Modeling Exoplanet Host Star Magnetic and Coronal Activity

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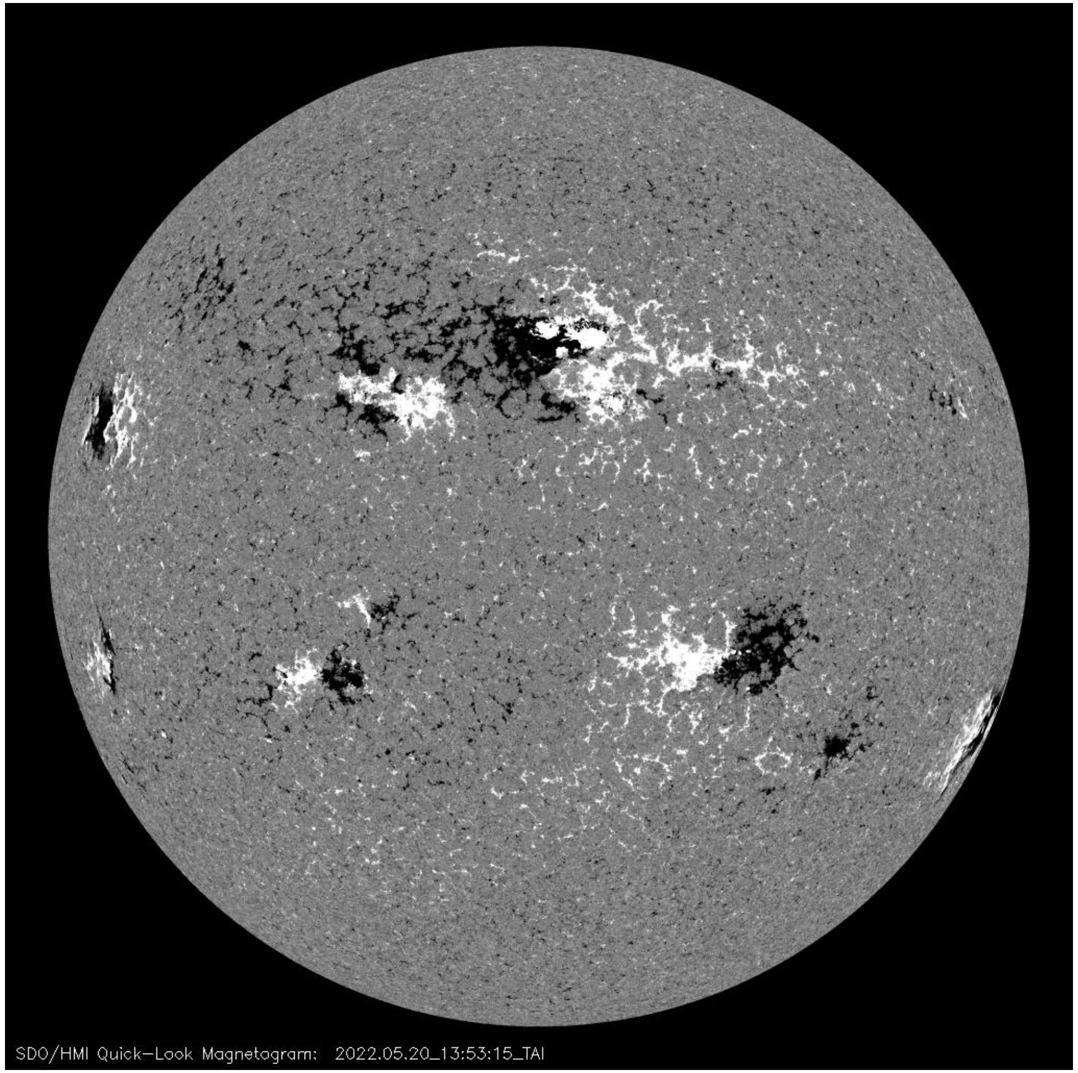
Motivation

- *Intrinsic properties of known exoplanet host stars* (SCI-07)
  - Emergence and transport of magnetic flux at stellar surface
  - Evolution of magnetic and coronal activity over short and long timescales

