Kepler’s Habitable Host Stars

Superflares, Rotation and Activity

D. J. Armstrong, C. E. Pugh
d.j.armstrong@warwick.ac.uk

THE UNIVERSITY OF WARWICK

Introduction

Of the most Earth-like planets known to date (via the Earth-Similarity Index), 15 have been observed by the Kepler satellite. These are Keplers 22b, 61b, 62e and f, 174d, 186f, 283c, 296e and f, 298d, 438b, 440b, 442b, 443b, and KOI-4427b.

We have 4 years of high precision photometry with which to study the host stars of these planets in great detail. We derive rotation periods, photometric activity indices, flaring energies, mass loss rates, X-ray luminosity and consider implications for the planetary magnetospheres and habitability.

Rotation Periods

- **We use KASOC filtered lightcurves[1], with filters of 30, 50 and 100 days. Shorter filters lead to cleaner lightcurves, but attenuate signals on longer timescales than the filter. The standard Kepler PDC detrended lightcurves damp signals on timescales larger than 21 days.**
- **Periods are derived using the auto-correlation-function (ACF) backed up by wavelet analysis. The ACF finds the most significant period, while wavelets can show the source of this signal but at a degraded period resolution.**

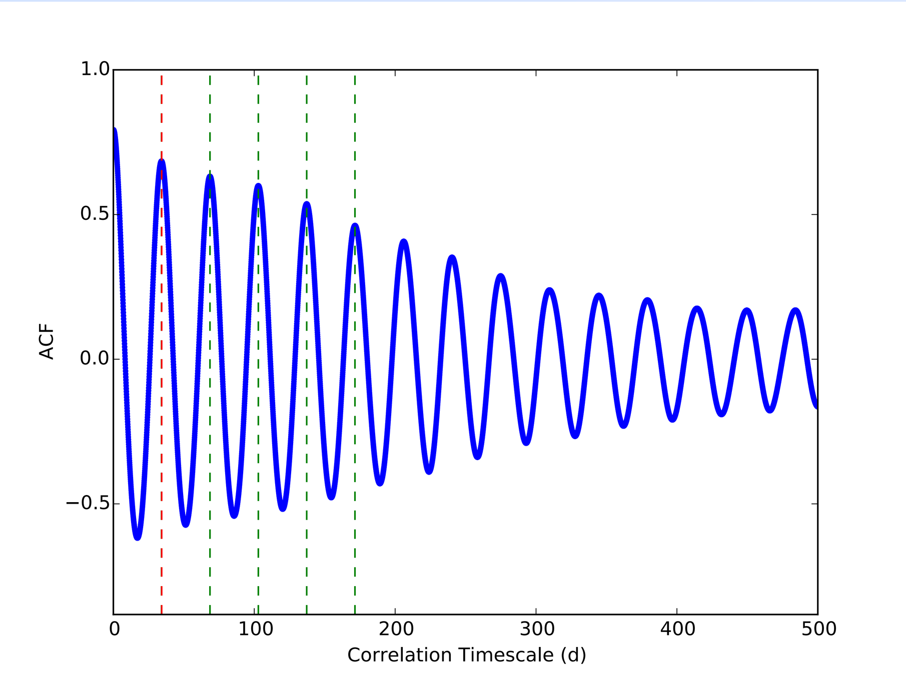

Figure: ACF of Kepler-186, showing the rotation period (red dashed line) and the harmonics also used to extract the period (green dashed lines). The rotation period matches that seen in the wavelet plot below.

