Spin-orbit alignment of exoplanet systems: ensemble analysis using asteroseismology

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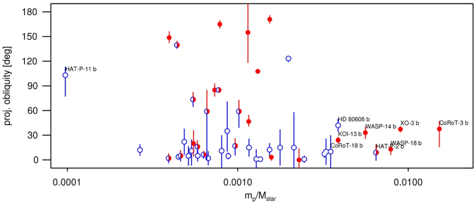
Rationale

Obliquities of hot-Jupiter systems:

- Measured in over 50 systems
- Mostly based on Rossiter–McLaughlin (RM) effect
- Influence of tides
  - Strong tides ⇒ Low obliquities
  - Weak tides ⇒ Broad obliquity range

Need to consider systems with smaller planets, longer-period planets, and multiple planets!

Obliquities vs. planet-to-star mass ratio

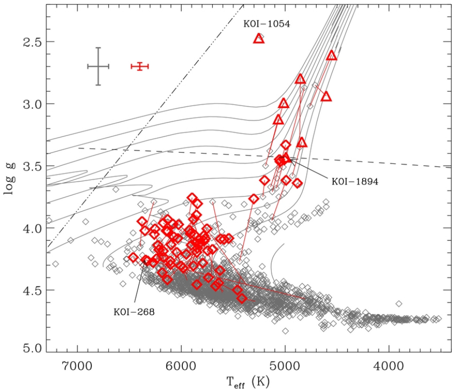


Albrecht et al. (2012)

Asteroseismology of *Kepler* exoplanet-host stars

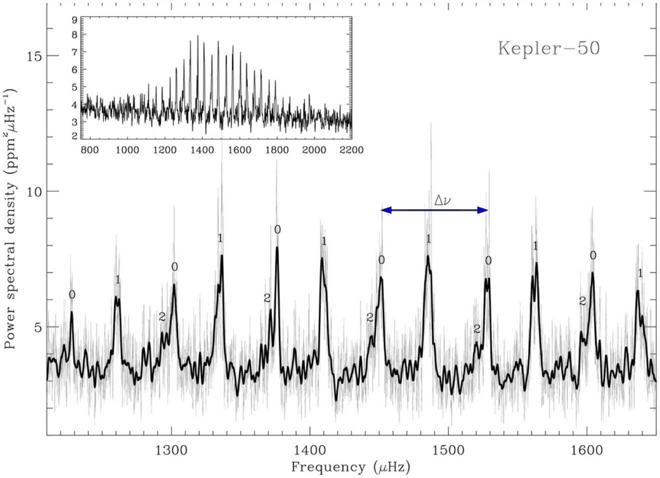
- Solar-like oscillations excited by turbulent convection
- Cool-star asteroseismology with *Kepler*:
  - Several hundred dwarfs
  - Over ten thousand red giants
- ~100 KOIs with detected oscillations
- 1.2 % precision in radius, 3.3 % in mass, and 14 % in age (Silva Aguirre et al. 2015)

KOIs with asteroseismic detections



Huber et al. (2013)

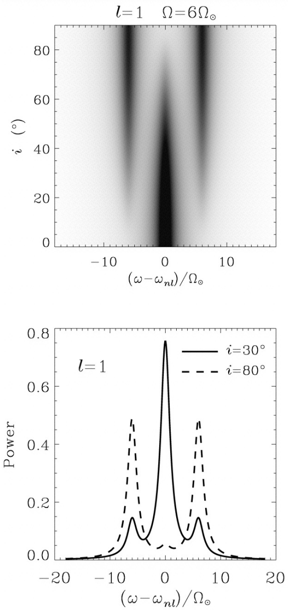
Power spectrum of solar-like oscillations



Chaplin et al. (2013)

Stellar inclination angle from asteroseismology

- Non-radial modes are split by rotation
- Relative visibility of split components depends on stellar inclination

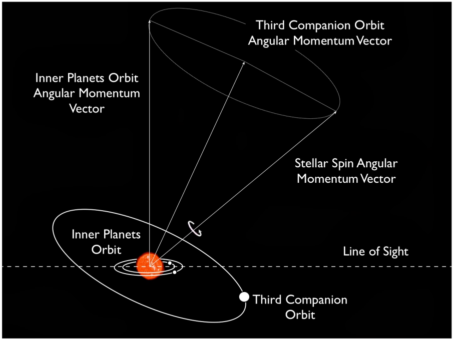


Gizon & Solanki (2003)

Previous applications of the asteroseismic technique

- Few hosts with single, non-transiting large planets (e.g., Gizon et al. 2013)
- Several *Kepler* Sun-like hosts (e.g., Benomar et al. 2014; Lund et al. 2014)
- Kepler-56: a misaligned multi-transiting system (Huber et al. 2013)

