Orbital Architectures of Triple-star Systems that Host Transiting Planets

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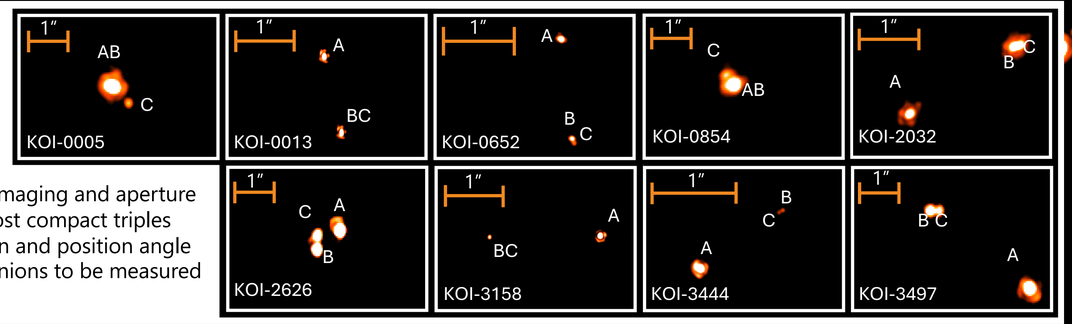
Abstract

Multiple star systems provide unique opportunities to study the environments in which planets would have formed. This is under the conservative assumption that planets form after stars, and therefore the stellar orbits that sculpted the protoplanetary environment are the same orbits observed today. We present an analysis of a novel sample of triple-star systems that host Kepler planets. Using long-term Keck adaptive optics monitoring, we have measured astrometric orbit arcs in 21 triple systems, including 12 newly identified triples from a homogeneous analysis of our Keck data and Gaia astrometry. While previous work has largely focused on planet-hosting binaries that have two orbital planes to consider (planetary and stellar), triples have an additional stellar orbital plane. We examine the alignment within the nine most compact systems (separations ~ 5–500 au), testing if either (or both) of the stellar orbits align with the edge-on orbits of their transiting planets. Our first-ever statistical sample of orbits in triple systems that harbour planets demonstrates, intriguingly, that the observed trend of stellar-planetary orbit-orbit alignment in binaries does not appear to extend to higher-order stellar systems.

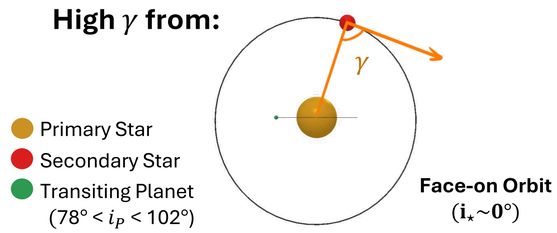
The Compact Sample



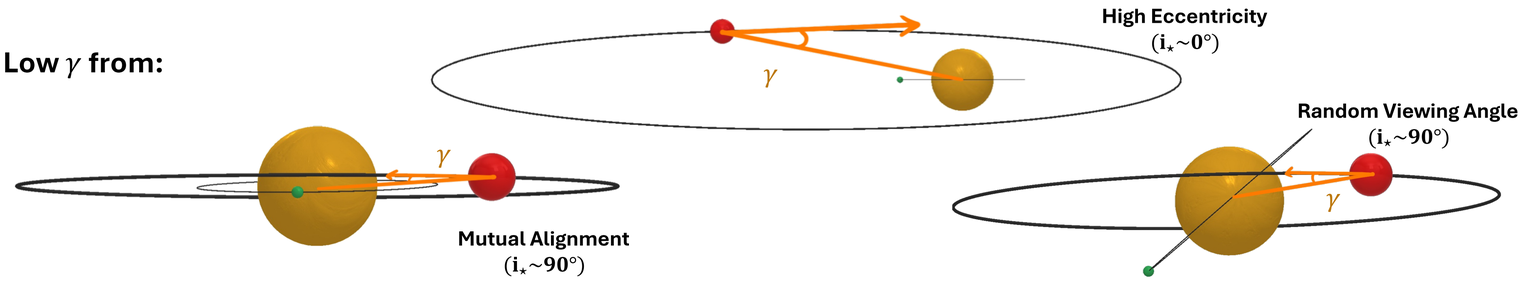
Multiple epochs of imaging and aperture masking of the 9 most compact triples allows the separation and position angle of the stellar companions to be measured over time.

1. Testing Alignment

High γ from:

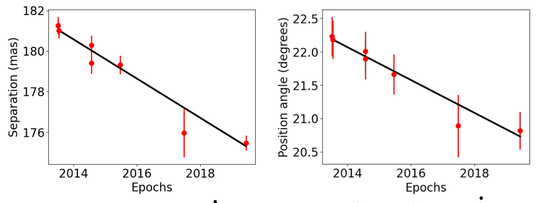


Low γ from:



2. Calculating γ

1) Linear fits to orbit arcs:



2) Proper motion:

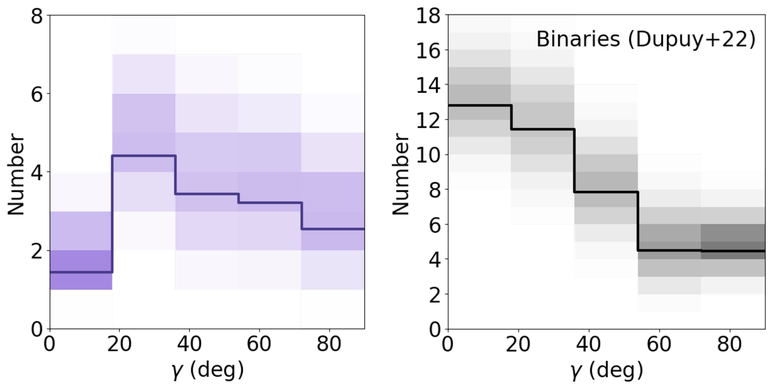
$$\rho = \rho_0 + \dot{\rho}t \qquad \theta = \theta_0 + \dot{\theta}t$$

