Measuring 34,030 Stellar Rotation Periods from Kepler Photometry With the AutoCorrelationFunction

Amy McQuillan, Tsevi Mazeh, Suzanne Aigrain

CoRoT 3 – KASC 7, July 2014

PROPOSAL FOR A PROJECT OF HIGH-PRECISION STELLAR RADIAL VELOCITY WORK

By Otto Struve

With the completion of the great radial-velocity programmes of the major observatories, the impression seems to have gained ground that the measurement of Doppler displacements in stellar spectra is less important at the present time than it was prior to the completion of R. E. Wilson's new radial-velocity catalogue.

I believe that this impression is incorrect, and I should like to support my contention by presenting a proposal for the solution of a characteristic astrophysical problem.

One of the burning questions of astronomy deals with the frequency of planet-like bodies in the galaxy which belong to stars other than the Sun. K. A. Strand's[1] discovery of a planet-like companion in the system of 61 Cygni, which was recently confirmed by A. N. Deitch[2] at Poulkovo, and similar results announced for other stars by P. Van de Kamp[3] and D. Reuyl and E. Holmberg[4] have stimulated interest in this problem. I have suggested elsewhere that the absence of rapid axial rotation in all normal solar-type stars (the only rapidly-rotating G and K stars are either W Ursae Majoris binaries or T Tauri nebular variables,[5] or they possess peculiar spectra[6]) suggests that these stars have somehow converted their angular momentum of axial rotation into angular momentum of orbital motions of planets. Hence, there may be many objects of planet-like character in the galaxy.

But how should we proceed to detect them? The method of direct

Otto Struve, 1952

200 *High-Precision Stellar Radial Velocity Work* No. 870

But there seems to be no compelling reason why the hypothetical stellar planets should not, in some instances, be much closer to their parent stars than is the case in the solar system. It would be of interest to test whether there are any such objects.

We know that *stellar* companions can exist at very small distances. It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit, or about 3,000,000 km. Its period around a star of solar mass would then be about 1 day.

Otto Struve, 1952

We can write Kepler's third law in the form $V^3 \sim \frac{1}{P}$. Since the orbital velocity of the Earth is 30 km/sec, our hypothetical planet would have a velocity of roughly 200 km/sec. If the mass of this planet were equal to that of Jupiter, it would cause the observed radial velocity of the parent star to oscillate with a range of $\pm$ 0·2 km/sec—a quantity that might be just detectable with the most powerful Coudé spectrographs in existence. A planet ten times the mass of Jupiter would be very easy to detect, since it would cause the observed radial velocity of the star to oscillate with $\pm$ 2 km/sec. This is correct only for those orbits whose inclinations are 90°. But even for more moderate inclinations it should be possible, without much difficulty, to discover planets of 10 times the mass of Jupiter by the Doppler effect.

There would, of course, also be eclipses. Assuming that the mean

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Mazeh, Peretz, McQuillan

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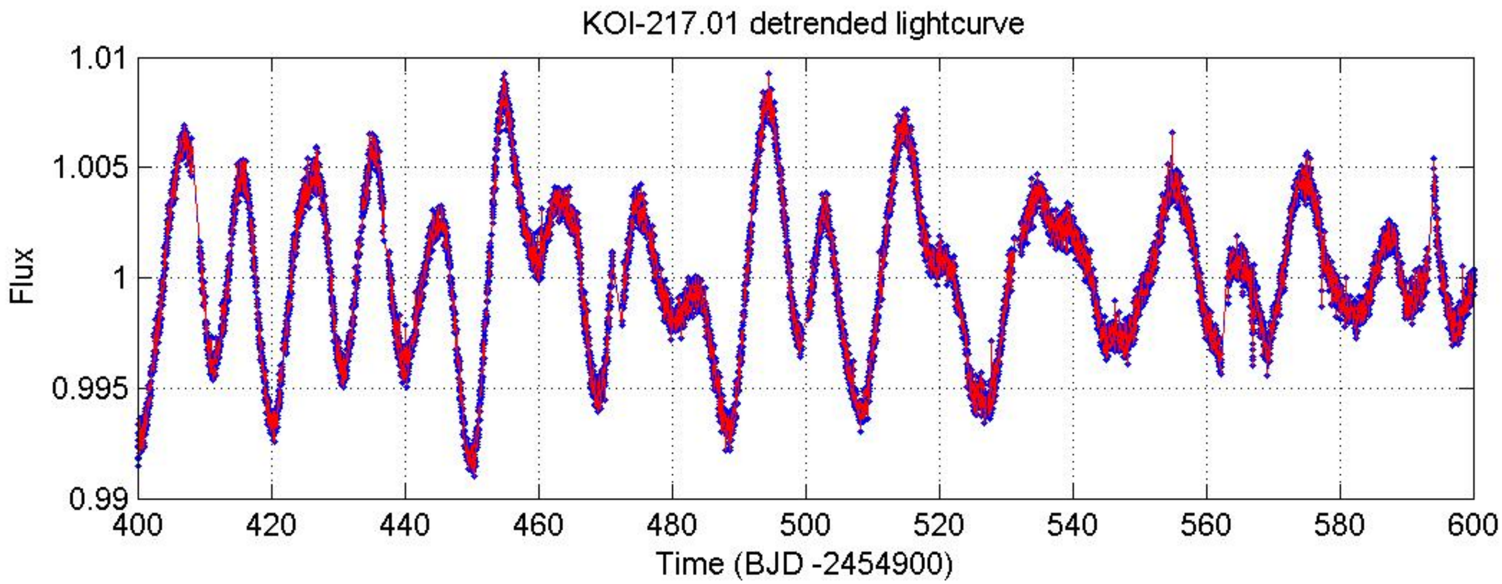
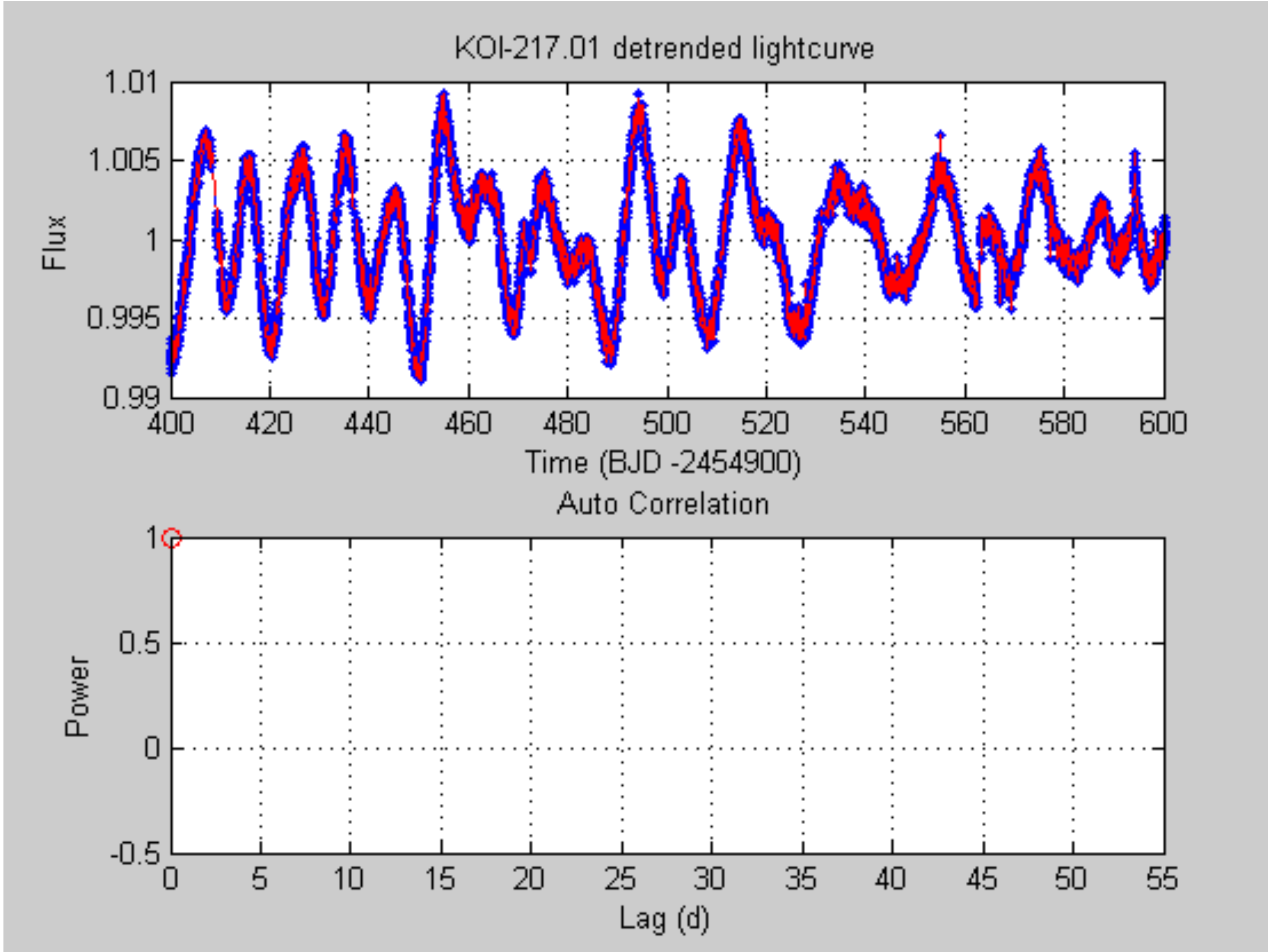
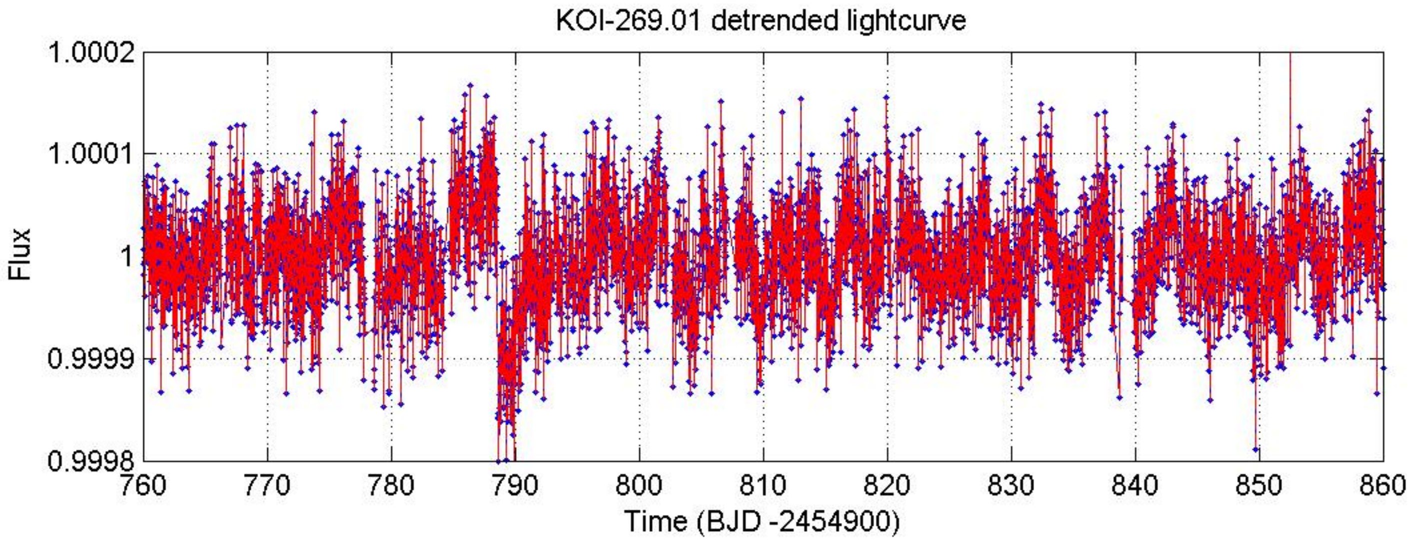


