STELLAR MAGNETIC ACTIVITY

(PAP351)

Lecture 11, April 10,2024

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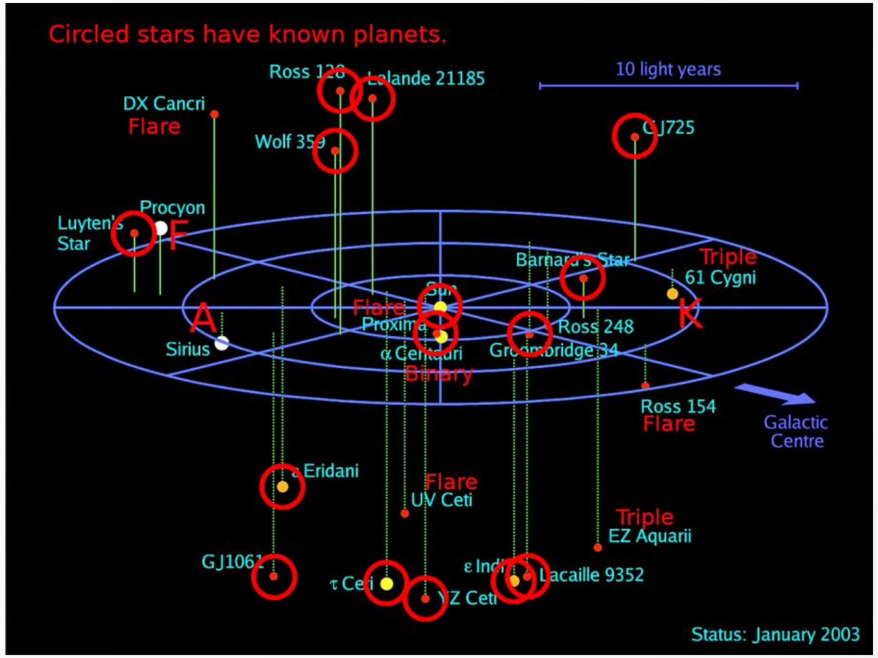
8. MAGNETIC ACTIVITY AND EXOPLANETS

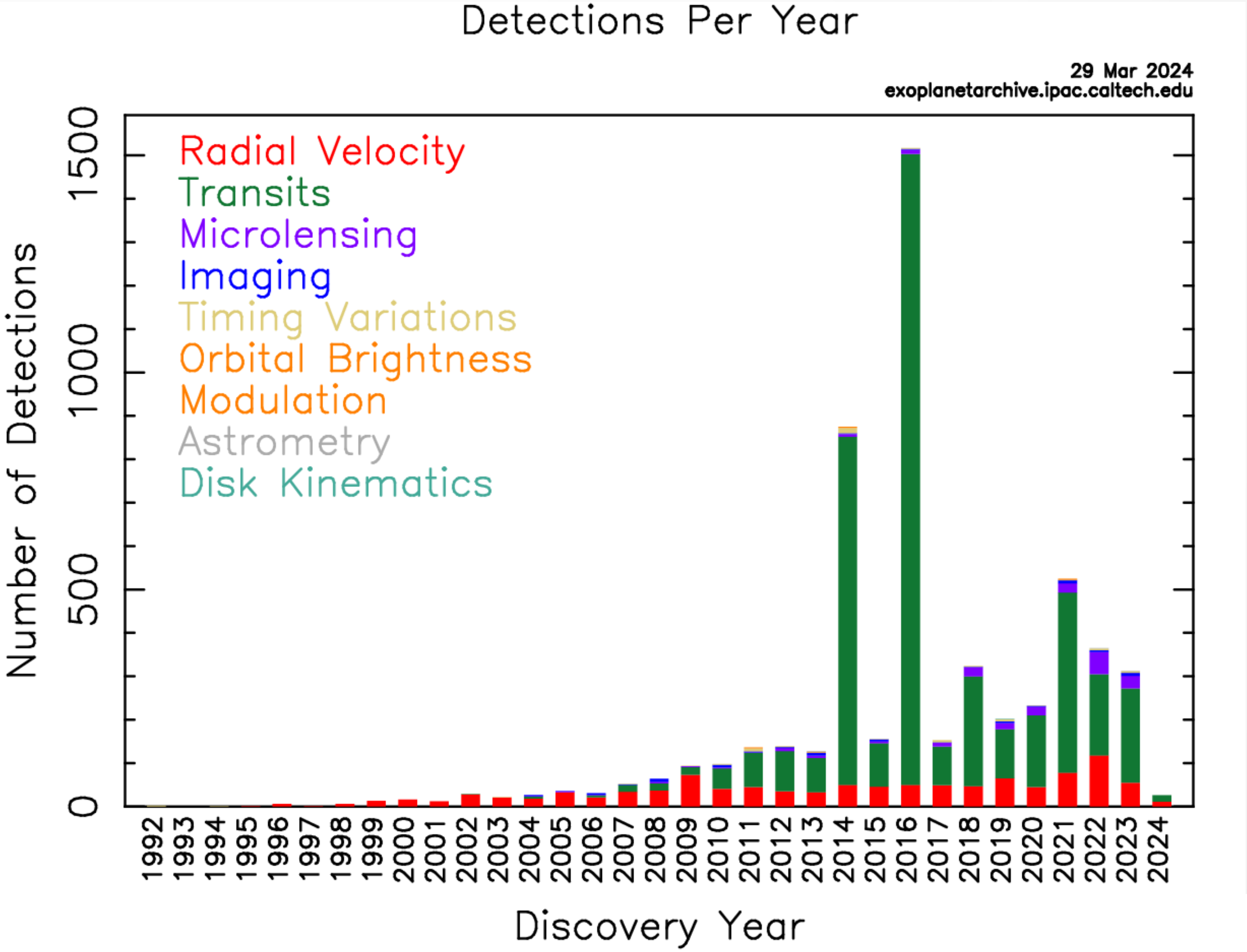
- Exoplanet populations and host stars.
- Magnetic activity and detectability of exoplanets.
- Interaction between active stars and exoplanets.
- Magnetic activity and habitability.



