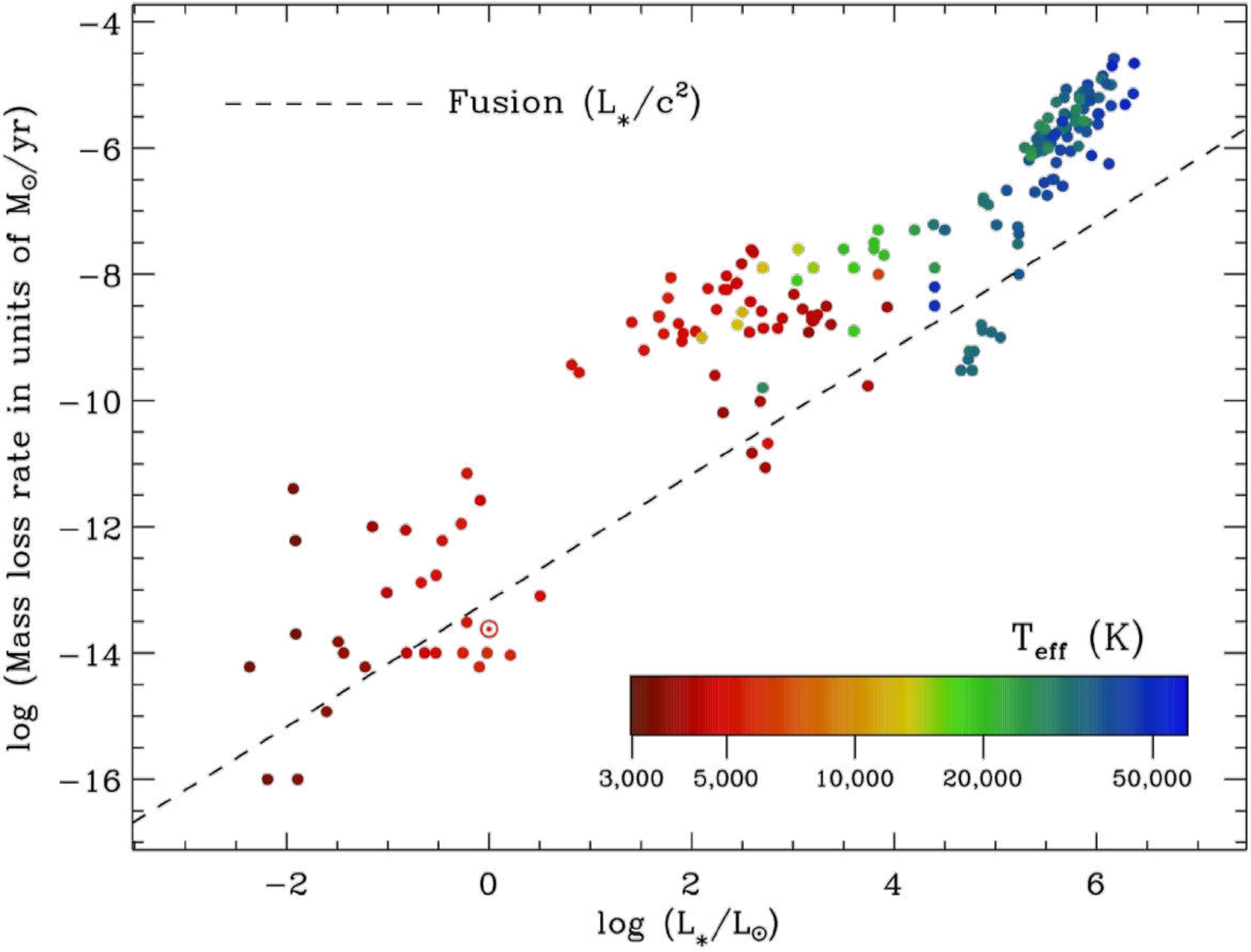




- Wood et al. (2001, 2002, 2005) distinguished cool ISM **H I Lyα absorption** from hotter "piled up" H^0 in stellar astrospheres. Derived *Mdot* depends on models . . .