KOI-217.01 detrended lightcurve
Flux
Time (BJD -2454900)
1.01
1.005
1
0.995
0.99
400
420
440
460
480
500
520
540
560
580
600


KOI-217.01 detrended lightcurve
1.01
1.005
1
0.995
0.99
Flux
400
420
440
460
480
500
520
540
560
580
600
Time (BJD -2454900)
Auto Correlation
1
0.5
0
-0.5
Power
0
5
10
15
20
25
30
35
40
45
50
55
Lag (d)


KOI-269.01 detrended lightcurve
1.0002
1.0001
1
0.9999
0.9998
Flux
760
770
780
790
800
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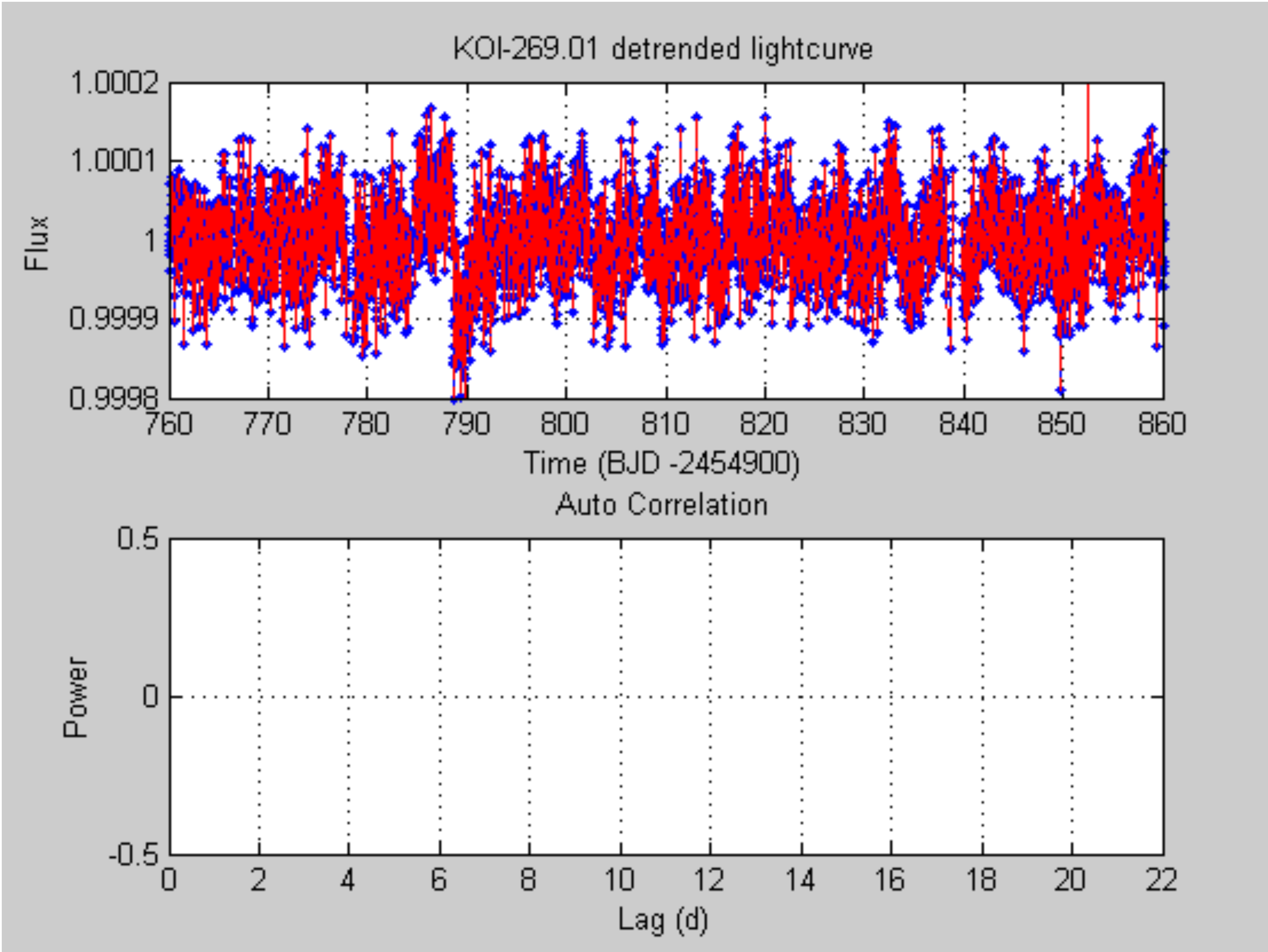
820
830
840
850
860
Time (BJD -2454900)



KOI-269.01 detrended lightcurve
Flux
1.0002
1.0001
1
0.9999
0.9998
760
770
780
790
800
810
820
830
840
850
860
Time (BJD -2454900)
Auto Correlation
Power
0.5
0
-0.5
0
2
4
6
8
10
12
14
16
18
20
22
Lag (d)