Nearby stars with detected planets (Fig. edited by M. Tuomi).

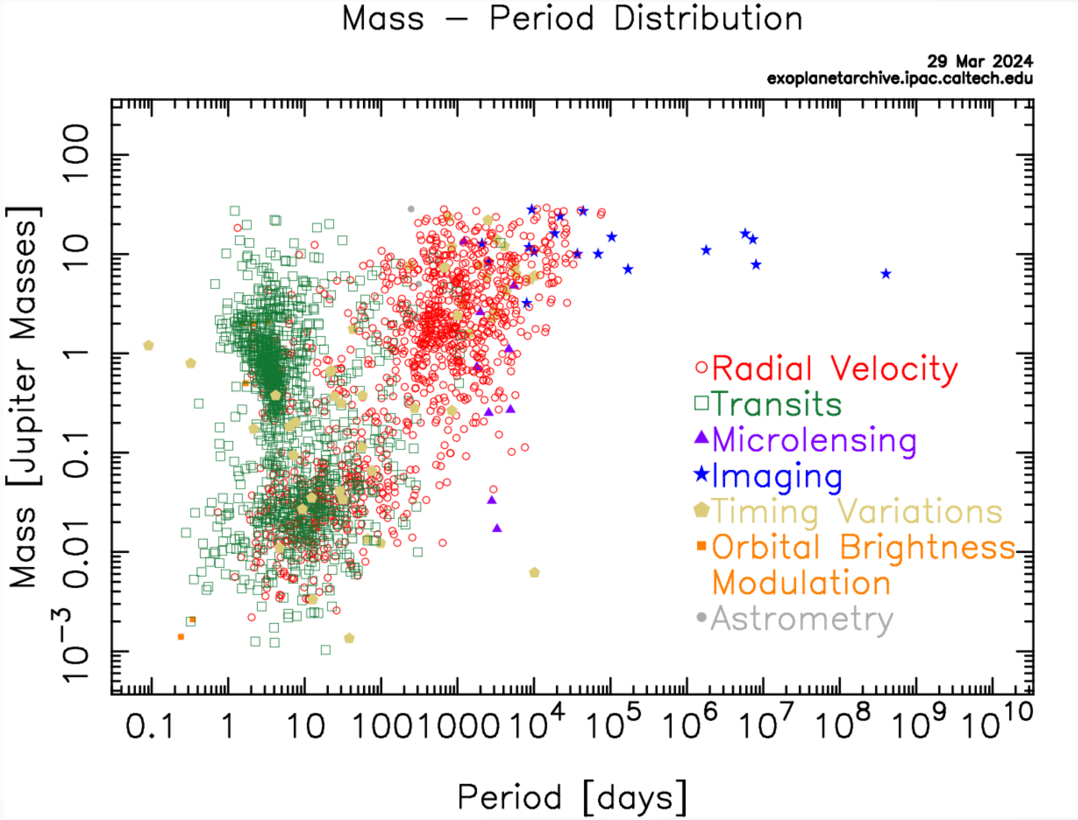
8.1 DETECTION OF EXOPLANETS

- 5 653 confirmed exoplanets in 4161 planetary systems by 4/2024.
- Main methods: Transits and radial velocity.



8.2 SELECTION EFFECTS

- Easiest to detect:
  - Massive/large planets.
  - Nearby orbits.
  - Planets of low mass/small stars.
- Currently impossible targets:
  - Earth-size planets at Earth-like orbits zone around solar analogues.
- Note also real effects: “Neptunian desert”.



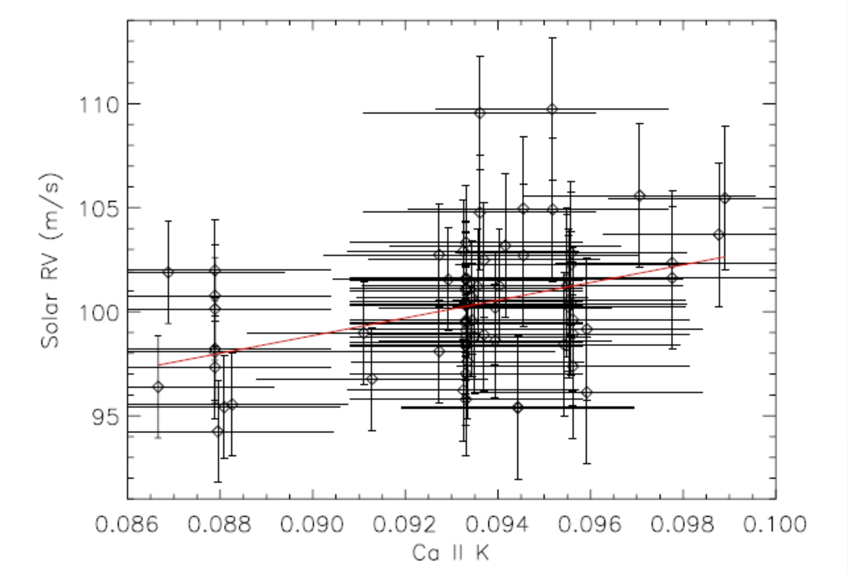
8.3 DEPENDENCE ON STELLAR PARAMETERS

- Metallicity (e.g., Wang & Fisher 2015):
  - Increased occurrence rate around metal-rich stars.
  - The larger the planet, the greater this increase.
- Mass/spectral class:
  - Most found exoplanets orbit late-type stars (note selection effect!).
  - Smaller stars => more smaller planets.
  - Most Earth-sized planets orbit red dwarfs (note selection effect!).
- Binarity:
  - Suppression of planet formation.
  - Disruption of orbits.

