Tightening the Spin-Orbit Angle Demographics of Hot Jupiters

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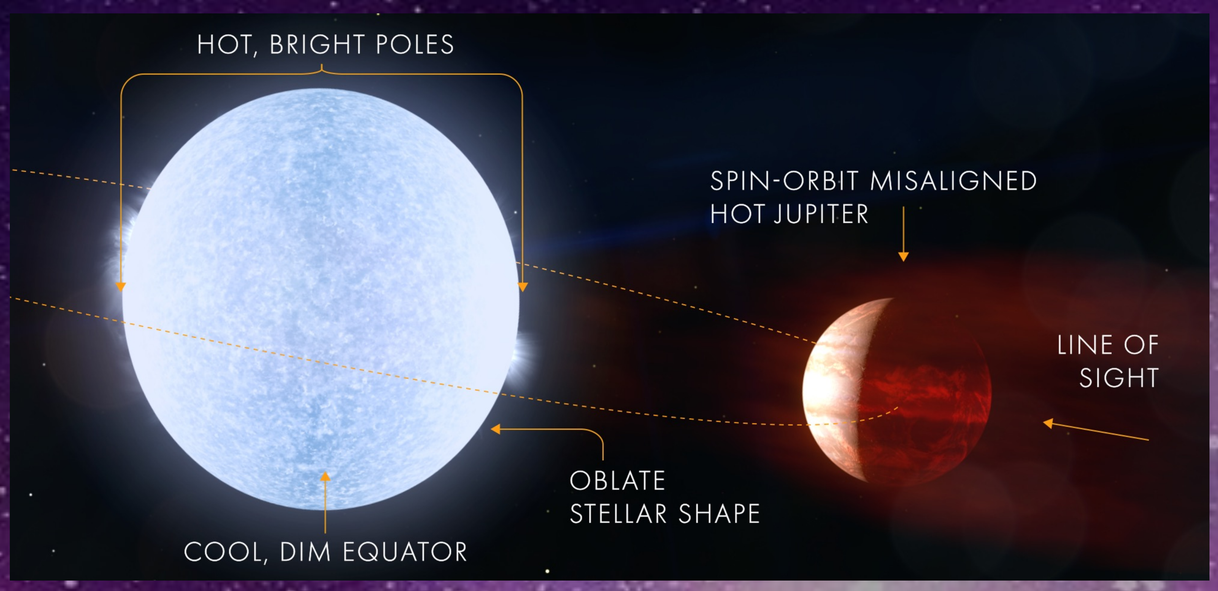
The angle between the stellar spin angular momentum and the planetary orbital angular momentum --- spin-orbit angle --- is one of the key parameters in understanding a planetary system's architecture and formation history. Traditionally, only a projected (or line of sight) version of this angle can be feasibly measured. A planet's true 3-D spin-orbit angle is more difficult to constrain; as such, only a handful of true spin-orbit angles have been determined to date. Our current research will significantly expand spin-orbit angle demographics by measuring true spin-orbit angles of hot Jupiters orbiting A/F-type stars observed by TESS, where spin-orbit misalignment is most common. We are measuring true spin-orbit angles using the gravity-darkening transit analysis technique, which applies specifically to high-mass, rapidly-rotating stars. With precision photometry from TESS, we have for the first time the opportunity to obtain true spin-orbit angles en masse in a straightforward and cost-effective way. Our team's proposed research will improve accessibility to studying planets transiting A/F stars, a subset that encompasses up to 40% of expected TESS planet discoveries. We will also measure valuable and difficult-to-obtain stellar parameters such as oblateness and effective temperature gradient, which will be necessary for future atmospheric studies of the selected planets.

Background: A/F Stars and Spin-Orbit Misalignment

CLICK HERE to watch a two-minute video summary of this project

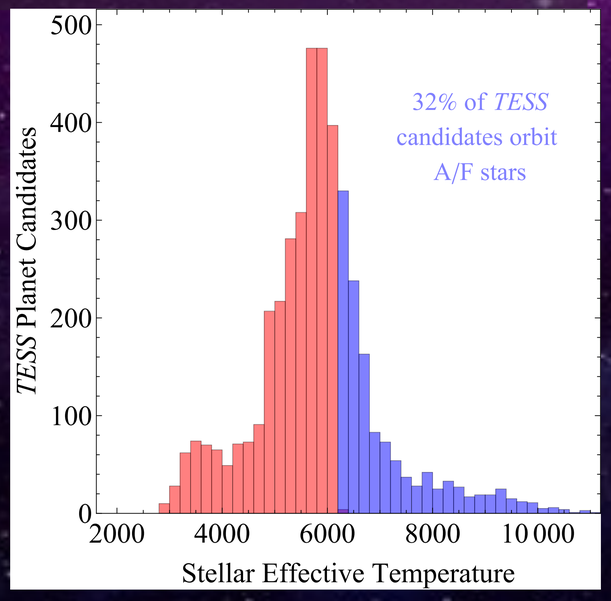


A/F stars rapidly rotate:
- Causes pole-to-equator luminosity gradient on stellar surface[1]
- Can make the star's effective temperature up to 2000 K cooler at the equator than at the poles[2]
- Causes the star to flatten into oblate shape[2]