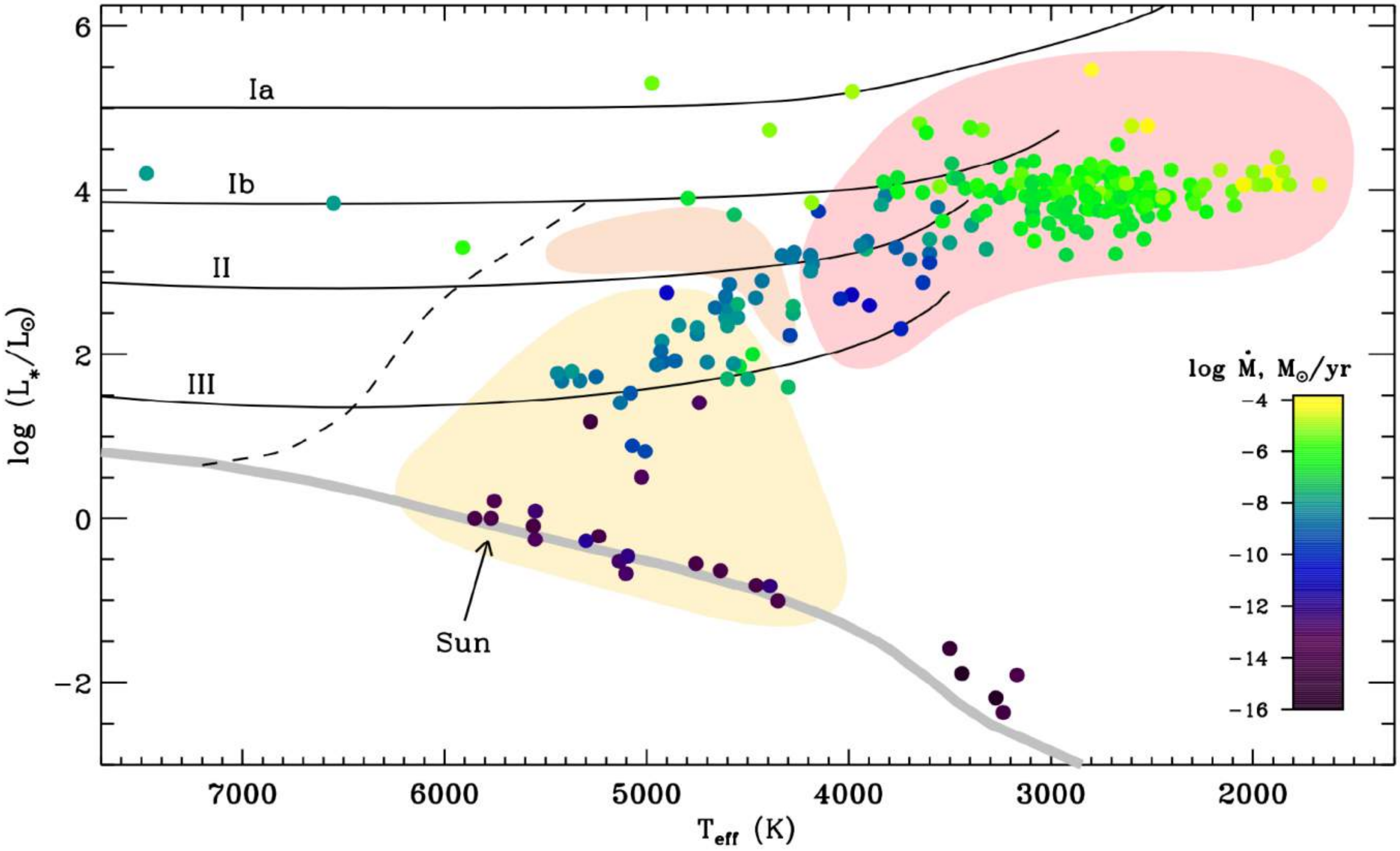
(2e) *Stellar mass loss*

Collection of observed values:



(2e) *Stellar mass loss*

Another view of observed values:

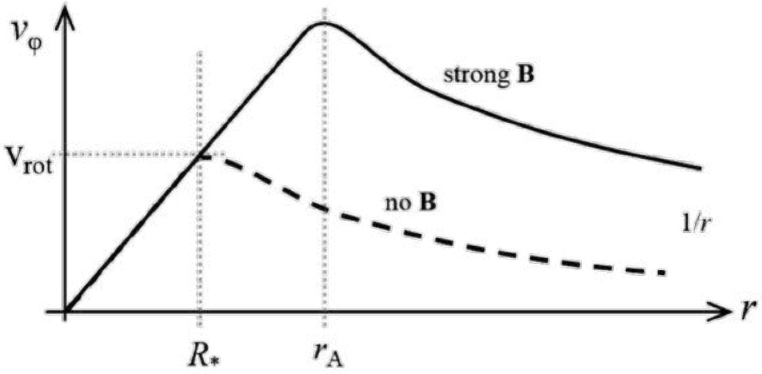


(3) *Models & simulations*

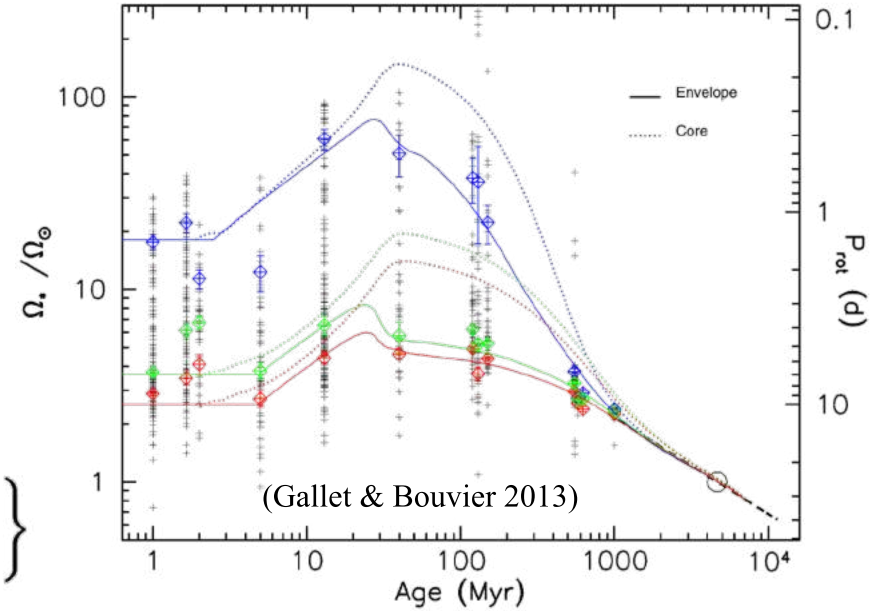
- Rotational spindown & the “Kraft break” are generally understood as the result of stellar winds carrying along angular momentum:

$$J_* \approx MR^2\,\Omega \qquad \frac{dJ_*}{dt} \approx \Omega R^2 \frac{dM}{dt} < 0 \quad \text{(for a wind).}$$

- However, the above scaling law accounts for only about 1% of the ang. mom. loss that we infer is happening from the Skumanich (1972) law.
- **Magnetic fields** force the wind to corotate far above the surface, and this longer “lever arm” produces more *dJ/dt*…