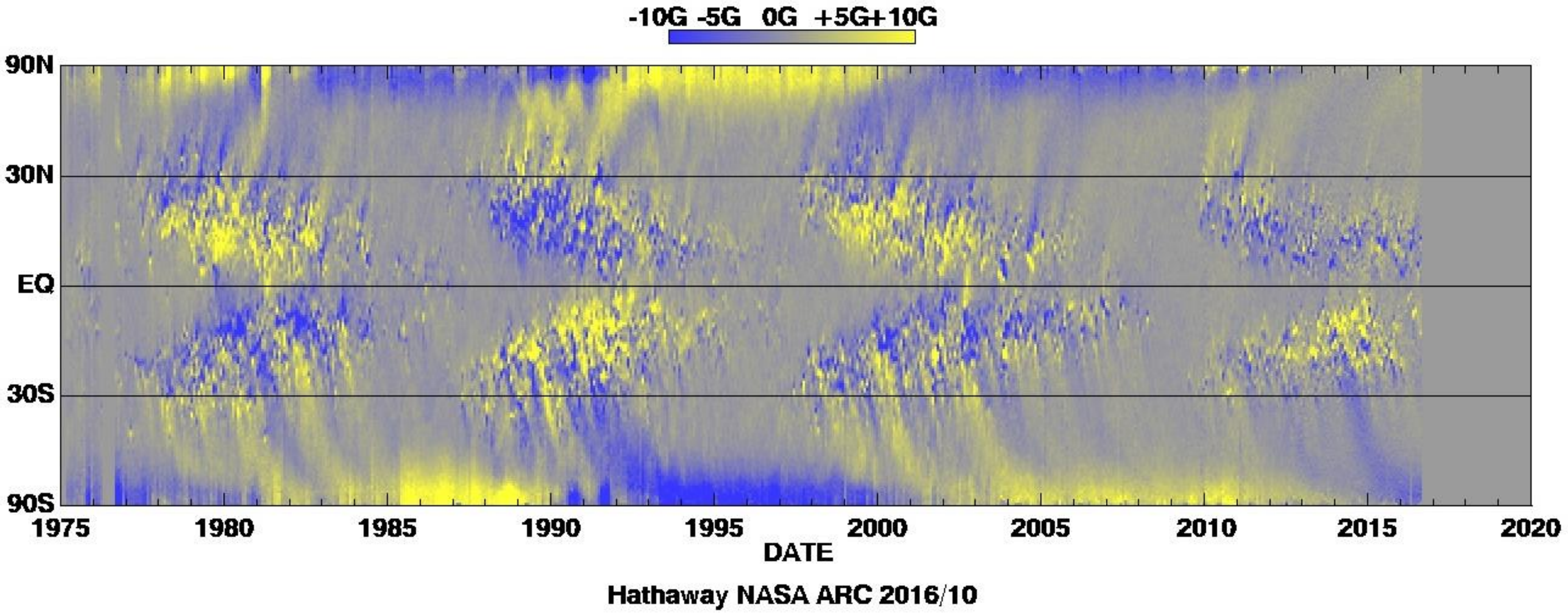
- *Modeling exoplanet atmospheres* (SCI-02)
  - Requires realistic inputs to magnetospheric/atmospheric models
    - High-energy coronal emission (X-rays, EUV)
    - Stellar wind parameters
    - Frequency of transient events, e.g. flares and CMEs

The 2021 NASA Exoplanet Exploration Program (ExEP) Science Gap List

Solar Magnetic Field Modeling



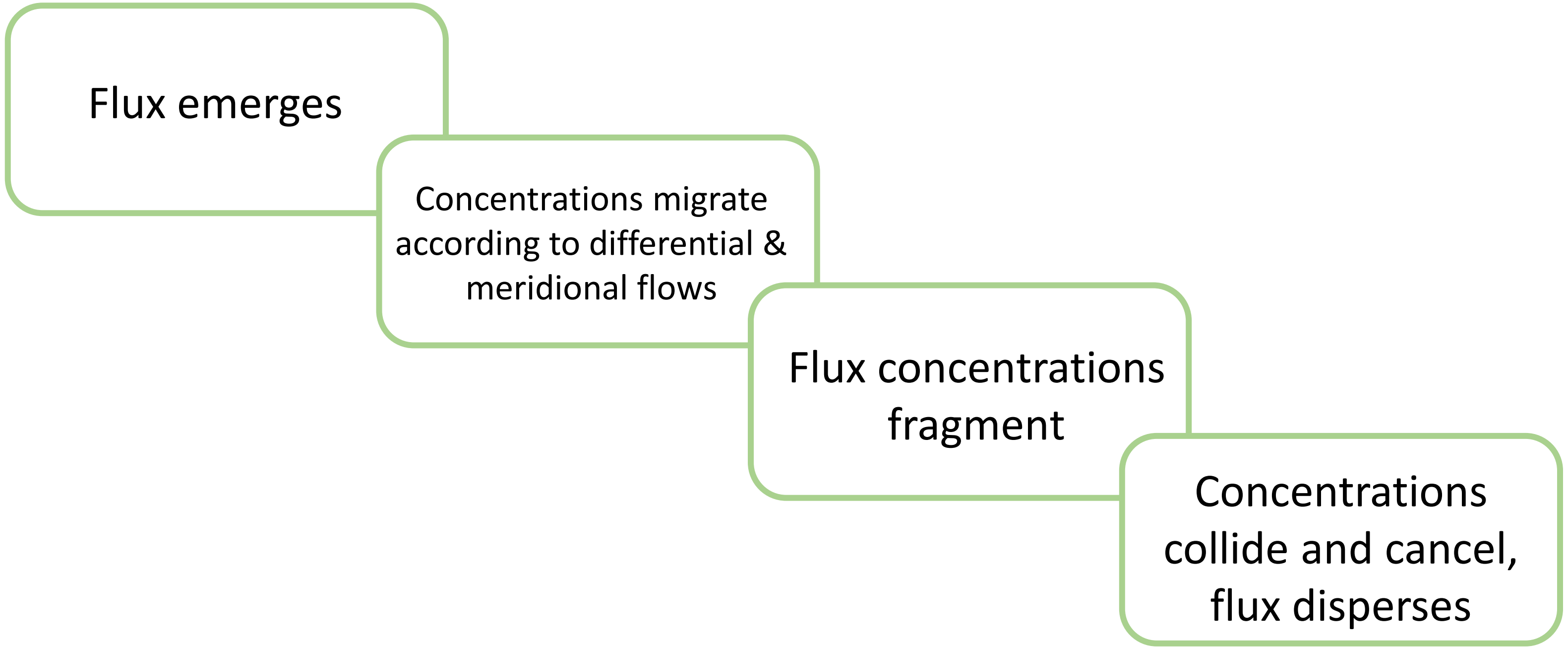
Solar Surface Magnetic Field



- Decades of solar observations have built a detailed picture of solar magnetic variability
  - Magnetic activity cycle manifests as the 11-year sunspot cycle
  - Large-scale flows: differential rotation and meridional circulation