Spin-Orbit Misalignment:
- The angle between a planet's orbit and its host star's rotation axis
- Caused by dynamic behavior during a system's formation or evolution[3]
- Occurs most commonly around A/F stars[3]

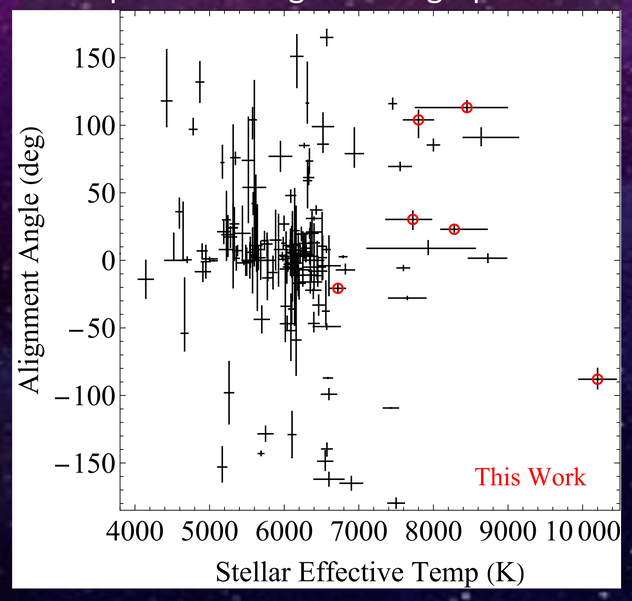
Motivation

TESS Planet Candidates



- 32% of current *TESS* candidates orbit A/F stars[4]
- Many of these planets likely orbit in spin-orbit misaligned configurations
- Most A/F host stars are rapid rotators, which need to be accounted for in photometric analyses

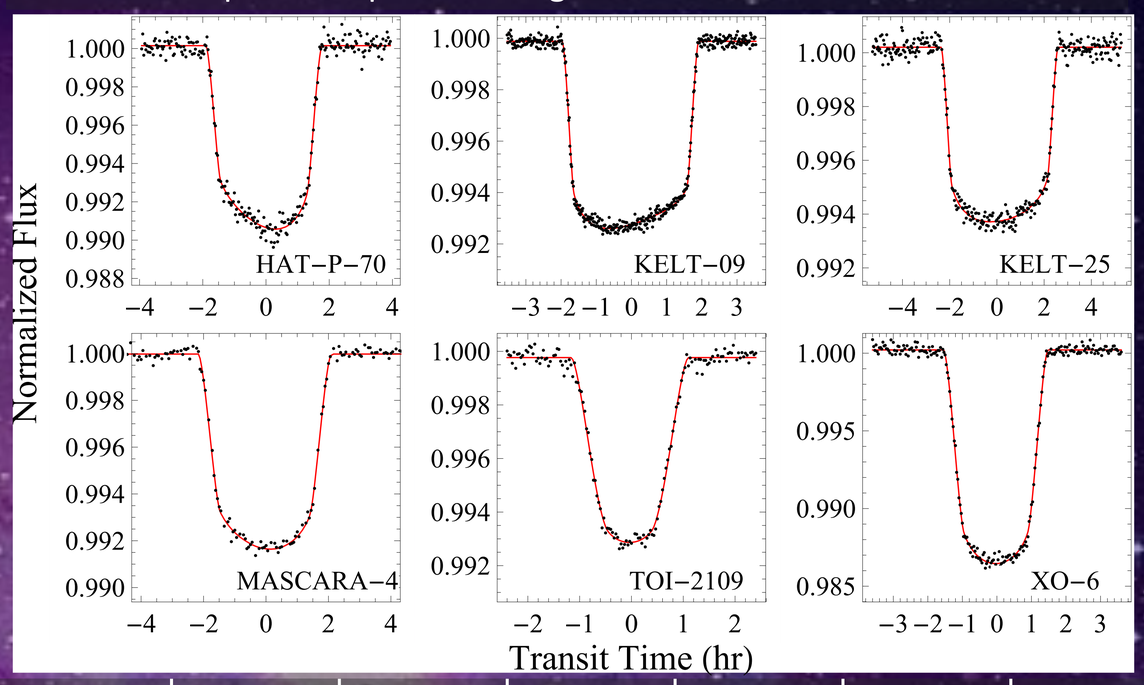
Spin-Orbit Angle Demographics



- 78% of planets around G/K/M stars are aligned with their host star
- 44% of planets around A/F stars are aligned with their host star
- A spin-orbit dichotomy appears to occur at ~6700 K, but demographics around A/F stars are currently weak.