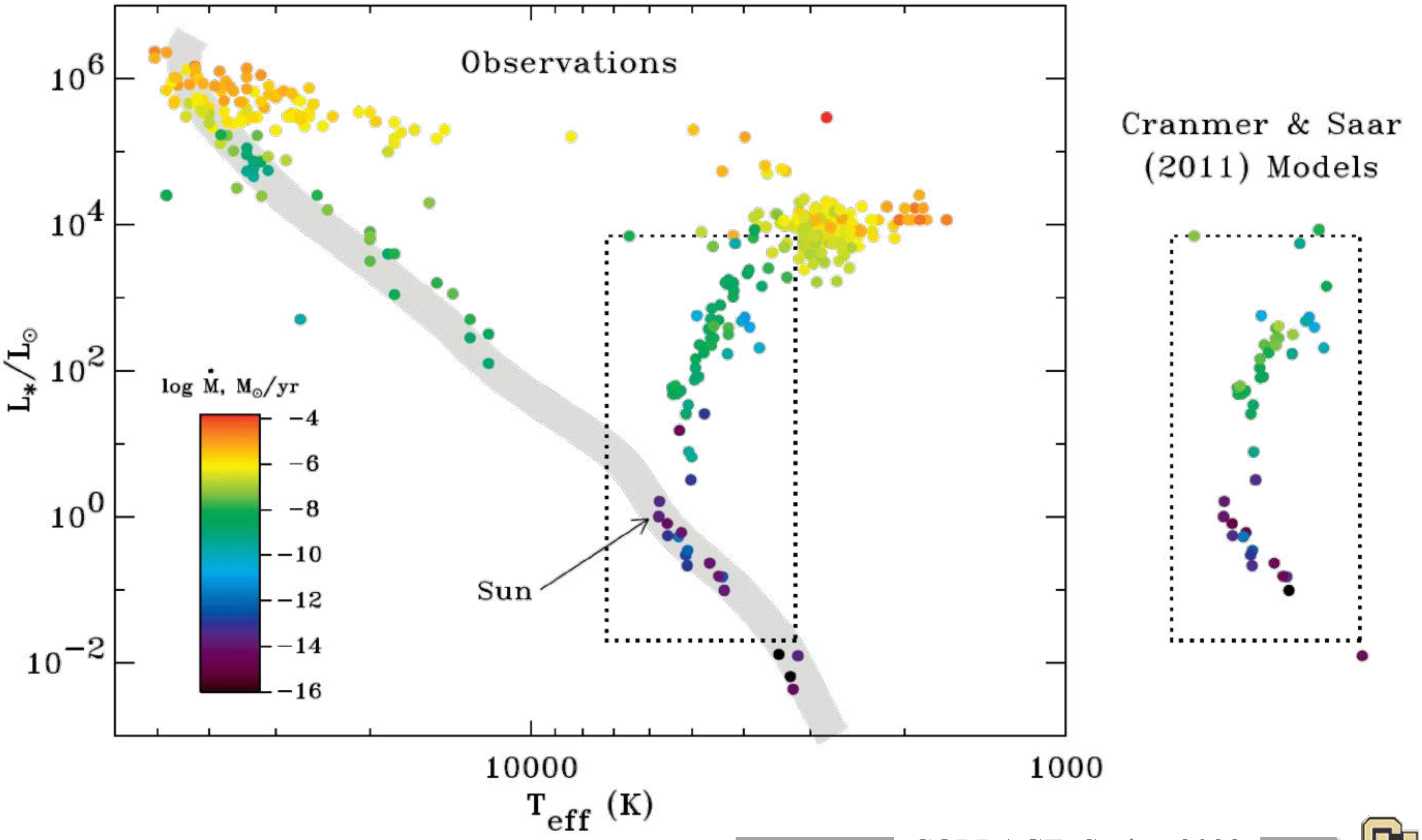
$$\frac{dJ_*}{dt} \approx \Omega r_A^2 \frac{dM}{dt} \approx \left\{ \begin{array}{c} \text{a few hundred times} \\ \text{the above “surface” value!} \end{array} \right\}$$



(Gallet & Bouvier 2013)