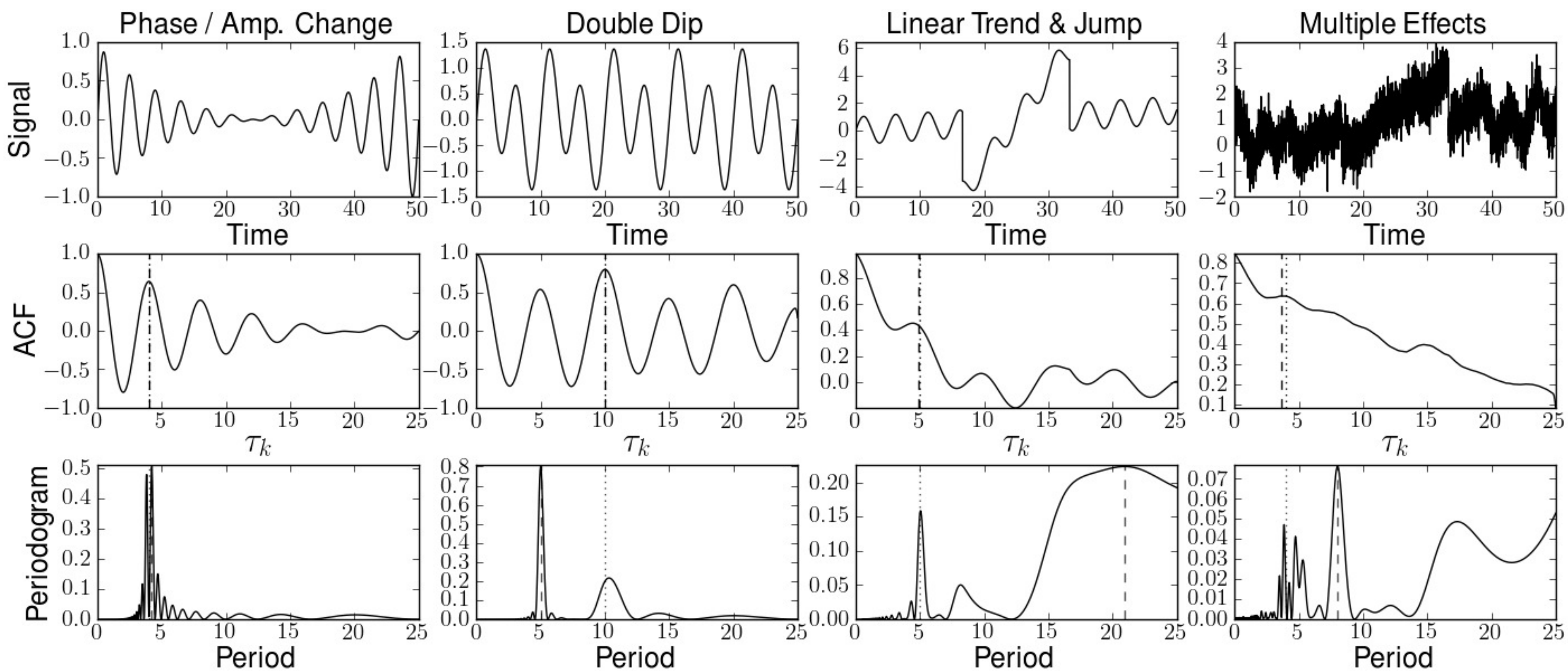
The Autocorrelation Function (ACF)

McQuillan, Aigrain & Mazeh, 2013

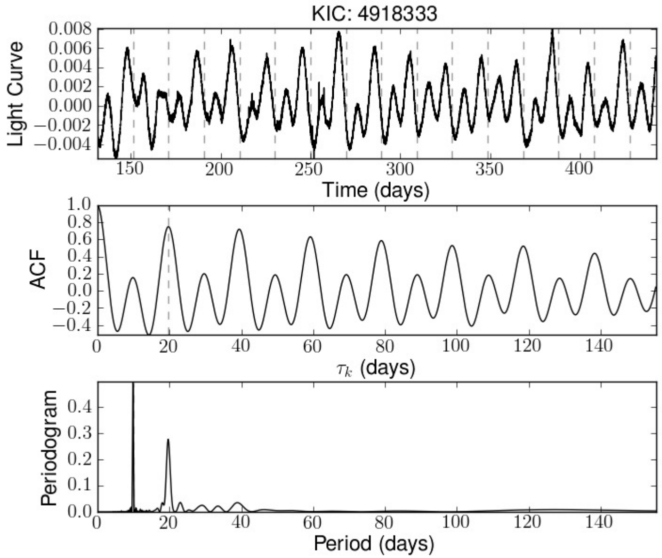
In signal processing, the ACF takes the standard form

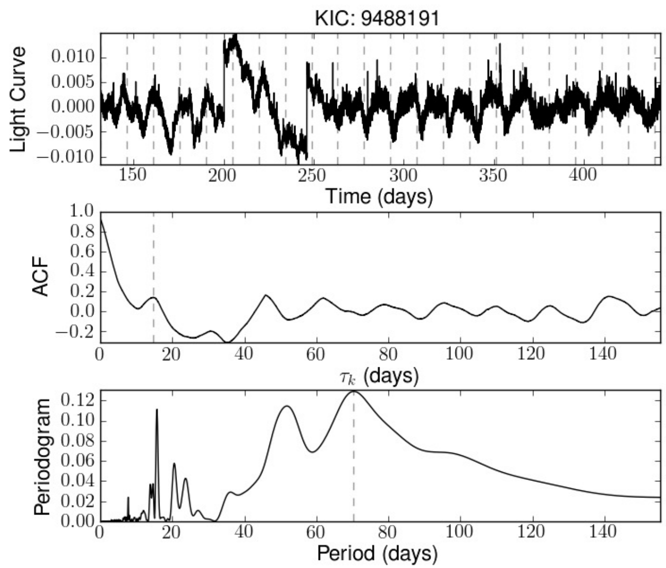
$$r_k = \frac{\sum_{i=1}^{N-k} (x_i - \bar{x})(x_{i+k} - \bar{x})}{\sum_{i=1}^{N} (x_i - \bar{x})^2}, \quad (1)$$

(see e.g. Shumway & Stoffer 2010) where r_k is the autocorrelation coefficient at lag k, for time series x_i ($i = 1, \ldots, N$).

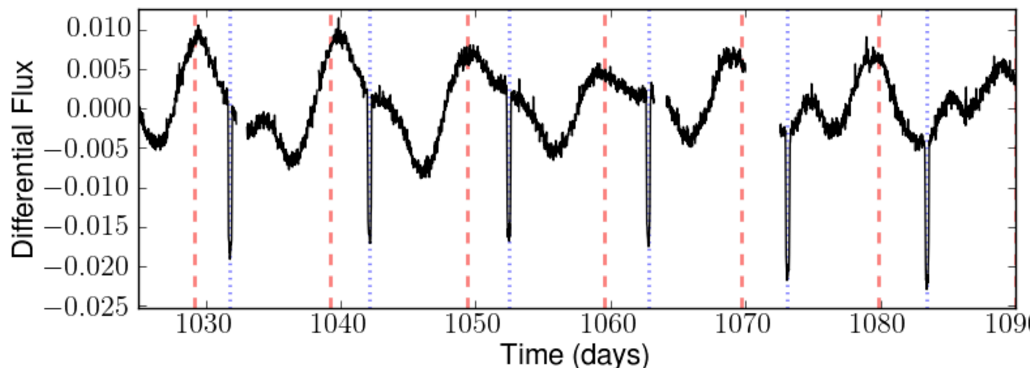


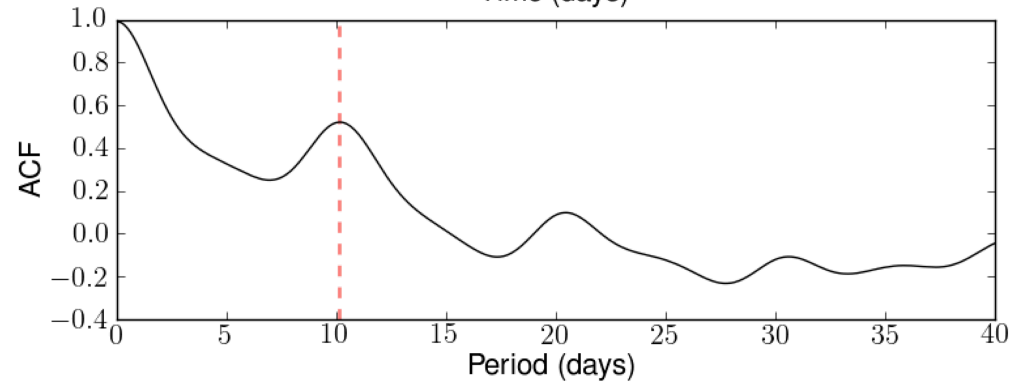
ACF Applied to Kepler Targets





KOI-85





Poster 106: Reinhold & Gizon

Poster 110: Ceillier, Garcia, Salabet & Mathur

Kepler search:

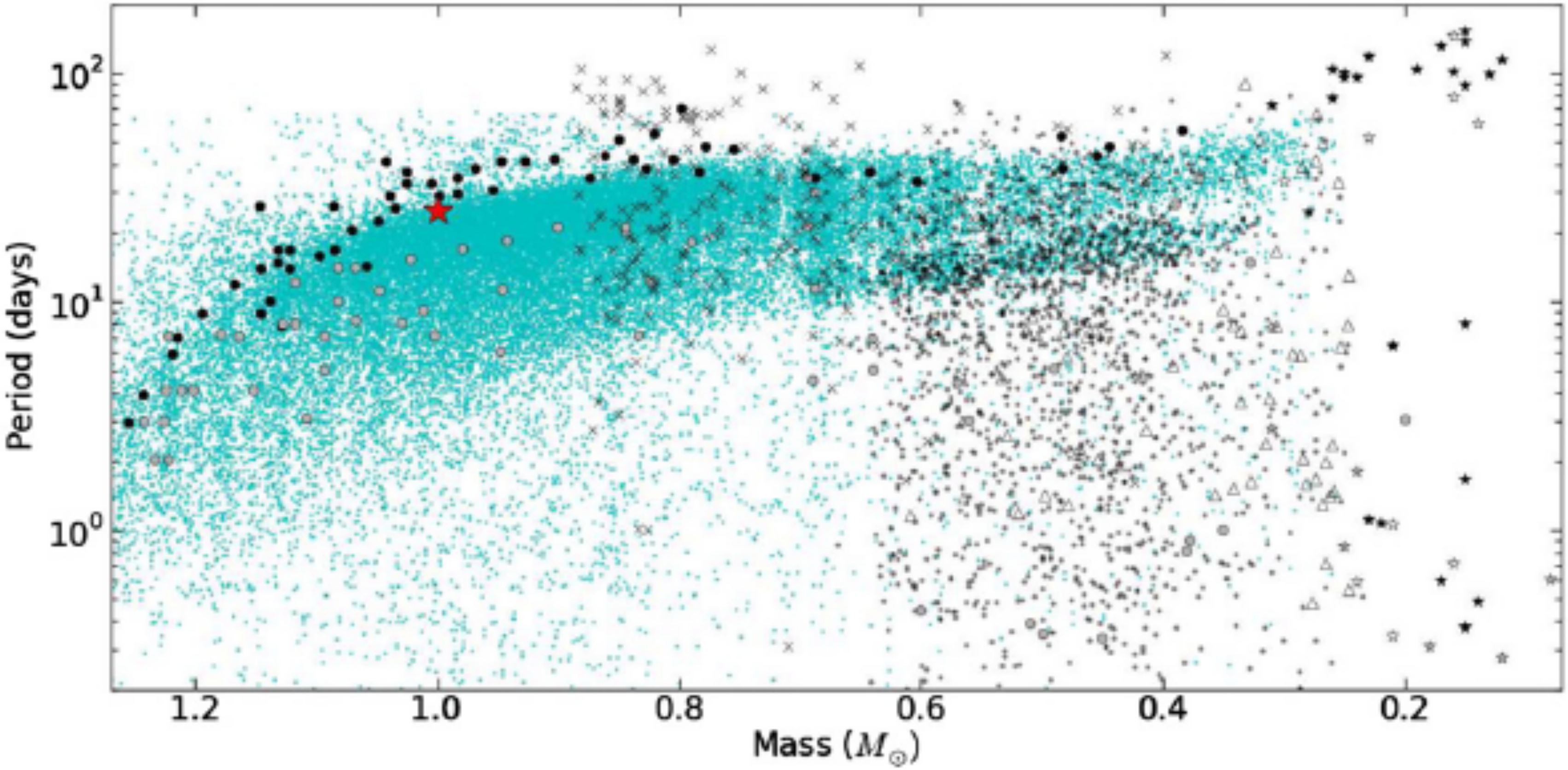
Q3-Q14
PDC-MAP

At least 8 Qs
Remove Giants
Remove EBs
Remove KOIs
Remove Teff> 6500

133,030 stars

Kepler Results: Comparison to Literature Results

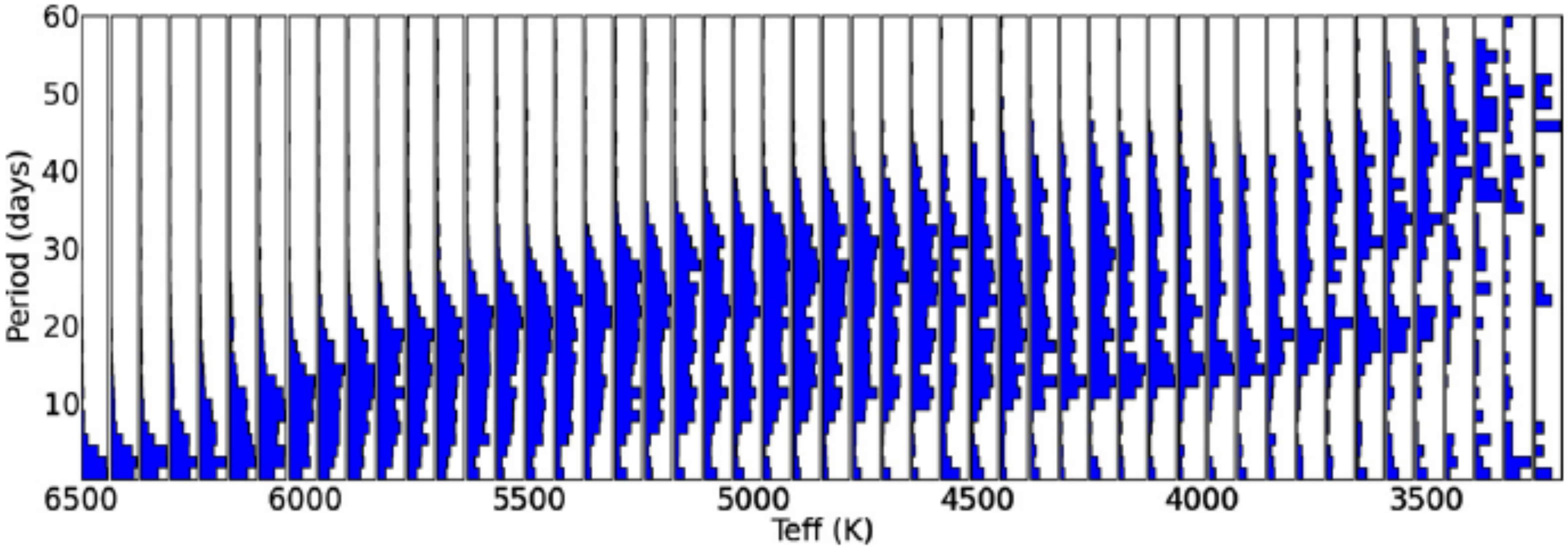
Kepler ACF Results: 34,030 period measurements (blue dots)



Literature Data from: Baliunas et al. (1996) and Kiraga & Stepien (2007) (114 circles)
Irwin et al. 2011 (41 stars) [Old = Black, Young = Grey]
Goulding et al. 2012 (65 triangles)
Hartman et al. 2011 (1686 grey dots)

Reinhold, Reiners & Basri, 2013 (24,124 periods)
Nielsen et al. 2013 (12,151 periods)

Mass from Baraffe et al. 1998



ure 2. Period vs. $T_{\rm eff}$ shown in histogram form for each temperature bin, clearly showing the bimodality in rotation period for cooler stars, and the slight dip in the er envelope of the period distribution at ~4000 K.

color version of this figure is available in the online journal.)

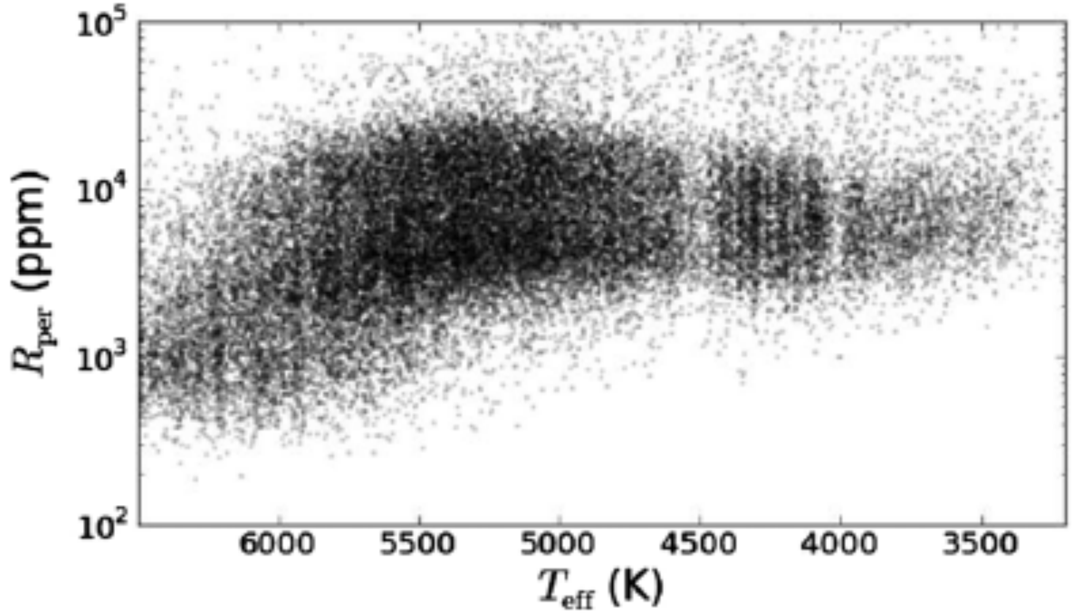


Figure 3. Distribution of periodic photometric variability amplitude, R_{per}, over the temperature range for all stars with derived rotation periods.

