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
Solar Magnetic Field Modeling
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.

Flux emerges

Concentrations migrate according to differential & meridional flows

Flux concentrations fragment

Concentrations collide and cancel, flux disperses

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:

\[ Ro = \frac{P_{rot}}{\tau_c} \]

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

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

\[ P_{cyc} \propto P_{rot}^{1 \pm 0.25} \]

\[ v_{me} \propto P_{cyc}^{-\left(10/9\right)} \]

\( \phi \) 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

\[ \frac{R_A}{R_{A,\text{solarmax}}} = \left( \frac{\phi_*}{\phi_{\text{solarmax}}} \right)^{-0.16 \pm 0.13} \]

- 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

Mercury
Average orbital distance - 58 million km (0.387 AU)
Orbital period - roughly 88 Earth days

Ross 128 b
Average orbital distance - 7.4 million km (0.0493 AU)
Orbital period - 9.9 Earth days

Ross 128
Distance - 11 light years
Location - Constellation Virgo
Mass - 0.15 solar masses
Radius - 0.21 solar radii
Luminosity - 0.00036 solar luminosity
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 \( R^*, L_{bol}, \tau_c \) 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 for cool stars.
Fig. 3 from Farrish et al. 2021, ApJ

Fig. 4 from Farrish et al. 2021, ApJ
Estimating X-ray Emission

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Comparison of scaled X-ray emission from modeled stellar photospheric distributions to observed stars
Fig. 4 from Farrish et al. 2021, ApJ
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)

Barnes et al. 2019, 2021

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

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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 astrospheric 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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