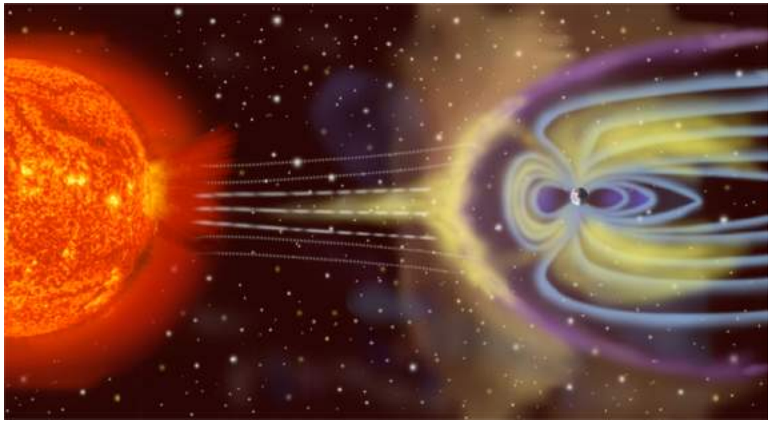
(3) *Models & simulations*

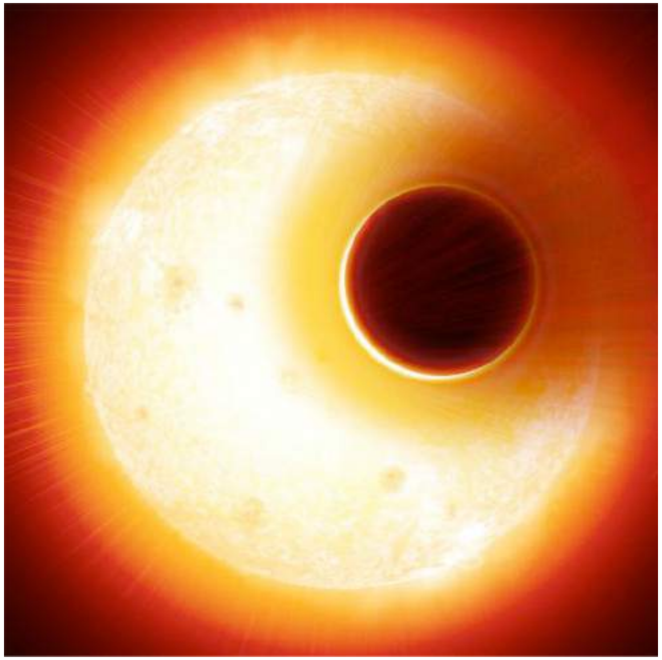
Coronal heating models for other stars are in ~roughly the same state as coronal heating models for the Sun… lots of well-developed ideas, but still no way to discriminate between them…



(4) *Impacts on exoplanets*

- All the space weather effects that we've surveyed in our solar system really ought to also be happening in other solar systems.
- We still have no unambiguous detections of exoplanetary **magnetospheres.**
- Ben-Jaffel et al. (2021) reported on an indirect detection of an extended plasmasphere & magnetotail for Neptune-mass exoplanet HAT-P-11b, but no actual magnetic fields were detected.
- The best bet for real detections may be radio-frequency electron cyclotron maser emission… currently too weak to detect, but next-generation missions may do it (see white paper for the previous decadal survey; https://arxiv.org/abs/0903.0873)