Surface Flux Transport (SFT) Modeling

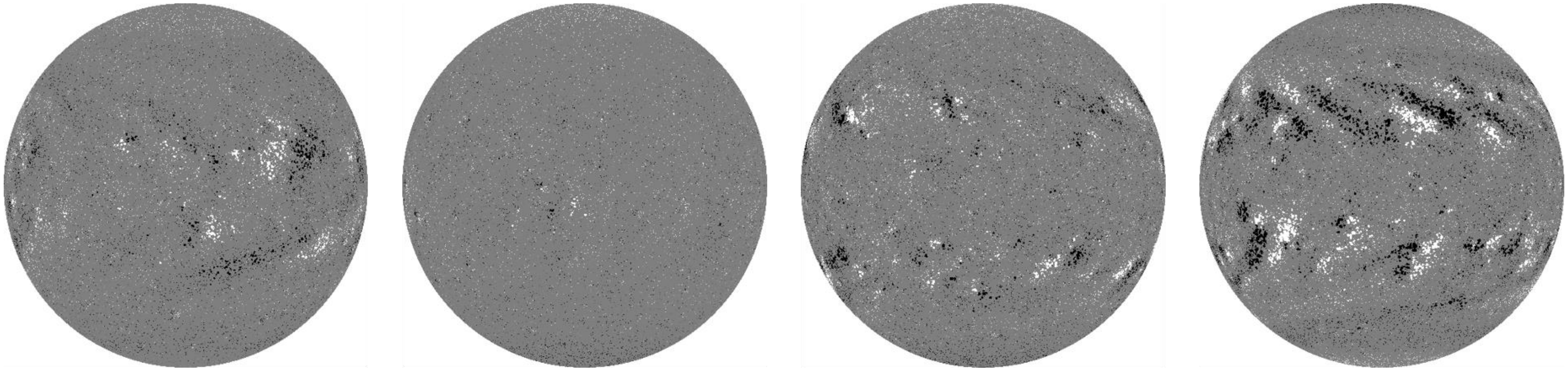
- Empirical-based model for solar photospheric flux transport
- Many tunable input parameters such as rotation period, differential and meridional flow profiles, flux emergence strength, etc.



Schrijver 2001, Schrijver & Title 2001, Schrijver et al. 2003

Surface Flux Transport

- SFT is capable of reproducing solar observations with good agreement
  - Good spatial and temporal resolution over many activity cycles



A typical solar test case cycle using the SFT

Key Stellar Parameters

- Simulate a range of stellar activity levels parameterized by:

$$Ro = P_{rot}/\tau_c$$

Rossby number, the ratio of rotation period to convective turnover time for the stellar interior; varies inversely with stellar magnetic activity.

$$\phi \propto Ro^{-1.5} R_*^2$$

$$P_{cyc} \propto P_{rot}^{1 \pm 0.25}$$

$$v_{me} \propto P_{cyc}^{-(10/9)}$$

ϕ is the magnetic flux at the stellar surface, R_* is the stellar radius.

P_{cyc} is length of the stellar cycle, P_{rot} is the stellar rotation period.
v_{me} is the meridional velocity.