From "Handbook of Exoplanets" (G. Mulders, 2018).

8.4 MAGNETIC ACTIVITY AND DETECTABILITY

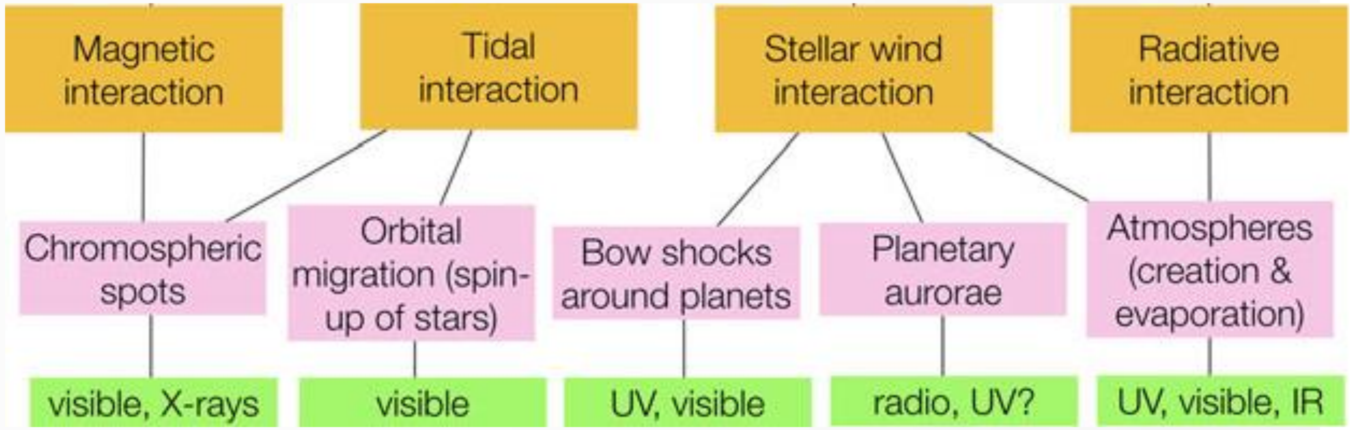
- Stellar magnetic activity causes:
  - Radial velocity jitter.
  - Brightness changes.
- E.g., the Sun as a star:
  - Radial velocity variations due to spots, bright regions, convection.
  - Observations 2006-2014 => variation amplitude of ~ 5 m/s (Lanza et al. 2016).
  - Correlation with activity.
- Detecting the Earth with RV-method would require a precision of ~ 0.1 m/s.



Solar RV vs. CaII K-index (Lanza et al. 2016).

8.5 ACTIVITY RELATED INTERACTION

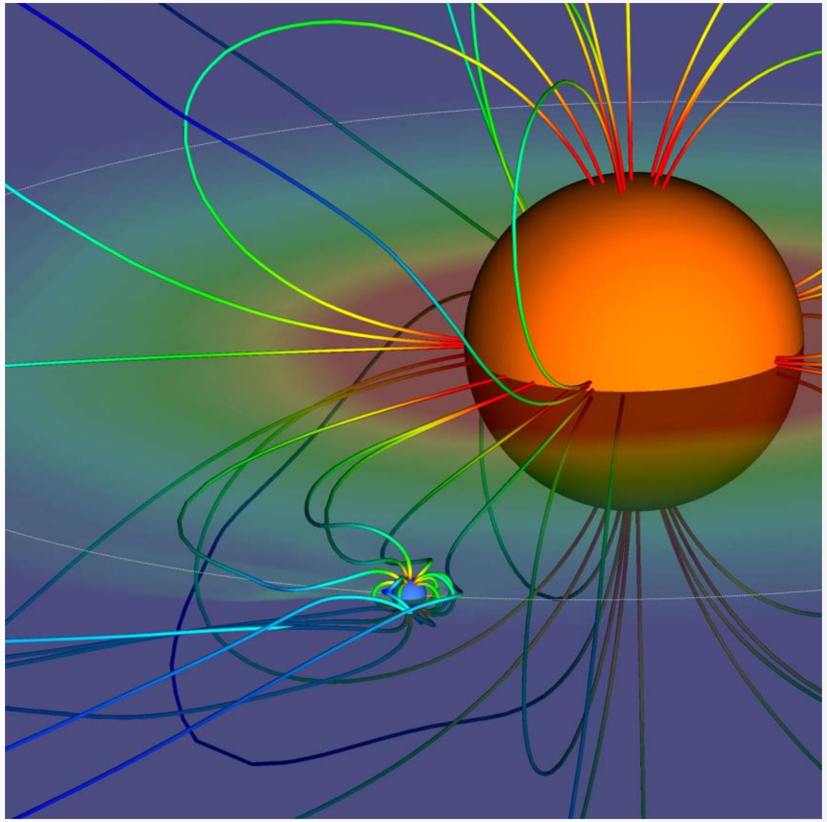
- Interaction directly related to magnetic activity:
  - Magnetic fields.
  - Stellar wind.
- Indirect activity related interaction:
  - Tidal interaction.
  - Radiation.



Different types of interactions between a planet and its host star (Vidotto 2019).