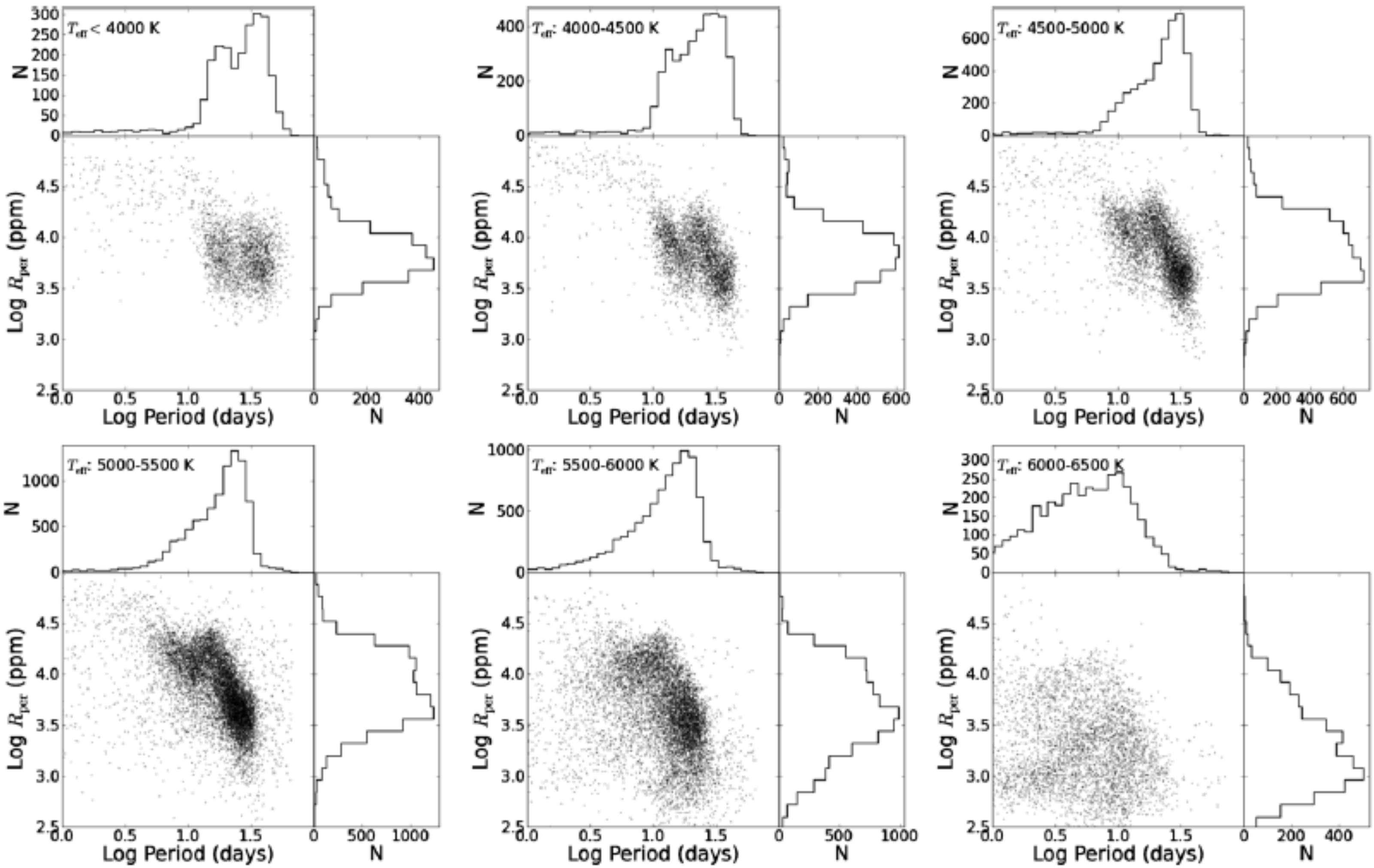
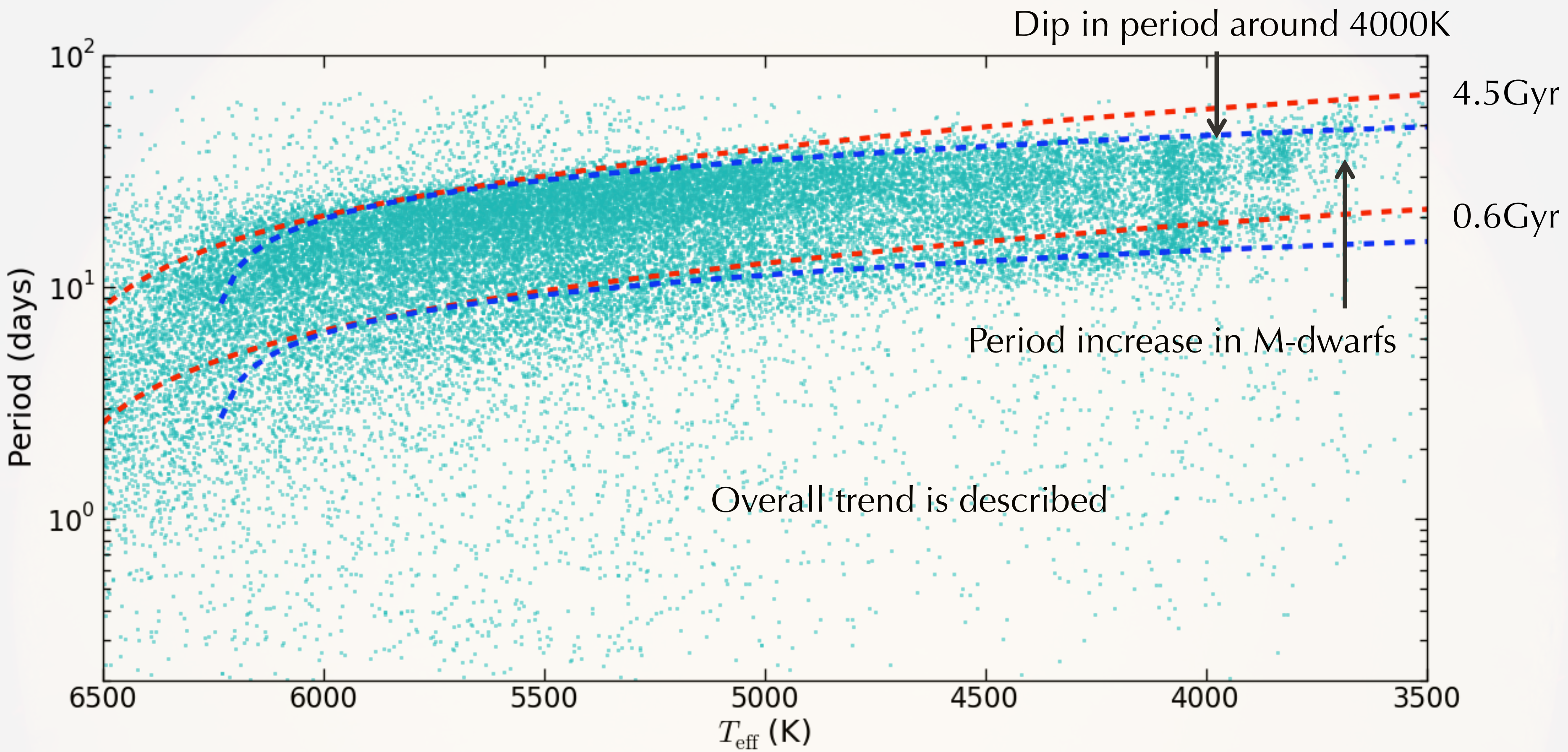


Figure 4. Log amplitude of periodic variability, $R_{\rm per}$, against log period (for periods >1 day), for each 500 K $T_{\rm eff}$ bin, as described in the top section of each panel. The top section of each panel shows the histogram of log period and the side section of each panel shows the histogram of log $R_{\rm per}$.

Comparison to Gyrochronology

4.5 & 0.6 Gyr Rotational Isochrones from Barnes (2007) and Mamajek & Hillenbrand (2008).