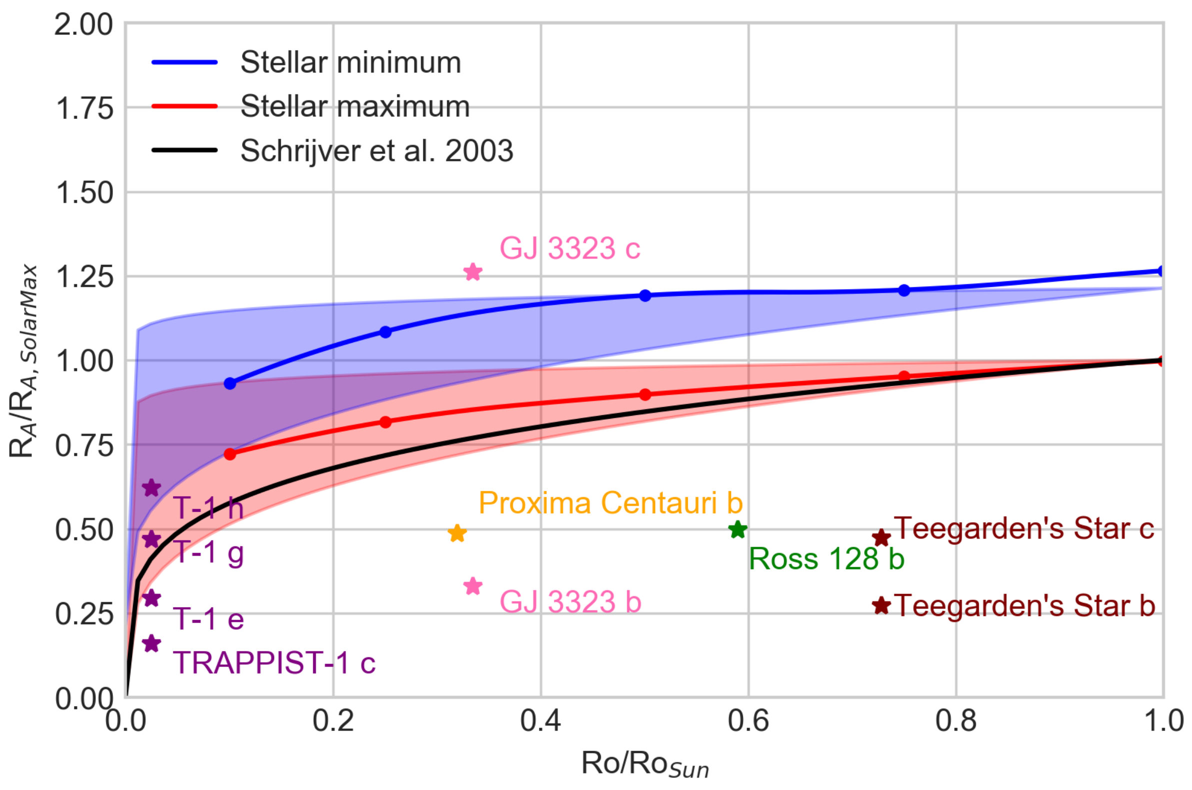
Asterospheric Magnetic Topology

Alfvén Surface

- $\frac{R_A}{R_{A,solarmax}} = \left(\frac{\phi_*}{\phi_{solarmax}}\right)^{-0.16\pm0.13}$

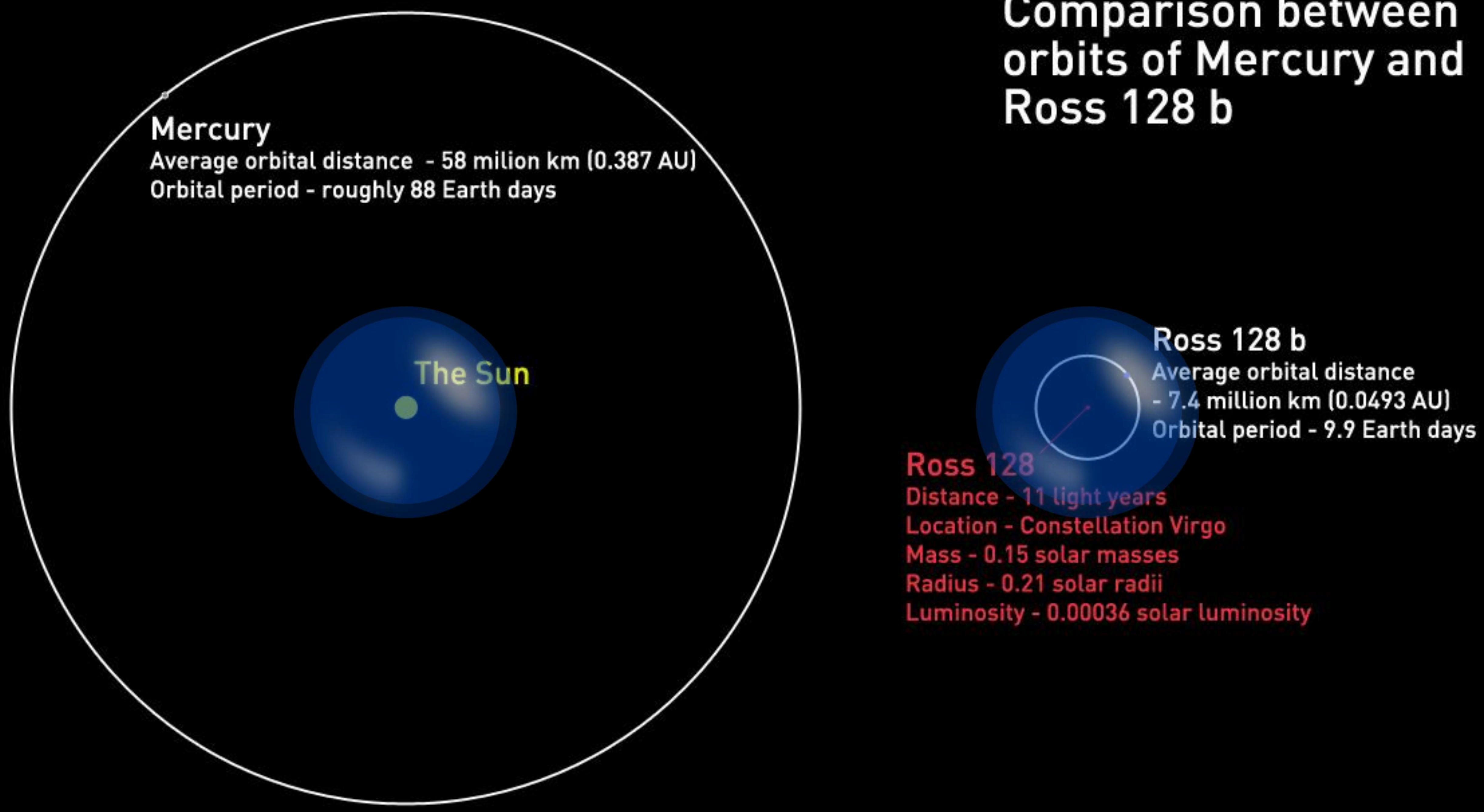
- Planets inside their star's Alfvén surface would directly interact with stellar corona
  - Boundary between sub-Alfvénic and super-Alfvénic stellar wind speeds

- Proxima Centauri b and other habitable-zone M-Earths within host star's Alfvén radius for whole activity cycle