8.6 WHICH INTERACTION?

- Both tidal and magnetic interaction may lead to spots on the stellar surface:
  - Tidal interaction by raising bulges => anomalous activity.
  - Magnetic interaction => magnetic field lines linking the planet to the star => anomalous activity.
- Tidal interaction => 2 bulges => typically modulation by $P_{\mathrm{orb}}/2$.
- Magnetic interaction => typically modulation by P_{orb}.



Idealized star and planet magnetic interaction (A. Strugarek).

8.7 COROTATING RADIUS

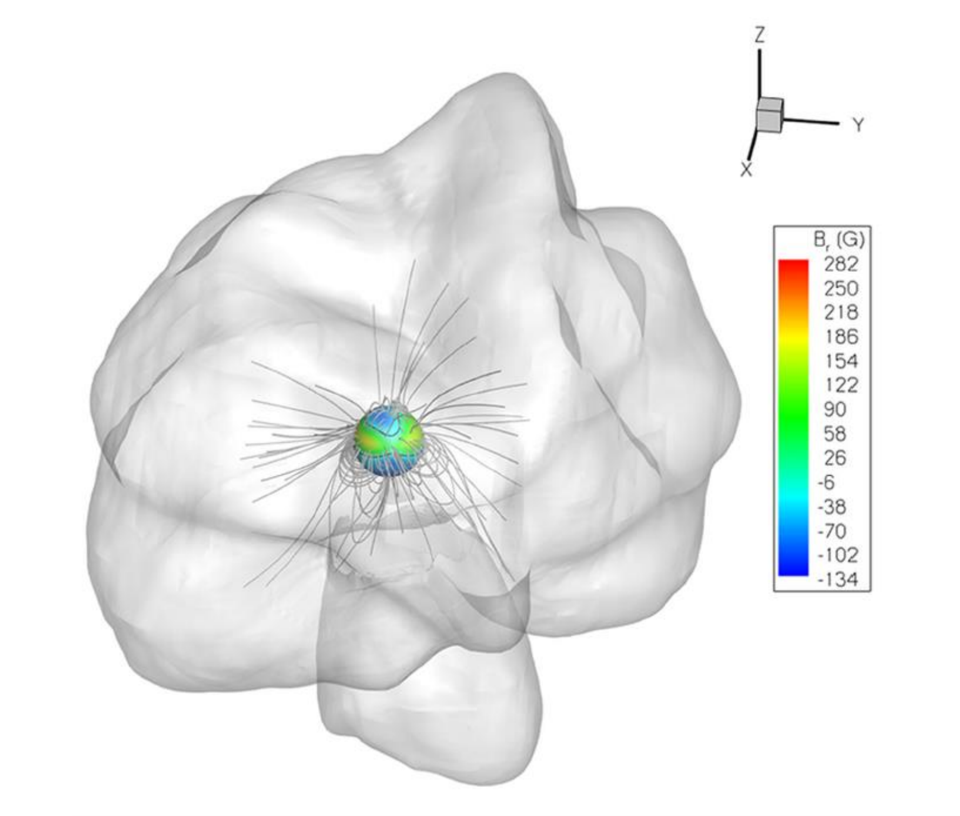
- Tidal interaction => force to synchronize P_{rot} and P_{orb}.
- Radius at which the orbital period P_{orb} is the same as the stellar rotation period $P_{\star,\mathrm{rot}}$.

$$r_{\mathrm{co}} = \left(\frac{G M_\star P_{\star,\mathrm{rot}}^2}{4\pi^2} \right)^{1/3} = 0.02\ \mathrm{au} \left(\frac{P_{\star,\mathrm{rot}}}{1\ \mathrm{day}} \right)^{2/3} \left(\frac{M_\star}{M_\odot} \right)^{1/3}$$

- E.g., if planets orbital distance is $> r_{\mathrm{co}}$:
  - => tidal interaction (if significantly strong) pushes the planet farther from star.
  - => star-planet interaction decreases.

8.8 ALFVÉN SURFACE

- The surface at which the stellar wind speed (u) equals the Alfvén speed ($v_A = B/\sqrt{4\pi\rho}$).
- Inside the Alfvén surface:
  - The stars magnetic field (and gravity) dominates plasma motions.
  - $=>$ Connectivity between magnetic fields of star and planet.
- The Alfvén surface can be estimated (extrapolated) from a stars surface magnetic field (+ stellar wind model).



Estimated Alfvén surface for the M-dwarf OT Ser (Vidotto et al. 2014).

8.9 STELLAR WINDS

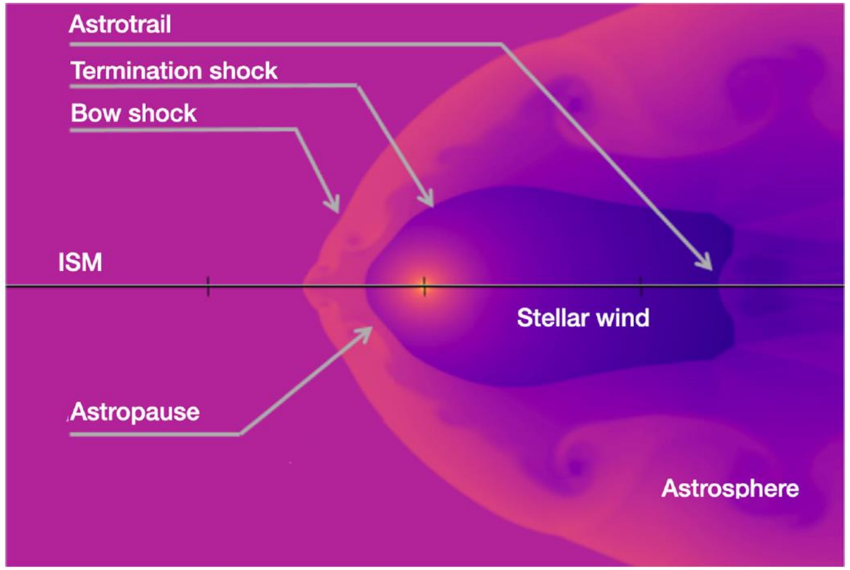
- Stellar winds are often quantified in units of the current solar mass loss rate:

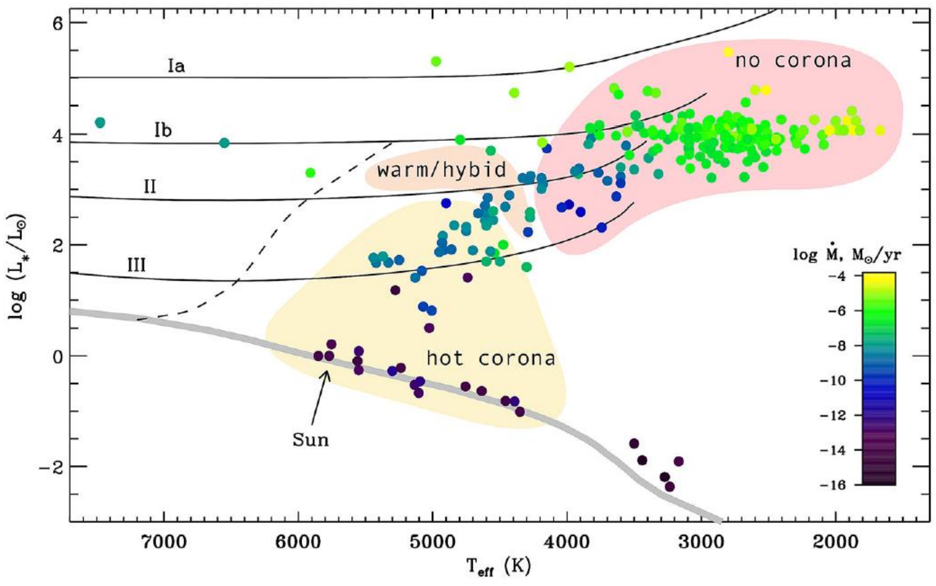
$$\dot{M}_{\odot} = 2 \times 10^{-14}\, M_{\odot}\mathrm{yr}^{-1}$$

- Stellar wind speeds can be estimated using the Alfvén speed $v_A = B/\sqrt{4\pi\rho}$ at the transition region.

- Magnetic activity decrease with age (t) => decrease in stellar wind, e.g. (Vidotto 2021):

$$\dot{M} \propto t^{-0.99}$$

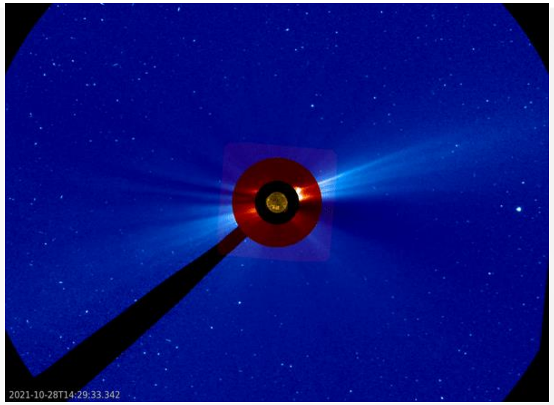




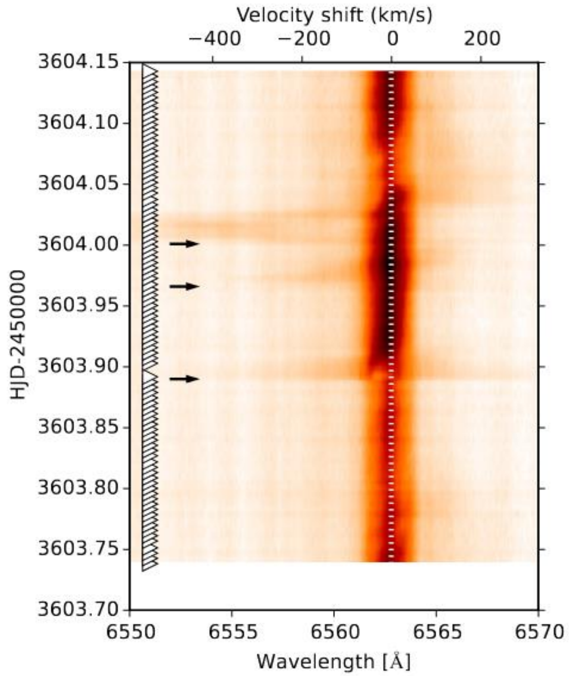
Stellar astrosphere (O´Fionnagaín (2020) and mass-loss rates in late-type stars (Cranmer & Winebarger 2019).

8.10 STELLAR CME:S AND EXOPLANETS

- Solar analogy: CME:s should be related to strong flares.
- Not always the case in active stars: Confinement of plasma by strong fields?
- Stellar CME:s => fast moving plasma => observable as Doppler shift in e.g., Hα-emission. (Why not use, e.g., Lyα $\lambda \approx 1215$ Å?)
- Also X-ray and UV-observations used.
- Stellar flares are much easier to observe. (Why?)
- Stellar CME:s will strongly affect nearby planets => possible destruction of atmosphere.