Talk by Van Saders Jennifer, Pinsoneault Marc, Rafael Garcia

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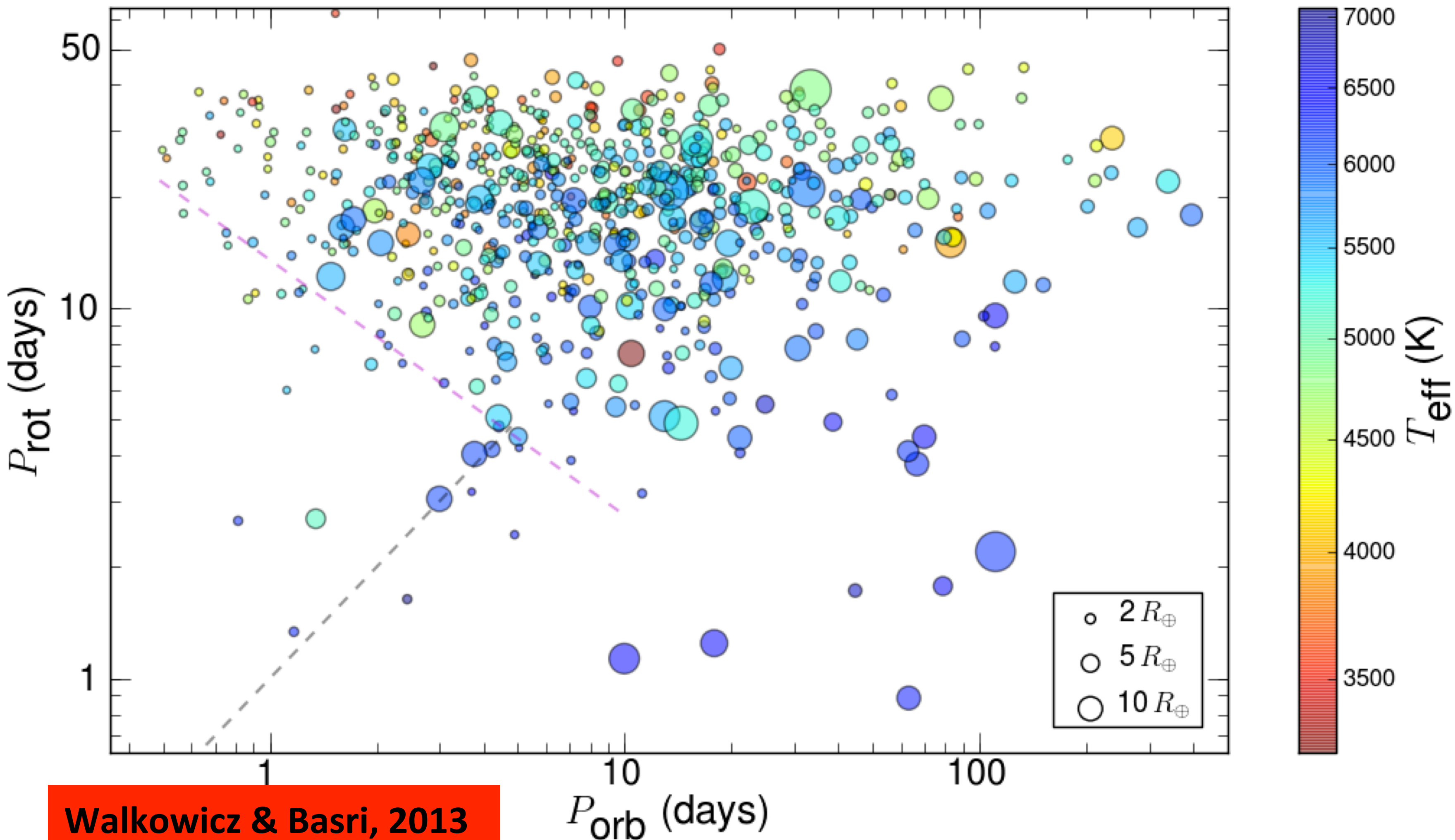
Application of ACF to the KOIs:

Short-Period Planets around Fast Rotators are Rare

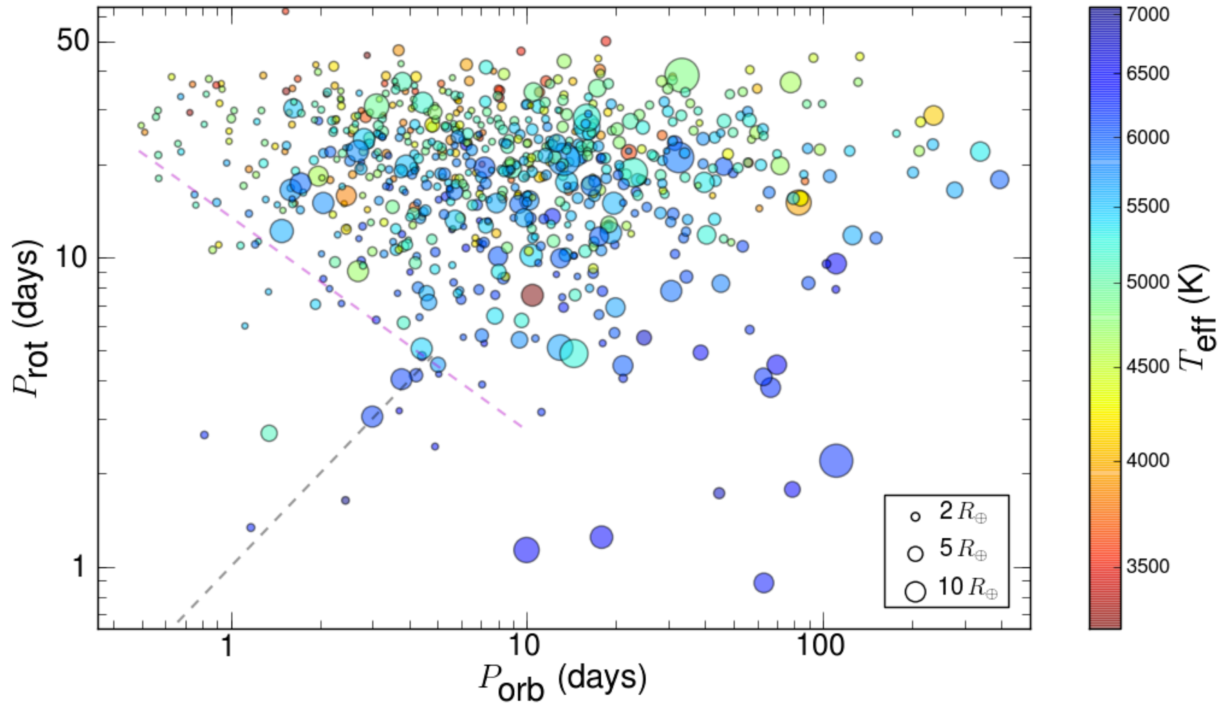
McQuillan, Mazeh & Aigrain, 2013



Walkowicz & Basri, 2013

Potential ExplanationS:

McQuillan, Mazeh & Aigrain, 2013



Tietler & Konigl (2014):
Short-period planets spiraled in,
and were swallowed by the parent star
The stellar envelope was spun up.
The NEXT planet appears with a longer period.

Lanza & Shkolnik (2014):
Short-period planets spiraled in,
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Stellar rotation as a stellar-age proxy.

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The observed rotational amplitude depends on the inclination angle of the stellar rotation axis

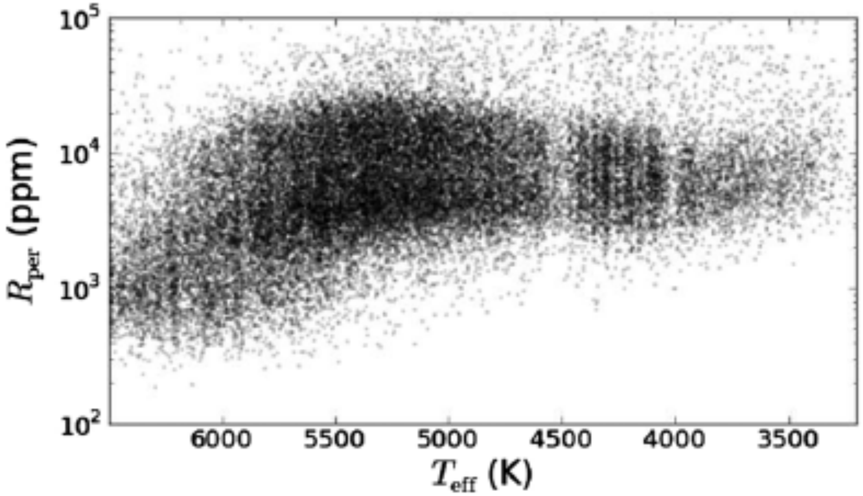

Figure 3. Distribution of periodic photometric variability amplitude, $R_{\rm per}$, over the temperature range for all stars with derived rotation periods.