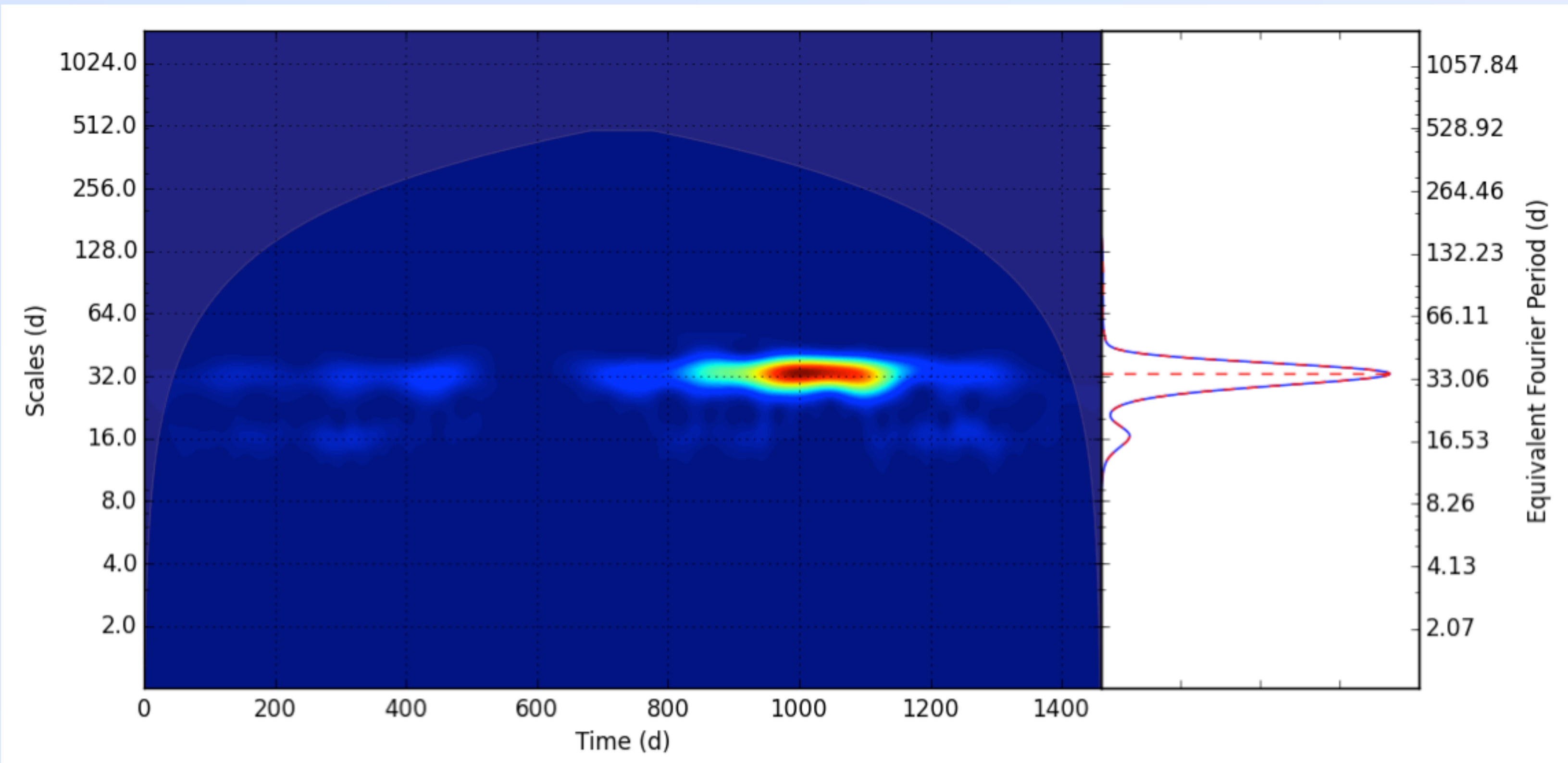

Figure: Wavelet plot for Kepler-186. A Morlet wavelet was used. The inset plot to the right shows the global wavelet spectrum, fit by a sum of Gaussians. The dominant period is present throughout, but a strong active region can be seen.