Farrish et al. 2019, ApJ

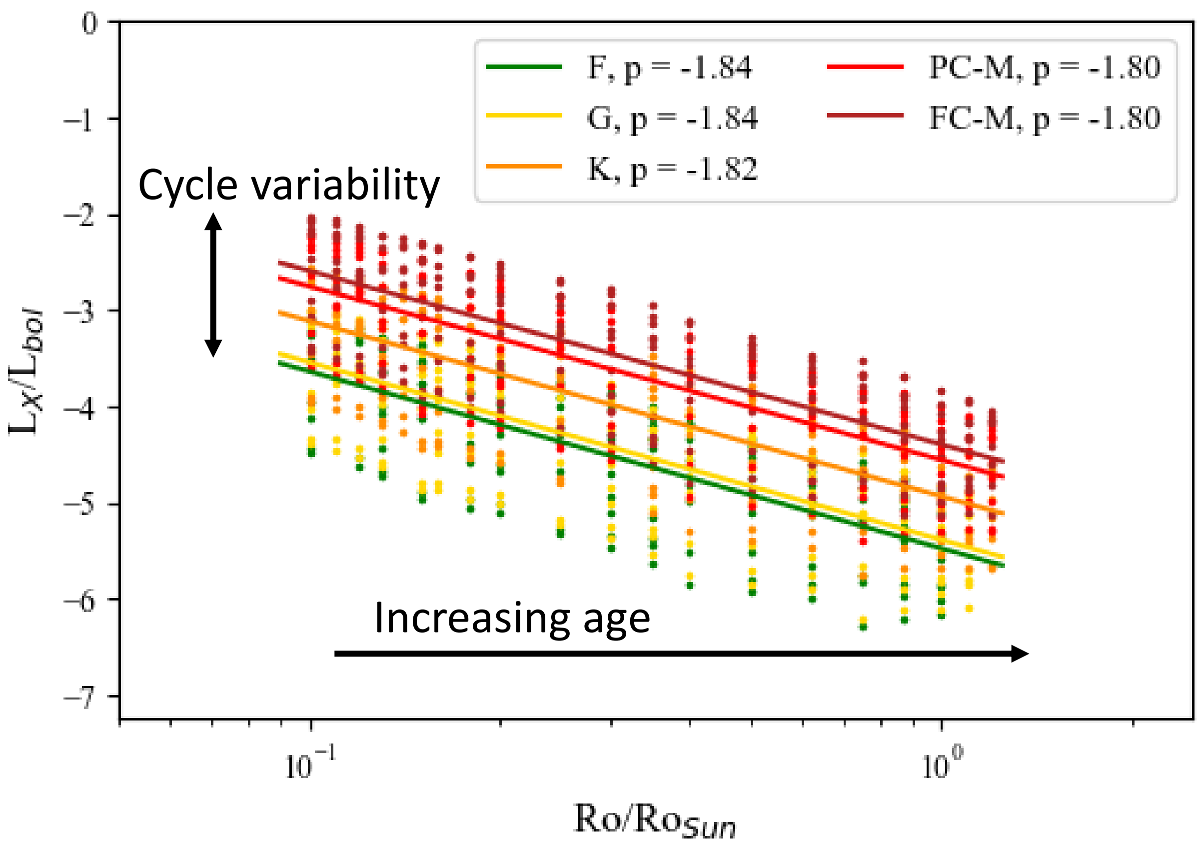
Comparison between orbits of Mercury and Ross 128 b



Stellar X-ray Activity

Estimating X-ray Emission

- Application of solar scaling relation between magnetic flux and X-ray emission (Pevstov et al. 2003):
  - $L_X \propto \Phi^{2.02}$
- Yale-Potsdam Stellar Isochrone (YaPSI, Spada et al.) models track evolution of R_*, L_{bol}, τ_c over time
- Validation against populations of cool stars
  - Both partially- and fully-convective cool stars captured



Modeled fractional X-ray luminosity vs. Rossby number for modeled stellar photospheric distributions
Fig. 4 from Farrish et al. 2021, ApJ

Comparison of scaled X-ray emission from modeled stellar photospheric distributions to observed stars
Fig. 3 from Farrish et al. 2021, ApJ