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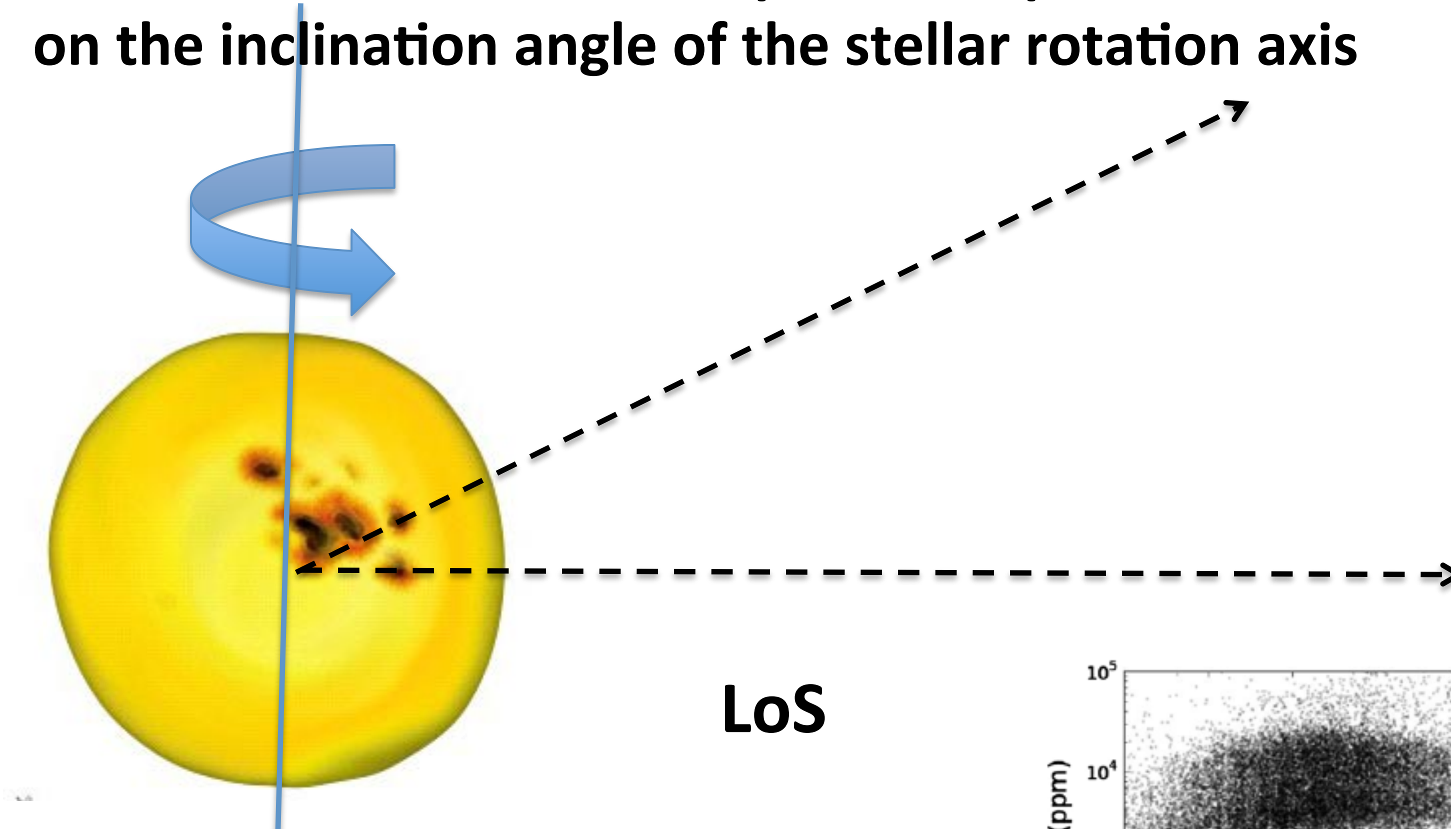
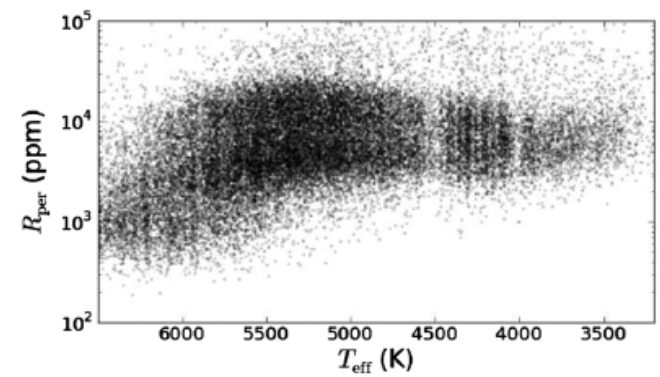


$$< R_{per} > \cong \frac{\pi}{4} < R_{per,real} >$$



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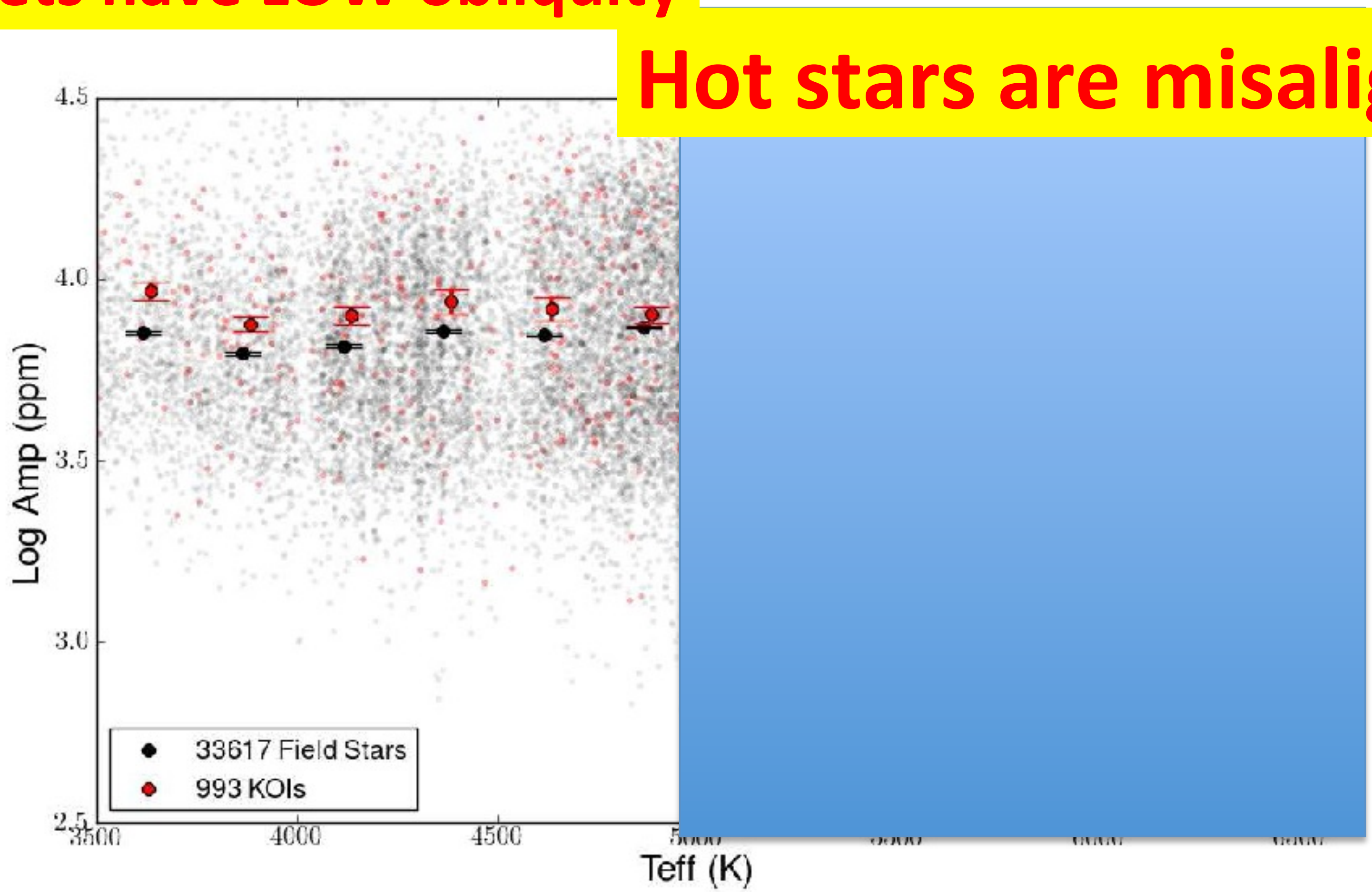
Rotational amplitudes of KOIs vs Single starsc