Stellar Activity

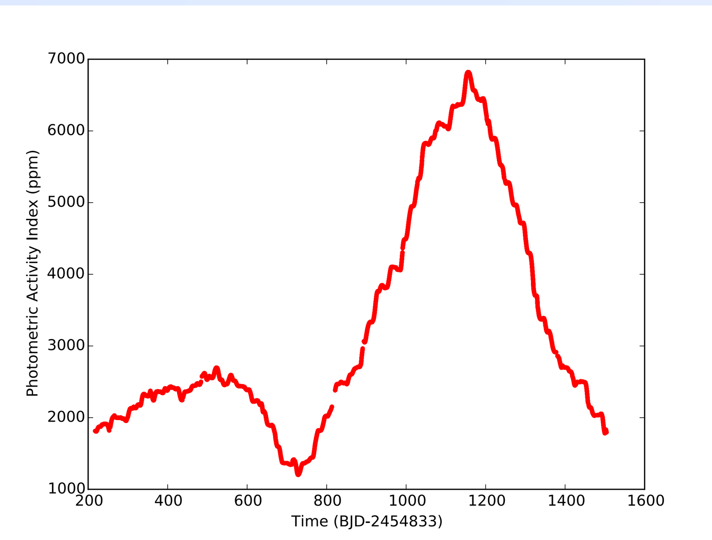

Figure: $S_{phot,5}$ index for Kepler-186. the increase in activity corresponds to power in the wavelet plot above.

We calculate the $S_{phot,5}$ index, which is the average of the standard deviations of a series of lightcurve windows of length 5 stellar rotation periods. When no rotation period was found, 30d was used to allow some determination. For comparison the Sun has a value of 166.1ppm[2]. All of the sample host stars are significantly more active than this.

Results

Star	P_{rot} (ACF) d	P_{rot} (GWS) d	S_{phot} ppm	Contrast	$\dot{M}$ $M_\odot yr^{-1}$	Rossby	Log R_X	B_{ZDI} G	$R_{magneto}$ (planet) $R_\oplus$
Kepler-22	-	-	312	2.47	$(2.5 \pm 0.6)x10^{-14a}$	-	-	5^b	8.7 (b)
Kepler-61	35.55 ± 0.38	34.8 ± 5.0	1680	1.45	$(2.1 \pm 1.2)x10^{-16}$	0.91 ± 0.07	-4.89 ± 0.09	2.4	12.7(b)
Kepler-62	39.77 ± 0.44	37.3 ± 13.3	405	1.11	$(1.4 \pm 0.2)x10^{-15}$	1.61 ± 0.06	-5.78 ± 0.12	1.1	11.1 (e), 13.2 (f)
Kepler-174	-	-	445	1.47	$(2.6 \pm 1.4)x10^{-15a}$	-	-	5^b	11.6(d)
Kepler-186	34.27 ± 0.07	33.8 ± 4.2	3270	2.32	$(4.6 \pm 1.5)x10^{-17}$	0.75 ± 0.03	-4.69 ± 0.06	3.1	19.2(f)
Kepler-283	18.27 ± 0.02	18.1 ± 2.2	2620	1.52	$(1.7 \pm 1.0)x10^{-15}$	0.54 ± 0.03	-4.42 ± 0.05	4.9	9.9(c)
Kepler-296	36.11 ± 0.13	35.0 ± 4.8	2800	1.36	$(2.9 \pm 2.3)x10^{-17}$	0.78 ± 0.05	-4.73 ± 0.08	2.9	13.7(e), 16.7(f)
Kepler-298	-	-	967	1.51	$(8.2 \pm 4.4)x10^{-16a}$	-	-	5^b	10.7(d)
Kepler-438	37.04 ± 0.08	36.8 ± 4.5	3260	1.90	$(3.2 \pm 1.8)x10^{-17}$	0.81 ± 0.05	-4.77 ± 0.08	2.8	13.2(b)
Kepler-440	17.61 ± 0.02	17.3 ± 2.1	2420	1.37	$(9.8 \pm 5.8)x10^{-16}$	0.47 ± 0.04	-4.33 ± 0.06	5.9	9.6(b)
Kepler-442	-	-	736	1.50	$(7.7 \pm 2.3)x10^{-16a}$	-	-	5^b	12.0(b)
Kepler-443	-	-	1250	1.25	$(2.4 \pm 0.6)x10^{-15a}$	-	-	5^b	10.6(b)
KOI-4427	-	-	1410	1.44	$(6.3 \pm 3.6)x10^{-17a}$	-	-	5^b	17.7(b)