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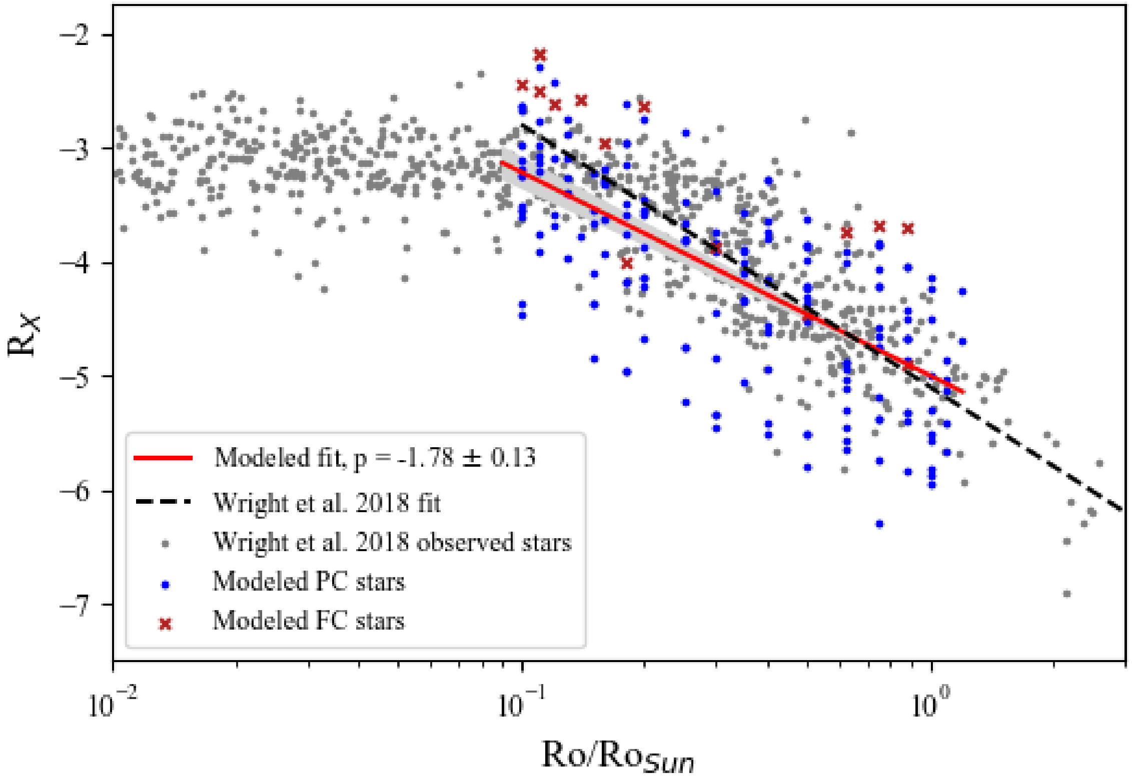

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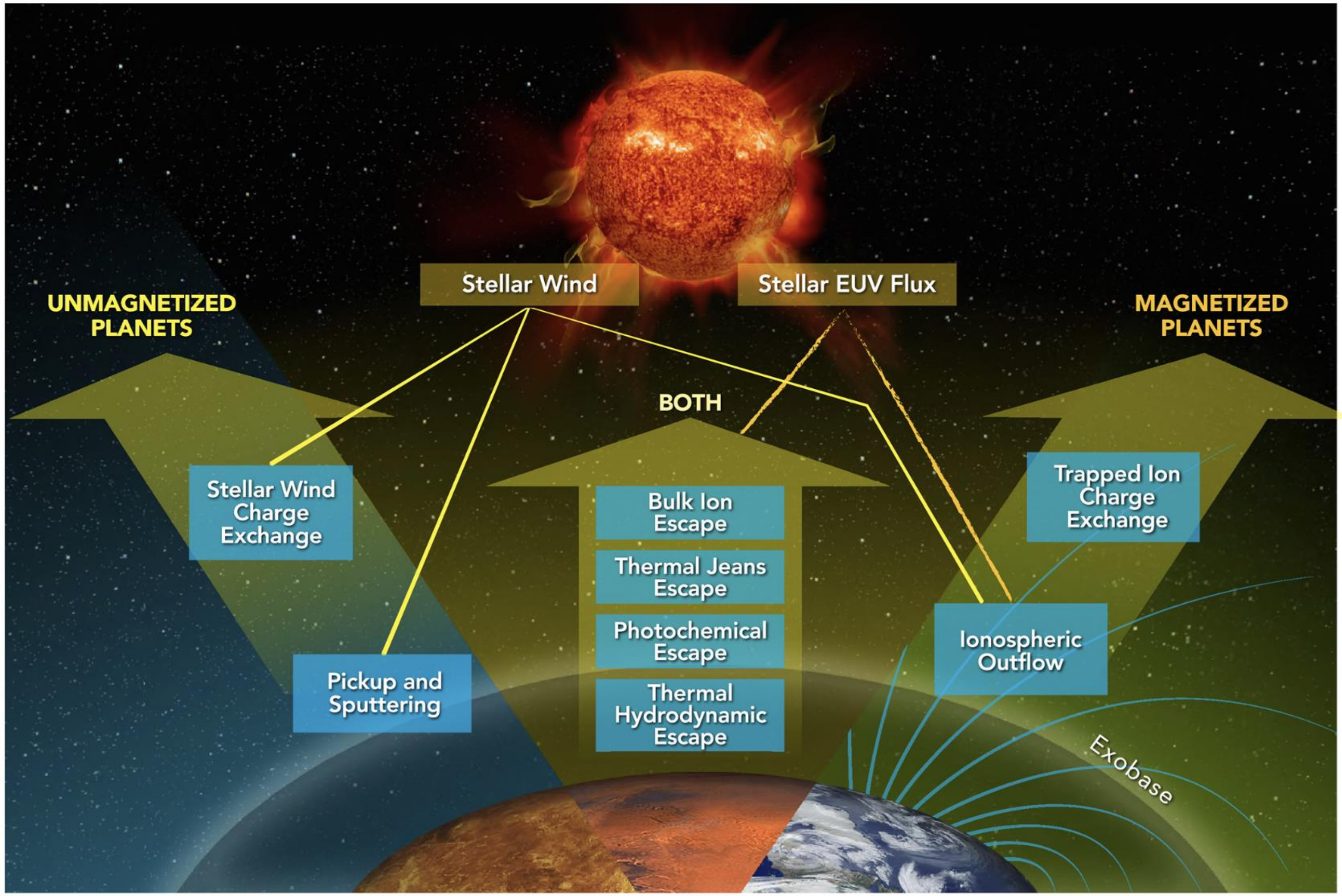
Coronal EUV Emission