Planets have LOW obliquity

Hot stars are misaligned



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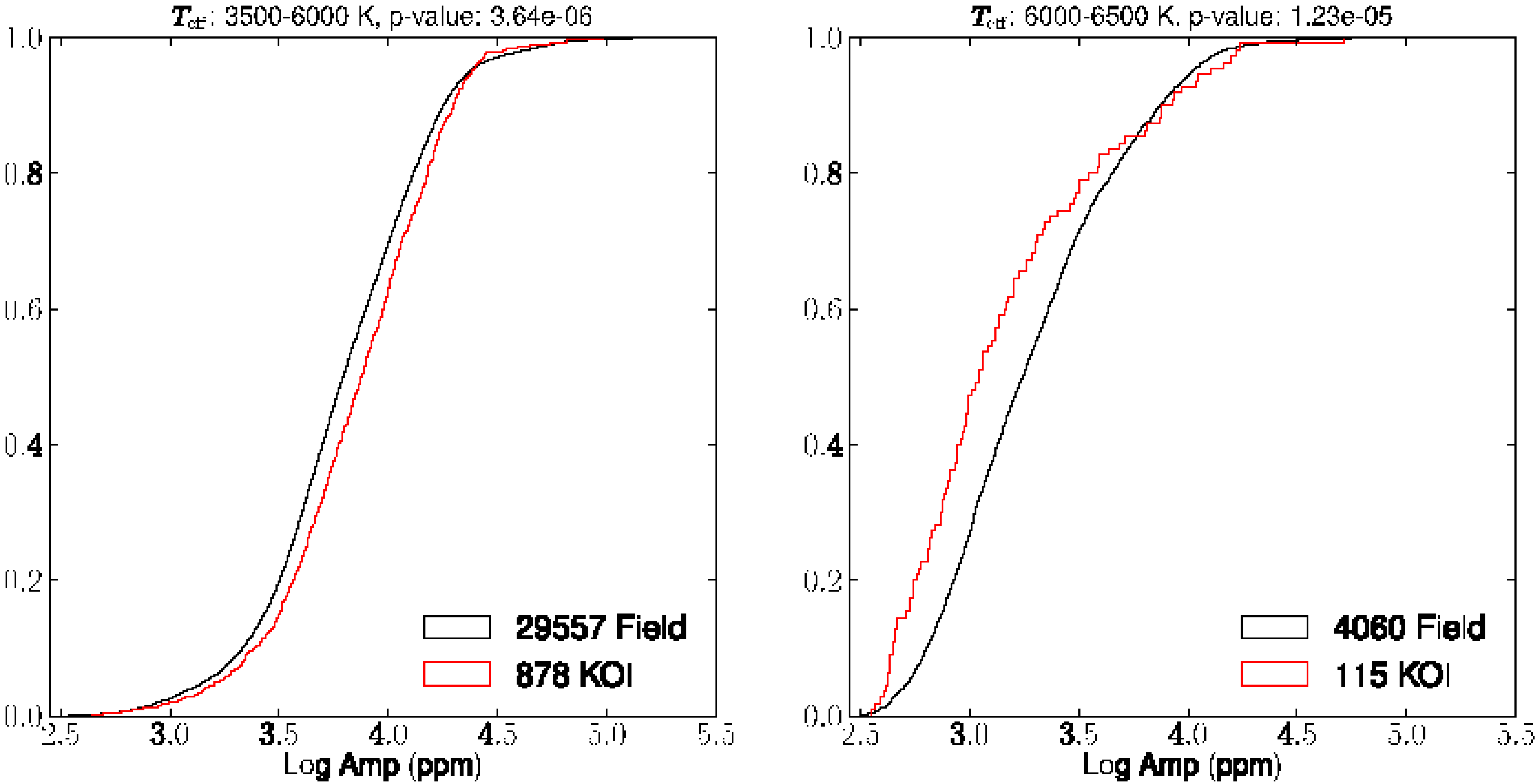
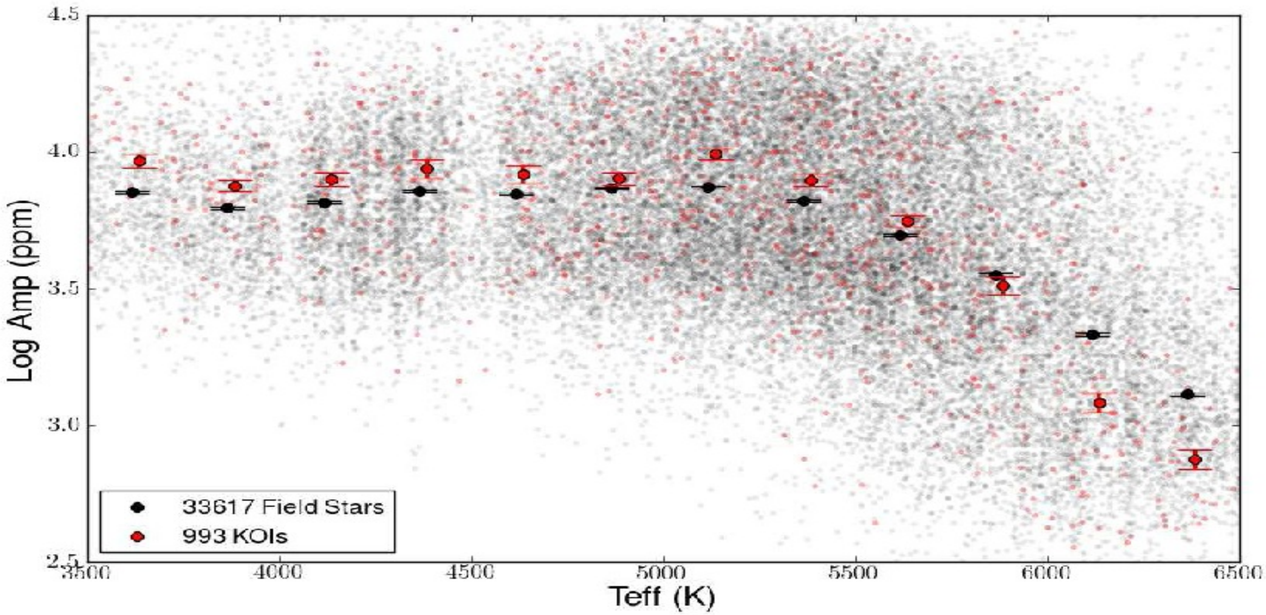
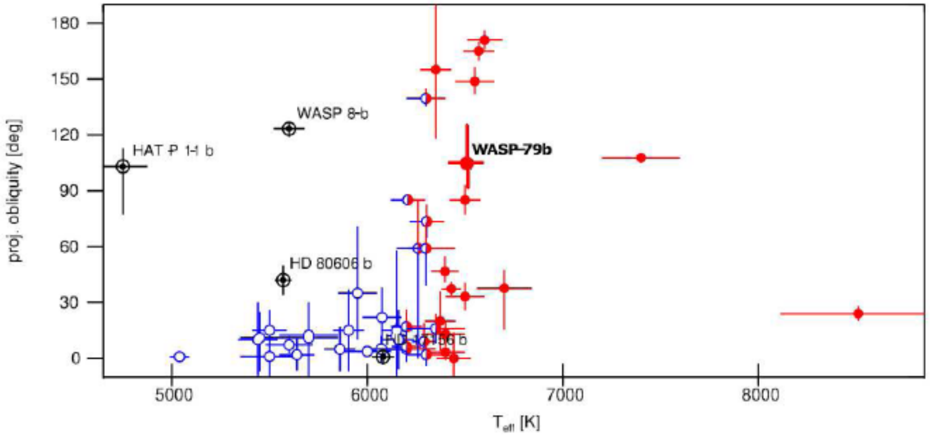




Albrecht et al. 2012



Summary

- ACF method is effective for rotation period measurement
- ~34,000 rotational periods from Kepler, roughly consistent with gyrochronology
- There is a dearth of close-in planets around fast rotators
- Planets around hot stars are **mis**aligned

But there seems to be no compelling reason why the hypothetical stellar planets should not, in some instances, be much closer to their parent stars than is the case in the solar system. It would be of interest to test whether there are any such objects.

We know that *stellar* companions can exist at very small distances. It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit, or about 3,000,000 km. Its period around a star of solar mass would then be about 1 day.

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There would, of course, also be eclipses. Assuming that the mean density of the planet is five times that of the star (which may be optimistic for such a large planet) the projected eclipsed area is about 1/50th of that of the star, and the loss of light in stellar magnitudes is about 0·02. This, too, should be ascertainable by modern photoelectric methods, though the spectrographic test would probably be more accurate. The advantage of the photometric procedure would be its fainter limiting magnitude compared to that of the high-dispersion spectrographic technique.

Perhaps one way to attack the problem would be to start the spectrographic search among members of relatively wide visual binary systems, where the radial velocity of the companion can be used as a convenient and reliable standard of velocity, and should help in establishing at once whether one (or both) members are spectroscopic binaries of the type here considered.

Berkeley Astronomical Department,
University of California.
1952 July 24.