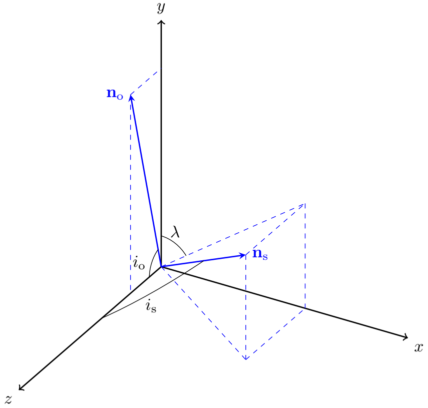
Kepler-56



Spin-orbit geometry

- For a transiting planet:
  - i_o from transit photometry
  - λ from RM effect
- i_s from asteroseismology or $\{R_s, P_{rot}, v \sin i_s\}$
- Only the spin-orbit angle ψ has intrinsic physical significance

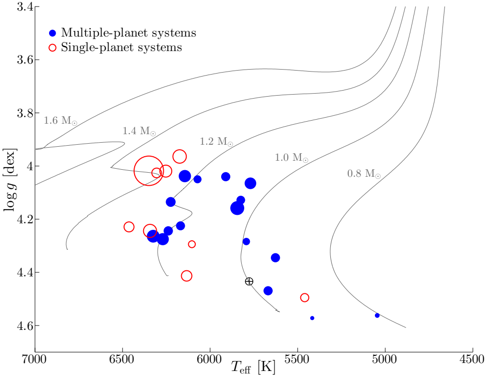
Observer-oriented coordinate system



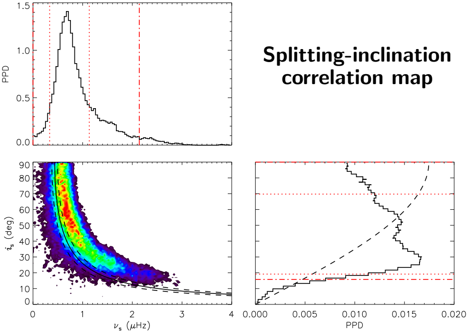
Asteroseismic analysis: sample characterization

- 25 solar-type KOIs
- Mostly main-sequence stars (a few subgiants)
- Late F to early K
- 14 multi- and 11 single-transiting systems
- Prevalence of systems with small and long-period planets

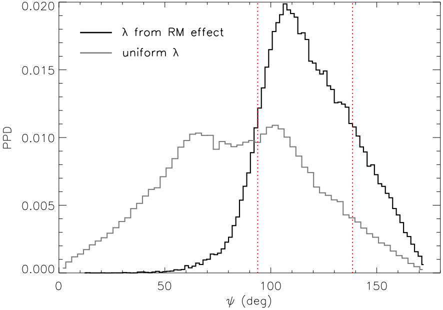
Asteroseismic sample



Asteroseismic analysis: the case of HAT-P-7

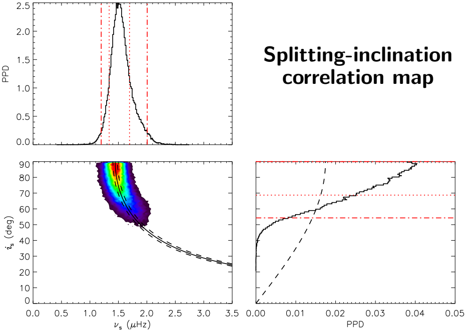


Posterior of spin-orbit angle ψ

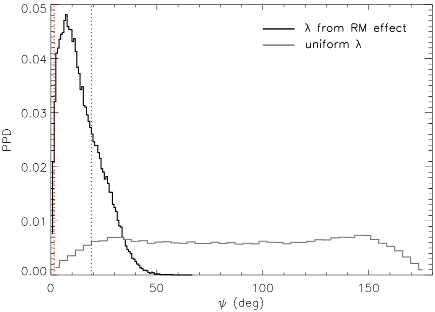


Asteroseismic analysis: the case of Kepler-25

Splitting-inclination correlation map

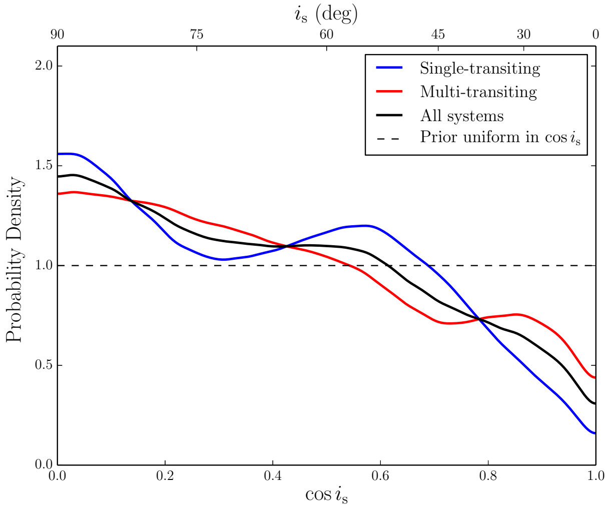


Posterior of spin-orbit angle ψ



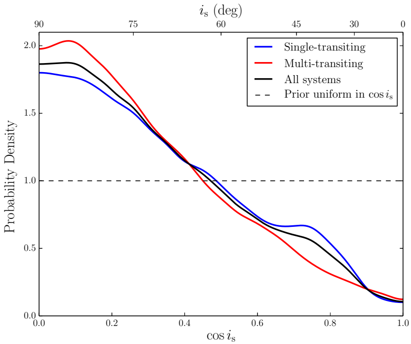
Asteroseismic analysis: statistical constraints

