Spin-orbit angles as a probe to orbital evolution

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Motivation	How did hot Jupiters migrate in?
Observable	The spin-orbit angle
Method	Observe the **Rossiter-McLaughlin** effect
Targets	40 out of the 75 planets discovered by WASP in the southern hemisphere
Instrument	HARPS, on the ESO-3.6m telescope

Results Our observations reveal a wide distribution in orbital angle indicative of **past dynamical interactions**. Our data also demonstrate the important effects that **tidal interactions** have in altering the spin-orbit angle distribution.

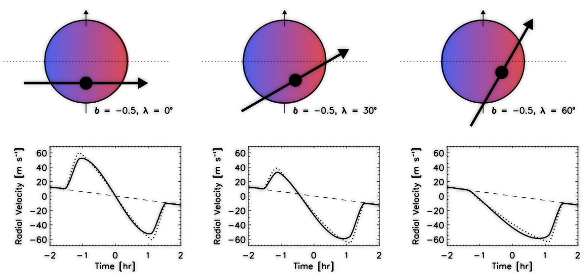

Fig 1: from Gaudi & Winn 2007, illustrating the Rossiter-McLaughlin effect. This effect occurs when a planet transits a rotating star. It produces an anomaly in the Doppler signal of the star, caused by the planet.
The spin-orbit angle can be called λ or β depending on authors.

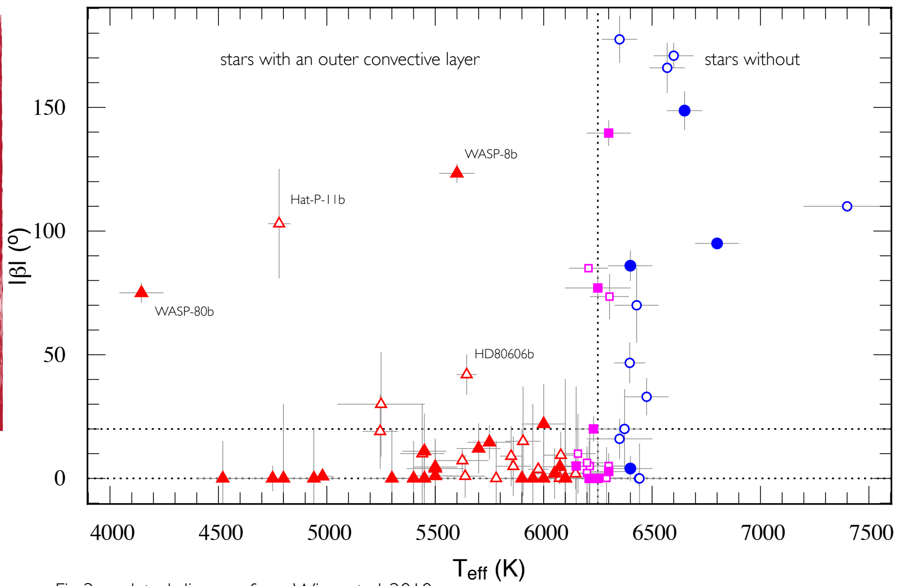

Fig 2: updated diagram from Winn et al. 2010.

Spin-orbit angle, β, as a function of the stellar T_{eff}.
red: objects< 6150K, blue: > 6350K; magenta: between the two. **Filled symbols**: observations using the **HARPS** spectrograph. Empty symbols: results from other groups.

The variety of angles indicate the presence of a process leading some planets onto highly inclined orbits. The fraction of aligned to misaligned objects is greater when they orbit stars having a massive outer convective layer (in red) corresponding to T_{eff} < 6250 K. Tides are dissipated more effectively when there is an outer convective layer (Zahn 1977).
Winn et al. 2010 have postulated that tides have changed the distribution in spin-orbit angles of planets orbiting stars < 6250K, but left the distribution intact for systems > 6250K. It is still unclear whether planets would realign or infall into the star, leaving only a mostly aligned population.