Current Results

Stellar gravity darkening causes transit asymmetry, which we use to measure the planet's spin-orbit angle.

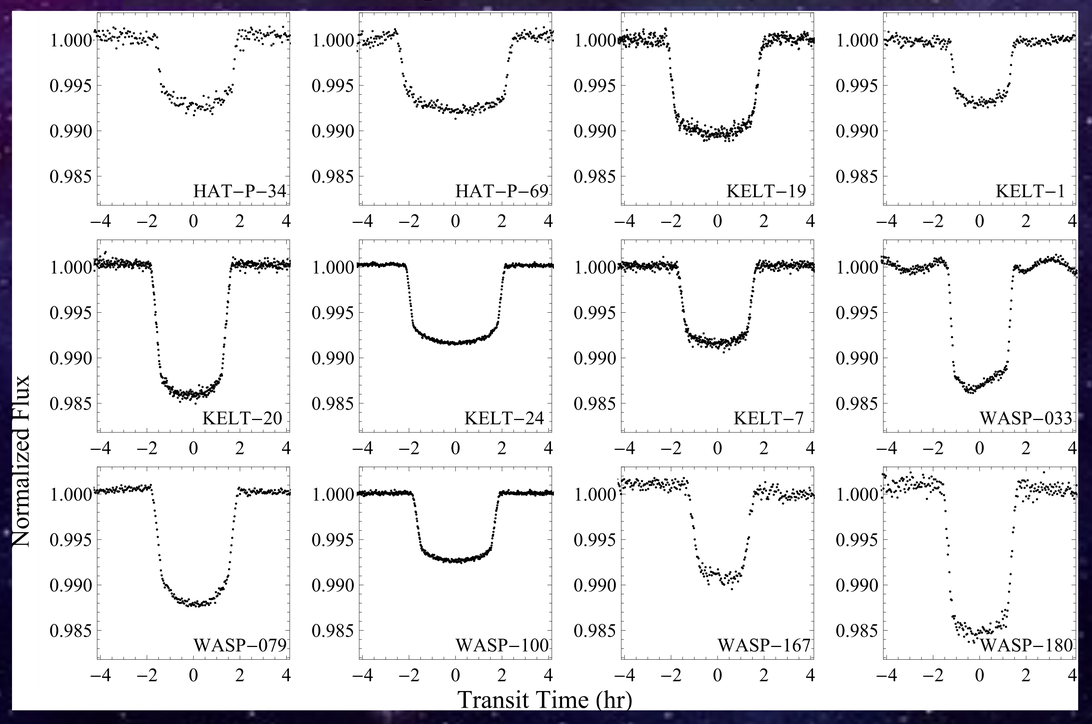


Planet	HAT-P-70	KELT-9[5]	KELT-25	MASCARA-4[6]	TOI-2109	XO-6
Spin-orbit angle	$97^\circ \pm 12^\circ$	$87^\circ \pm 11^\circ$	$36^\circ \pm 19^\circ$	$104^\circ \pm 13^\circ$	$2^\circ \pm 20^\circ$	$-21^\circ \pm 20^\circ$

KELT-9 and MASCARA-4 results currently published. Other results to be published in upcoming paper.

Future Work

Future targets selected for analysis:



- Current findings support that spin-orbit misalignment occurs frequently around high-mass stars.
- 12 more *TESS* targets currently selected, with ~20 more expected targets in the future.
- With strong spin-orbit demographics around high-mass stars, we can explore what mechanisms cause misalignment to occur and investigate why misalignment happens most often around A/F stars.

1. Von Zeipel, H. "The radiative equilibrium of a slightly oblate rotating star." *Monthly Notices of the Royal Astronomical Society* 84 (1924): 684-701.
2. Monnier, John D., et al. "Imaging the surface of Altair." *Science* 317.5836 (2007): 342-345.
3. Albrecht, Simon H., et al. "A Preponderance of Perpendicular Planets." *arXiv preprint arXiv:2105.09327* (2021).
4. Data from the exoplanet archive
5. Ahlers, John P., et al. "KELT-9 b's Asymmetric TESS Transit Caused by Rapid Stellar Rotation and Spin–Orbit Misalignment." *The Astronomical Journal* 160.1 (2020): 4.
6. Ahlers, John P., et al. "Gravity-darkening analysis of the misaligned hot Jupiter MASCARA-4 b." *The Astrophysical Journal* 888.2 (2020): 63.