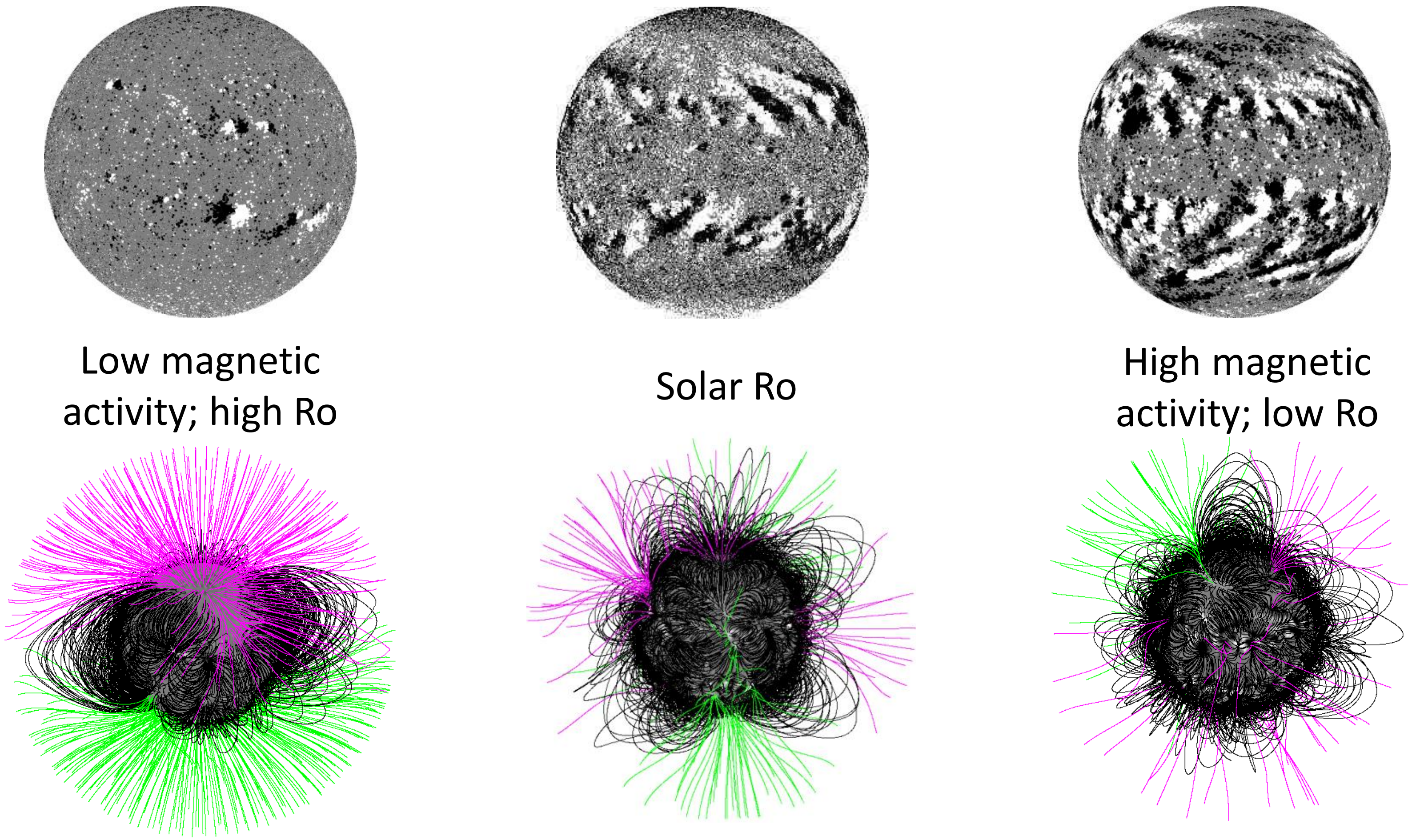
EUV & Atmospheric Loss

- Stellar EUV flux is key driver of escape processes
- EUV emission is difficult to observe for other stars – extinction by ISM
  - Modeling can fill gaps in our understanding
- EUV dependence on stellar magnetic structure and strength is less constrained than X-ray
  - Treat emission via 3-D coronal heating model