Average posterior of $\cos i_s$

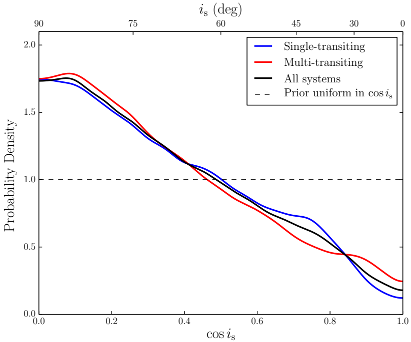


Extending the sample

Morton & Winn (2014)



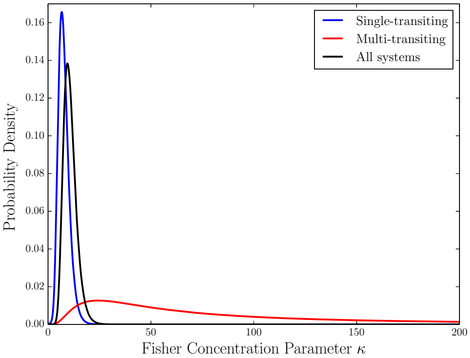
Morton & Winn + Asteroseismic sample (totaling 87 systems)



Combined sample: statistical constraints

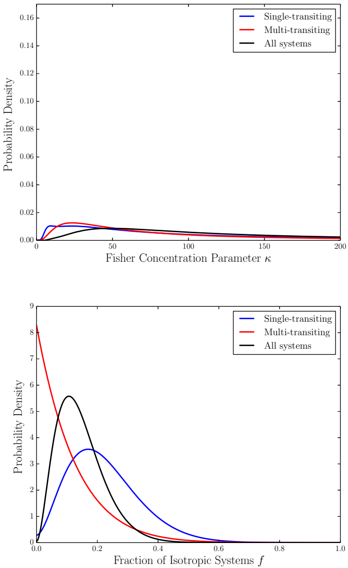
- True distribution of spin-orbit angle ψ?
- Hierarchical Bayesian analysis (Hogg et al. 2010)
- Model distribution function of ψ as Fisher
  - Small $\kappa \Rightarrow$ broad distribution
  - Large $\kappa \Rightarrow$ low obliquities
- Consistent with Morton & Winn

Single-Fisher model



Combined sample: statistical constraints

Mixture model



- Mixture model (isotropic + Fisher)
- f represents fraction of isotropic systems
- Obliquity distribution of single-transiting systems may be multimodal: two distinct migration channels?

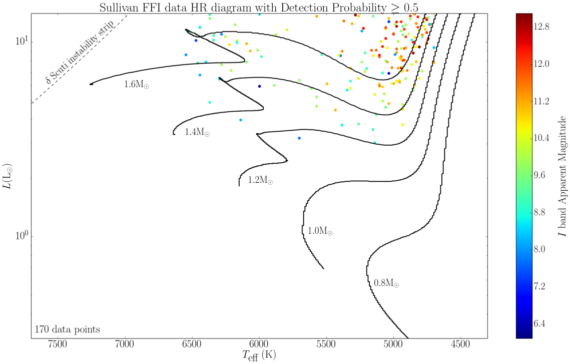
Implications

- Kepler-56 (Huber et al. 2013) remains as the only unambiguous misaligned multiple-planet system
- Ensemble analysis suggests correlation between directions of stellar spin and planetary orbital axes
- Our analysis favors migration mechanisms capable of exciting large obliquities in explaining hot-Jupiter formation
- No significant difference between posteriors of single- and multi-transiting systems based on asteroseismic sample

Outlook

- Obliquities of systems with evolved hosts with *TESS*?
- *PLATO* will extend these measurements to bright solar-type hosts in wide fields

Predicted *TESS* asteroseismic yield for exoplanet hosts (full-frame images)



Acknowledgments

M. N. Lund[2,1], J. S. Kuszlewicz[1,2], G. R. Davies[1,2], W. J. Chaplin[1,2], S. Albrecht[2], J. N. Winn[3,4], T. R. Bedding[5,2], O. Benomar[6], D. Bossini[1,2], R. Handberg[2,1], A. R. G. Santos[7,1], V. Van Eylen[2,4], S. Basu[8], J. Christensen-Dalsgaard[2], Y. P. Elsworth[1,2], S. Hekker[9,2], D. Huber[5,10], C. Karoff[11,2], H. Kjeldsen[2], M. S. Lundkvist[2], T. S. H. North[1,2], V. Silva Aguirre[2], D. Stello[5,2], T. R. White[12]