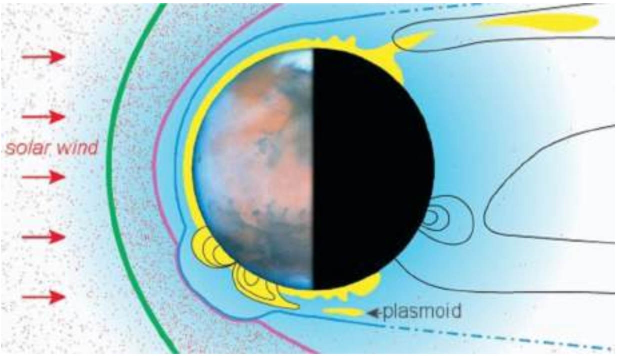




(4) *Impacts on exoplanets*

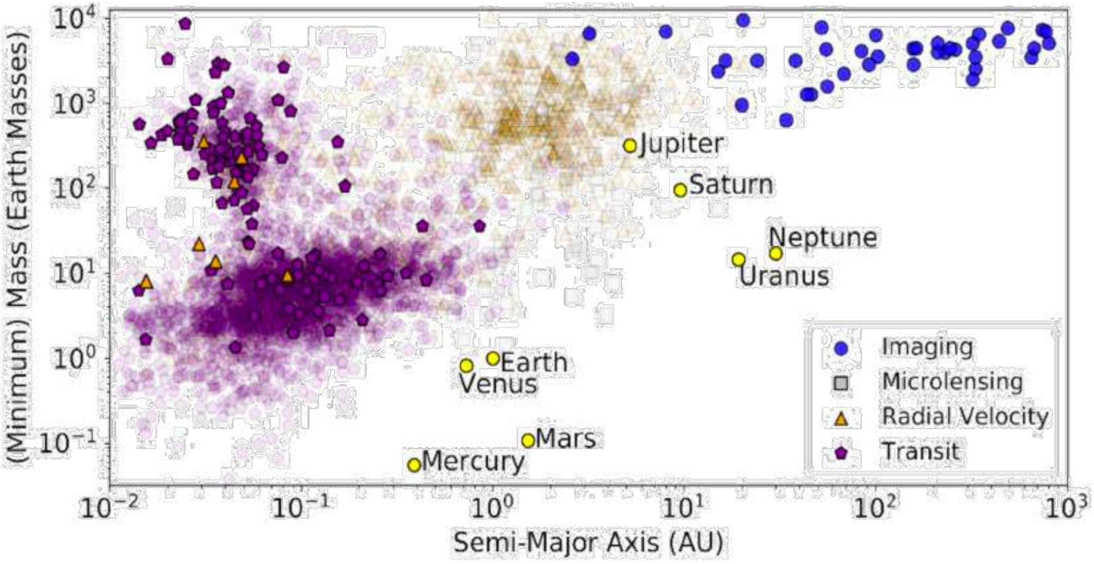
- Space weather also exists for planets *without* global magnetic fields; e.g., Venus & Mars.

- Stellar wind & CME plasma gets closer to the planet & induces a thin ionosphere/magnetosphere.



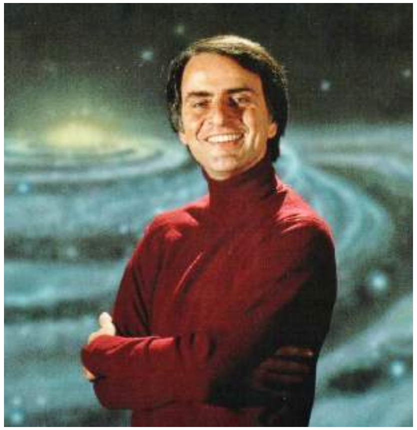
- When our Sun was young, both the wind's $\dot{M}$ and X-ray/EUV flux were higher. This probably ablated 99% of Mars' atmosphere!

- It's also been suggested that stellar winds & X-ray/EUV fluxes are responsible for totally destroying planets that get closer to their stars than ~0.01 AU (Lammer et al. 2003).



(4) *Impacts on exoplanets*

- *"The past is a foreign country; they do things differently there." – L. P. Hartley*
- **The Faint Young Sun Paradox:** There's **geological** evidence for the young Earth being warm enough for liquid water to exist, but the **astronomical** evidence (i.e., a lower solar luminosity) says that Earth's $T < 0^{o}$ C !
- Carl Sagan & George Mullen first realized this was a problem in 1972.