Gronoff et al. 2020, JGR

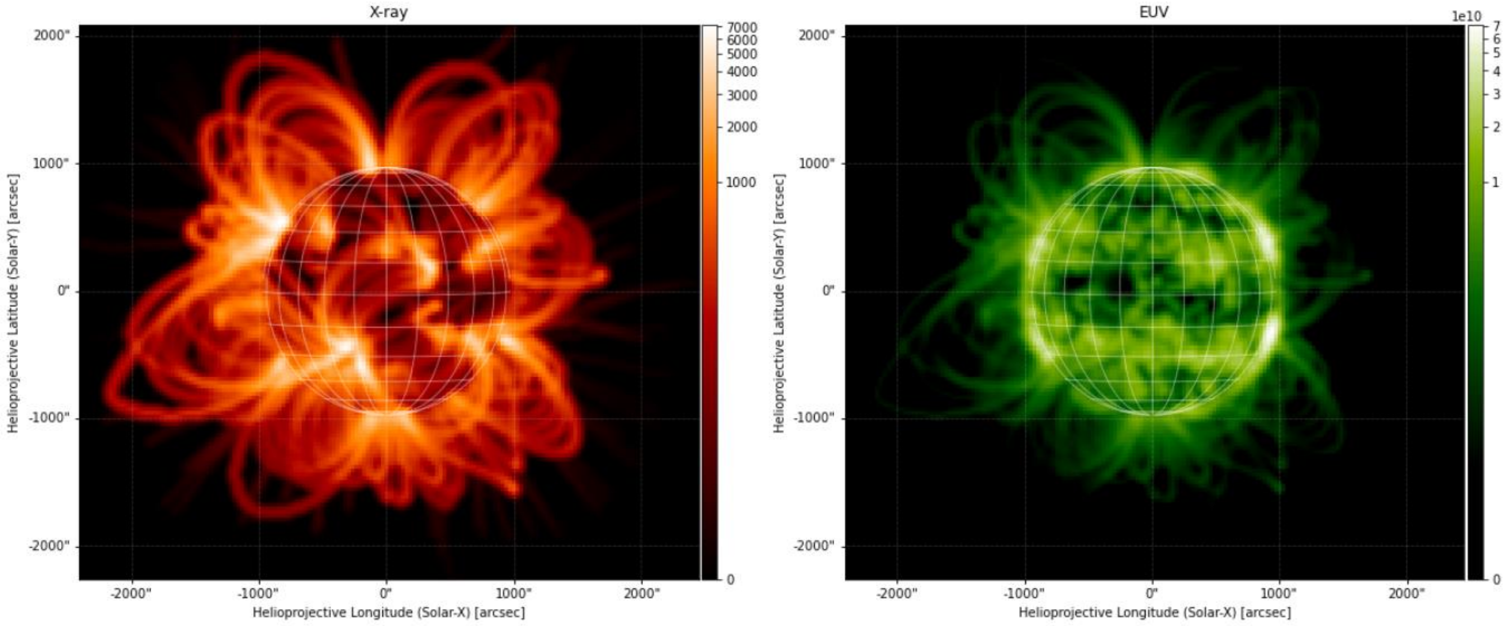
Coronal Field Extrapolation



- Potential Field Source Surface (PFSS) model for 3D coronal field extrapolation
  - Incorporates "source surface" at which field lines become radial

X-ray and EUV Modeling

- **synthesizAR**: Modular pipeline for coronal emission modeling from input magnetogram
  - Extrapolate 3D magnetic field
  - Choice of heating and plasma distribution
  - Synthesis of emission based on choice of ions/transitions from CHIANTI
  - Display emission based on detector bandpass and geometry (e.g. AIA)



Solar maximum phase
broadband X-ray (red, 1-100 Å) and
broadband EUV (green, 100-1000 Å)

Barnes et al. 2019, 2021

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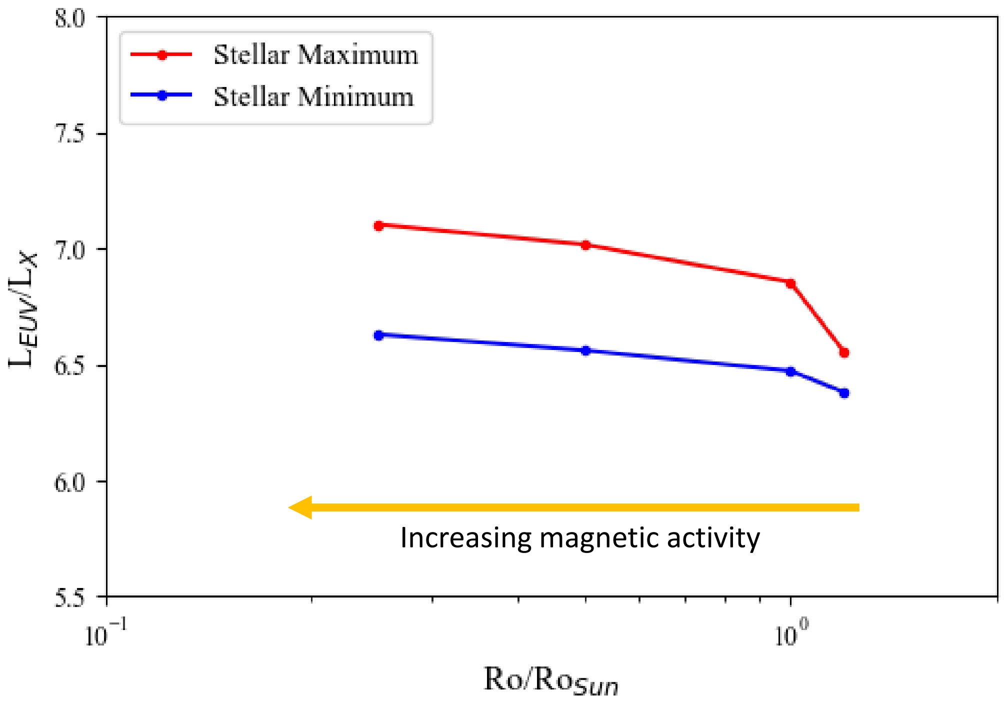

EUV over X-ray luminosity vs. Ro

Barnes et al. 2019, 2021

Conclusions

- Modeling stellar photospheric magnetic fields
  - Variation on activity cycle timescales, over main sequence lifetimes
  - Origin of space weather and asterospheric fields

- Constraining stellar coronal X-ray and EUV emission
  - Important drivers of atmospheric escape processes

- Intersection of heliophysics, astrophysics, and planetary science

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