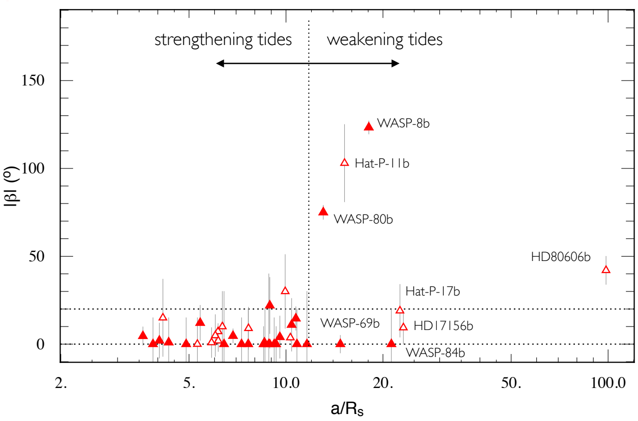

Fig 3: updated from Albrecht et al. (2012); spin-orbit angle as a function of $a/R_\star$

$a/R_\star$ is obtained directly from the transit geometry. It is also a parameter that determines the strength of tides, with the tidal timescale $\tau \propto (a/R_\star)^{-6}$. The larger $a/R_\star$ is, the weaker the tides.

Selecting only objects orbiting stars cooler than 6150 K (in red in Fig 2), we observe that **the weaker the tides the more likely misaligned orbits occur**. This indicates hot Jupiters may have been more frequently misaligned in the past. No such pattern is visible for the sample orbiting hotter stars as expected; tides are weakened due to the lack of an outer convective layer.

Recent addition: WASP-80b orbits a K7-M0 star and although the coldest in our sample, it is observed on an inclined, circular orbit just like hot Jupiters orbiting mid F stars (Triaud et al. 2013).

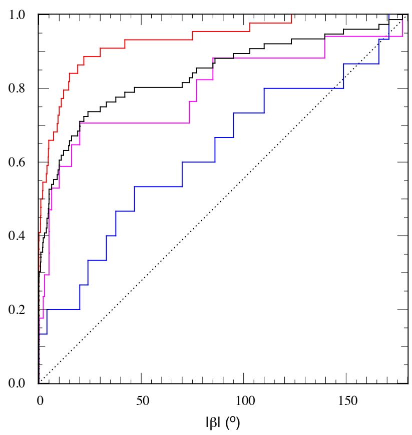

Fig 4: cumulative distributions of the sample in Fig 1. **Colours correspond to Fig 2.** Black is the full sample.

We clearly see how the spin-orbit distribution changes as a function of effective temperature. Objects orbiting stars hotter than 6350K produce a near isotropic distribution.

Some of those hot stars will cool to temperatures below 6150 K during their Main Sequence lifetime, thus crossing the T_{eff} boundary.

We therefore should expect an effect with the age of the system as tides will kick in when a convective layer will start to develop.

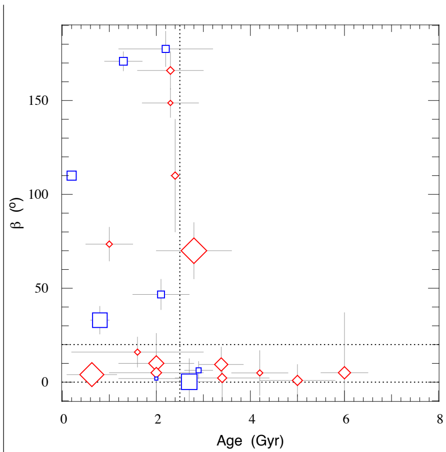

Fig 5: from Triaud 2011

This is a subset of objects orbiting stars > 1.2 M☉, for which ages can be determined more accurately. Blue squares are stars > 1.3 M☉.

There is weak evidence that the spin-orbit distribution changes with the age of the system. This is a further manifestation of tidal interactions.

Presumably **the distribution changes as an outer convective layer develops** while those stars evolve and cool down. Again there is no evidence that the planets survive or do not survive realignment, only that the distribution changes.