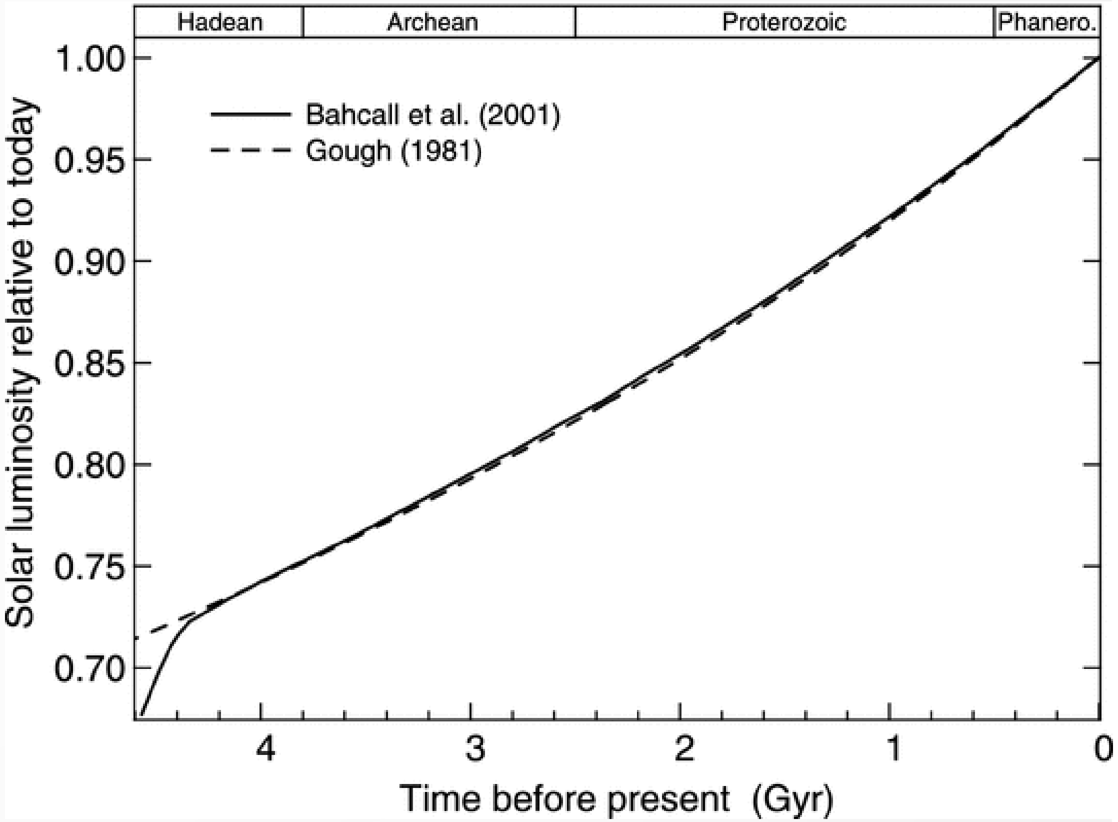
Solar CME in white light (ESA & NASA)



Dynamic Hα spectra of V374 Peg (M4V): Strong flare events and CMEs (Vida et al. 2016).

8.11 MAGNETIC ACTIVITY OF THE YOUNG SUN

- Stripping of Venus', Earth's and Mars' early atmospheres by solar wind and eruptions.
- Destruction of H_2O on Venus by solar UV => reduced capture of $C0_2$ => runaway greenhouse effect.
- Stronger UV-radiation on Earth => facilitated emergence of life.
- Possible extra heating of Earth to compensate for young faint Sun.
- Scattering and expulsion of interplanetary gas and dust by strong solar wind.



Young faint Sun: Evolution of solar luminosity over the four geologic eons (Fig. from Feulner 2014).

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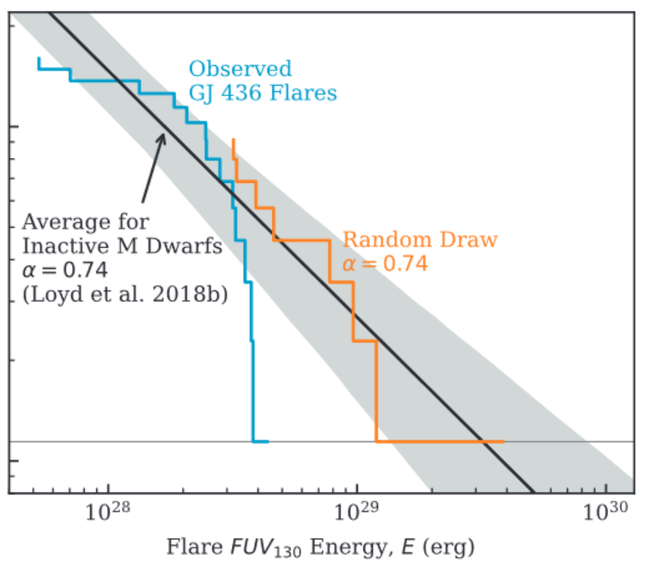
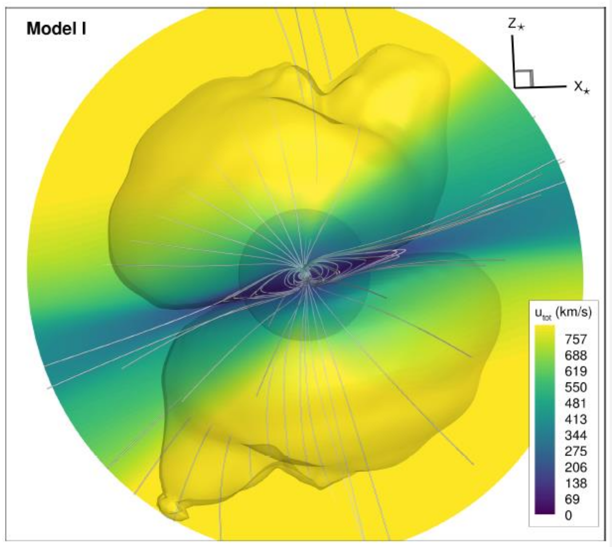
8.12 SPACE WEATHER OF GJ 436B