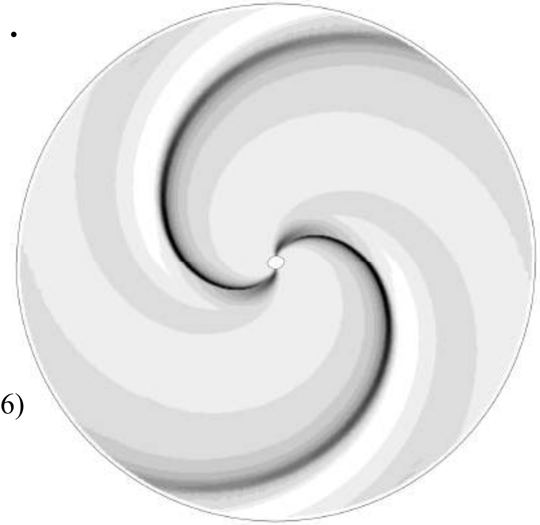


- The evidence for early (mostly one-celled) life in the oceans, during this supposedly frozen time, is very strong.
- Still an unsolved problem! Proposed answers include:
  1. A more massive young Sun? (I'm skeptical)
  2. Way more greenhouse gases on young Earth? MOST LIKELY
  3. Far fewer clouds, so lower albedo?
  4. **Space weather?** stronger SEPs generated N_2O? (Airpetian 2016)
  5. Frictional heating from tides (newborn Moon *was* much closer)?

(5) *Impacts on exoplanets… **and beyond…***

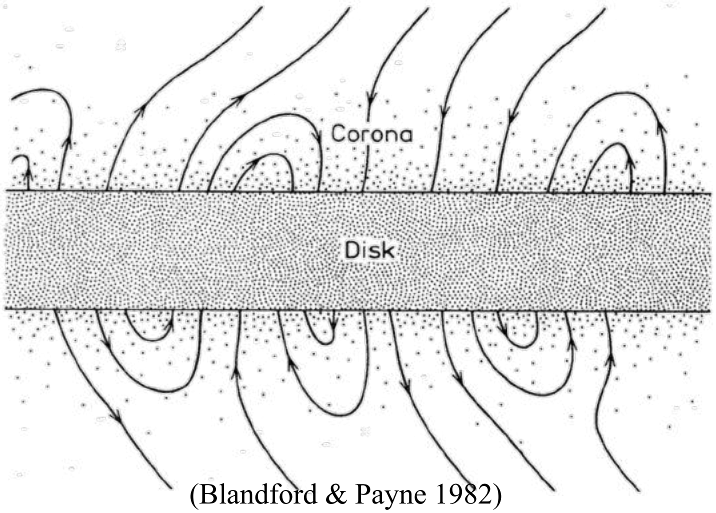
A few examples of helio-inspired phenomena in astrophysics…

- Some massive stars exhibit recurring narrow absorption features in wind lines that could be due to **corotating interaction regions (CIRs).**

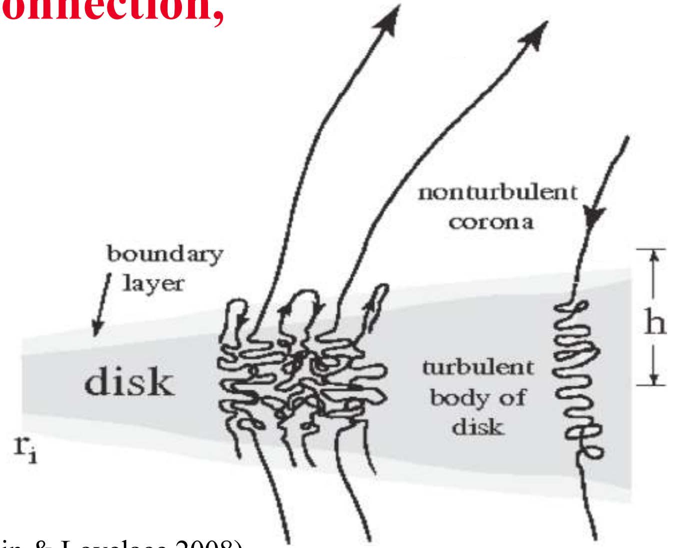


(Cranmer & Owocki 1996)

- Accretion disks around stars & black holes are likely to contain MHD **turbulence,** frequent magnetic **reconnection,** & hot UV/X-ray **coronae…**



(Blandford & Payne 1982)



(Rothstein & Lovelace 2008)

For next week

- Next week is the last class.

- Come prepared with any remaining questions, speculations, or wild ideas about what might be possible in the realms of coronal heating, solar/stellar winds, and space weather…