3) Gamma:

$$\gamma = \tan^{-1}(\dot{\theta}/\dot{\rho})$$

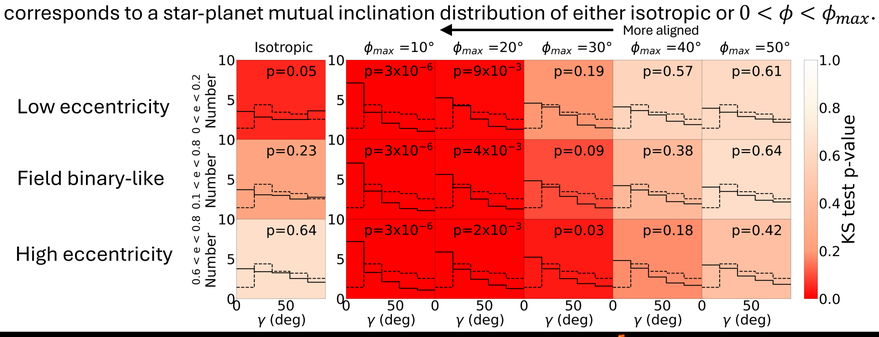
3. Comparing to binaries

The histogram for the γ values (*left*) shows the average over 10^4 Monte-Carlo trials with the shading corresponding to the fraction of trials resulting in that value for each bin. Dupuy (2022) looked at 45 binaries (*right*) and found an overabundance of low γ values consistent with a majority of edge-on orbits, which is not seen in the triples.

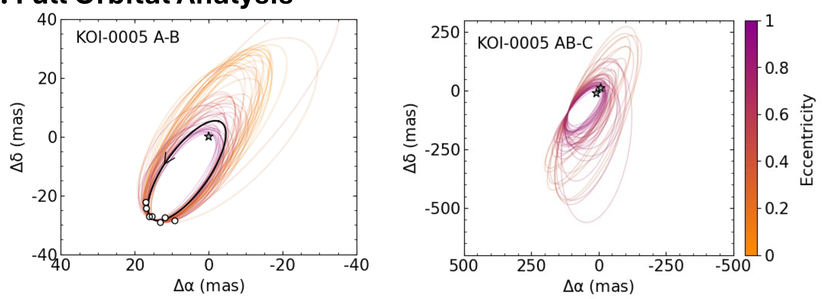


4. Comparing to simulated distributions

Simulating synthetic orbits allows the γ distribution of the triples (*dashed)* to be compared to expected distributions of random orbits *(solid)*. The colour of each test corresponds to the p-value of a K-S test. Each row is a uniform eccentricity distribution, and each column corresponds to a star-planet mutual inclination distribution of either isotropic or $0 < \phi < \phi_{max}$.



5. Full Orbital Analysis



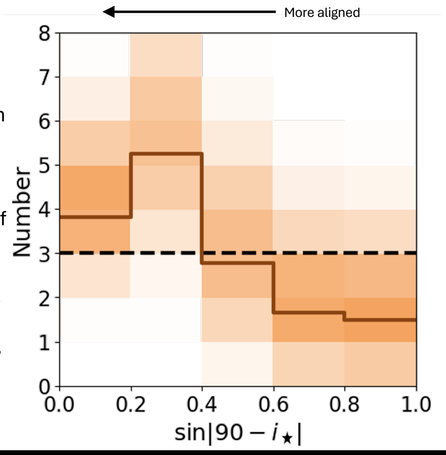
Astrometry and proper motion allows the orbital characterisation of the inner binary (*left*, using ORVARA) and the outer companion relative to the barycentre (*right,* using LOFTI_GAIA), which provides better inclination constraints as it incorporates stellar mass information.

6. Mutual Inclination

$$\cos i_{\star-P} = \cos i_\star \cos i_P + \sin i_\star \sin i_P \cos(\Omega_\star - \Omega_P) \quad (1)$$

$$\cos i_{\star-P} = \sin(90 - i_\star) \cos(\Omega_\star - \Omega_P) \quad (2)$$

Equation 1 describes the mutual inclination between two orbital planes (stellar and planetary). Transiting planets have an inclination of i_P~90°, simplifying the equation. As the longitude of the ascending node (Ω) for the planet is unknown, $90 - i_\star$ can be used as a measure of the minimum misalignment. For a random distribution of orbits, a flat $\sin(90 - i_\star)$ distribution is expected, however the resulting histogram (*right)* shows a surplus of low values, implying there is some star-planet alignment in these systems.



7. Conclusions and Future work

The observed distribution of γ for the triples is unlikely to be produced from random orbits with an isotropic viewing angle. Like the binaries, this means that the planets are likely to be influenced by more than one of the stars in the system. With such a small sample, we are unable to say with any statistical certainty whether triple systems are more likely to be aligned (as was the case with the binaries) or misaligned, from the γ angle alone. Full orbital analysis does however show that there is an overabundance of systems with a low mutual inclination between the stellar and planetary orbit. Future work will look at an increased sample size of ~100 binaries which should give a better comparison between the two demographics.

References: Metchev S. A. & Hillenbrand L. A., 2004, ApJ, 617, 1330 Kraus, A. L. et al., 2016, AJ, 152, 8 Cuntz, M. et al., 2022, ApJS, 263, 33 Pearce L. A. et al., 2020, ApJ, 894, 115 Brandt T. D., et al., 2021c, AJ, 162, 186 Dupuy T. J et al.,2022, MNRAS, 512, 648 Christian et al, 2022, AJ, 163, 207