- GJ 436: M2.5V, $P_{\mathrm{rot}} \approx 44$ d.
- GJ 436b: M=25$M_\oplus$, R= 4.1$R_\oplus$, P_{orb}=2.1 d.
- Planet orbit is (probably) partly inside the Alfvén surface of GJ 436.
- => Triggering of flares.
- => Anomalous flare energy distribution.

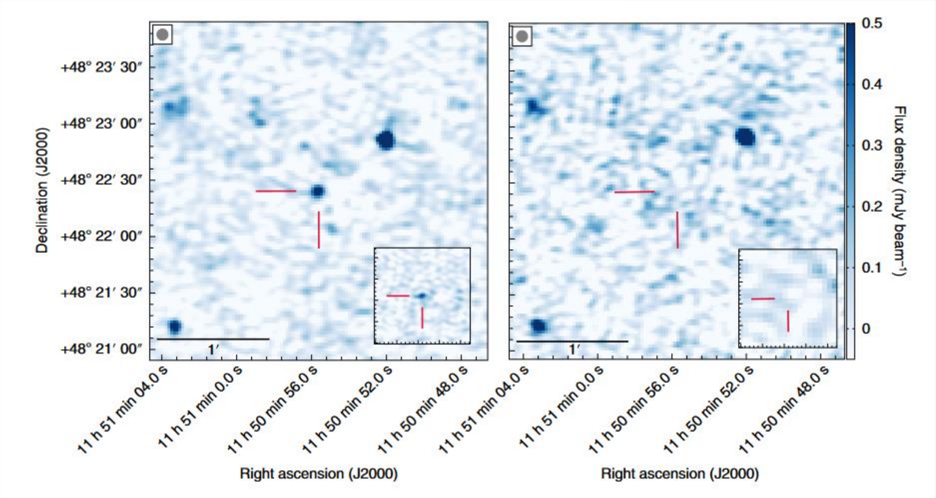




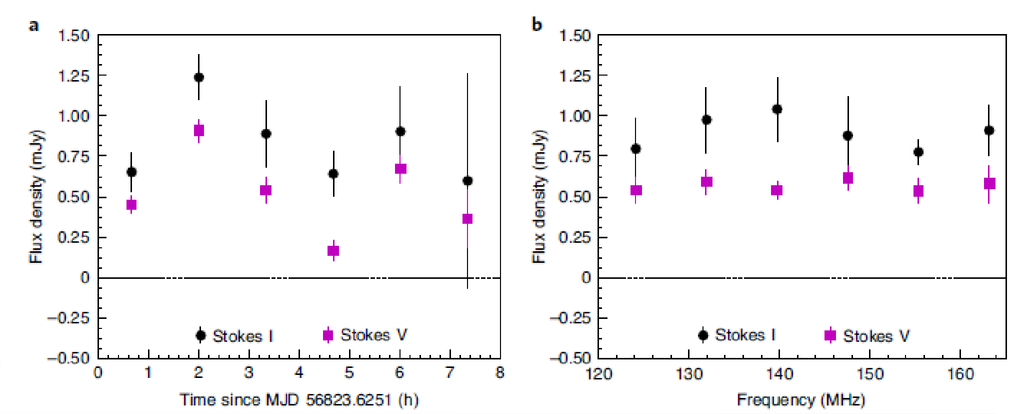
Flare energy distribution (Lloyd et al. 2023), Alfvén surface and stellar wind for GJ 436 (Vidotto et al. 2023).

8.13 POSSIBLE AURORA DETECTION

- GJ 1151: M4.5V, $P_{rot} \approx 125 \pm 23$ d.
- Observations from Low Frequency Array (LOFAR, $\nu \leq 150$ MHz) Two-Metre Sky Survey (LoTSS).
- Source visible on June 16, but not May 28, 2014.
- The emission consistent with sub-Alfvénic interaction with an Earth-size planet with $P_{orb} \sim 1$-5 d.



Intensity images of the region of GJ 1151 for 16 June 2014 and 28 May 2014. Stokes-V in the inserts (Vedantham et al. 2020).



Temporal and spectral variability of the of the radio source in GJ 1151 (Vedantham et al. 2020).

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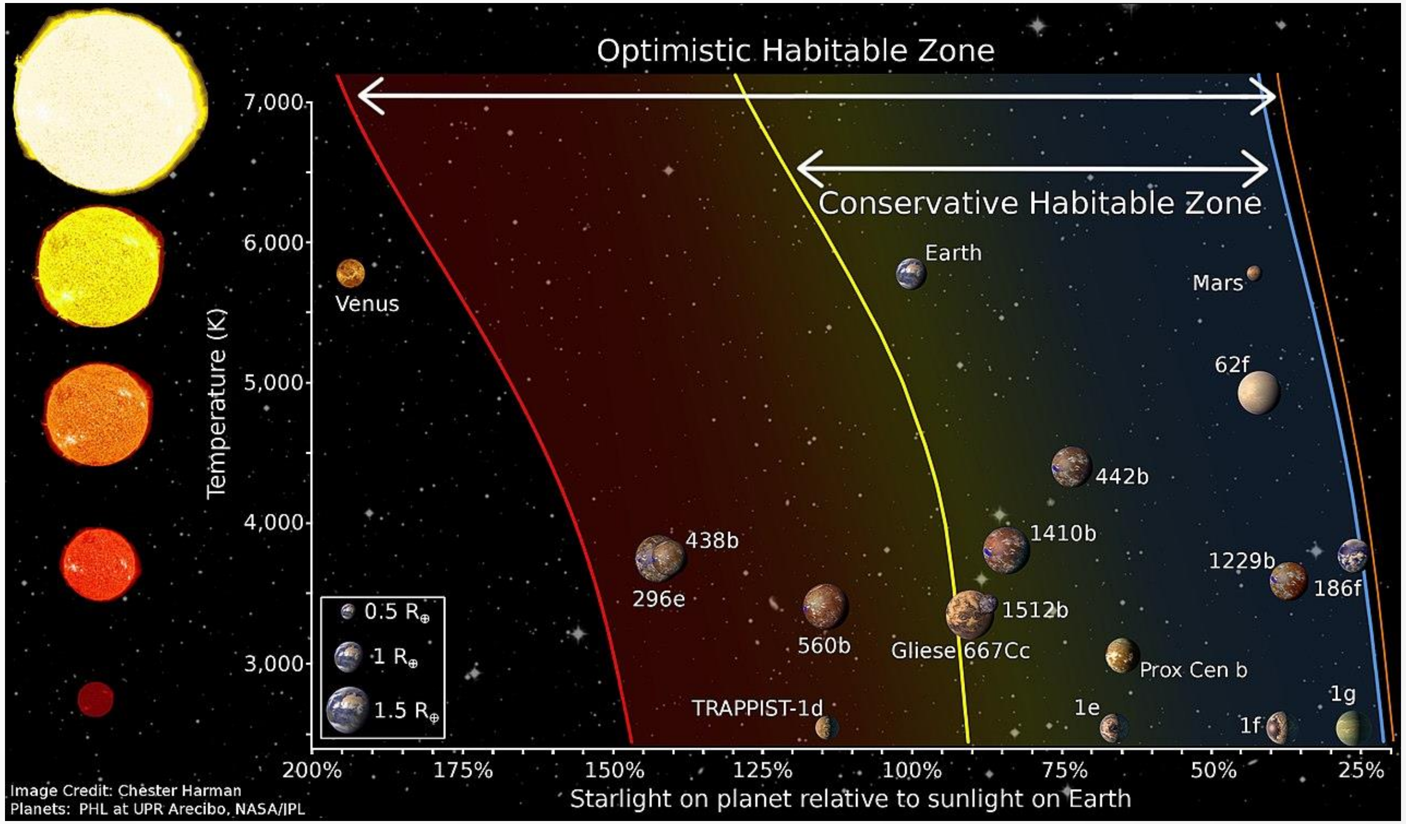
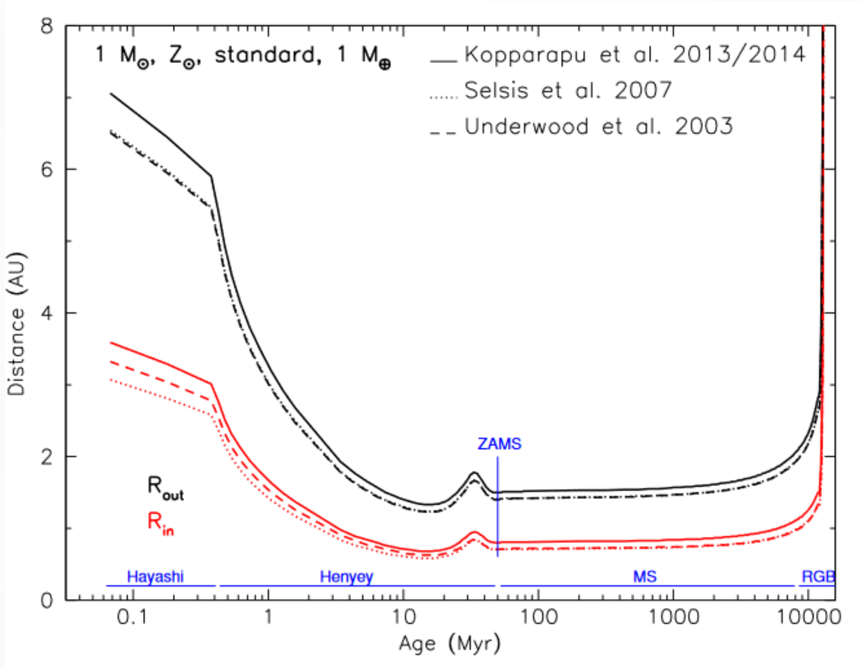
8.14 HABITABLE ZONE (HZ) FOR EXOPLANETS

- Usual definition: Distance region from host star, where water based life is possible.
- Kepler data estimates for Milky Way:
  - ~ 10 billion Earth-sized planets orbiting in HZ of Sun-like stars.
  - ~30 billion red dwarfs in the Milky Way.



8.15 MAGNETIC ACTIVITY AND HABITABILITY

- Position of HZ changes as stars evolve.
- Most Earth size planets within HZ are hosted by M-dwarfs. (Why?)
- Less luminous star ⬄ HZ closer to host star.
- Close distance:
  - Tidal effects (tidal locking).
  - Possible magnetic interaction.
  - Strong effects from flares, CME:s and stellar wind.
- For G and K-type stars, magnetic activity may also help emergence of life.



Evolution of the inner (red) and outer (black) limits of solar HZ (Gallet et al. 2017).