[a]Using rotation period of 30 days and error of 1 day
[b]Example value used as no rotation period available

See [3] for more detail of how each value is derived.

Superflares

KEPLER-438 FLARES

Quarter	Time BJD - 2400000	Energy $\times10^{32}$ erg
2	55058.86	4 ± 2
3	55141.14	7 ± 3
6	55379.24	14 ± 6
8	55572.92	8 ± 4
9	55701.39	11 ± 5
10	55799.08	6 ± 3
12	55974.30	4 ± 2

Kepler-438 is a strongly flaring star, showing 7 energetic flares in the Kepler data alone. Two of these qualify as potential Superflares (>10^{33} erg). The flares are not seen near data gaps or quarter boundaries, and have a shape characteristic of previously observed stellar flares.

Flare energies were calculated in a similar manner to [4], assuming a flare temperature of 9000+-500K.

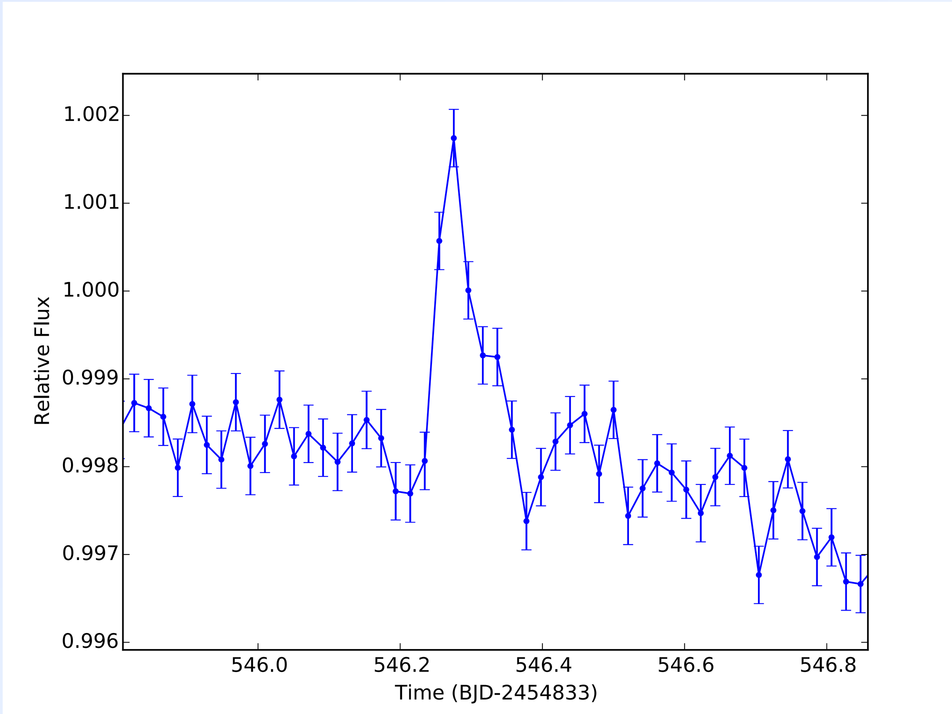

Figure: The most energetic flare in the Kepler-438 lightcurve. The characteristic rapid rise and exponential decay is seen.

Table: 5 sigma upper limits on flare energy in the remaining host star lightcurves. LC=Long Cadence, SC = Short Cadence

Star	Lightcurve	Energy Limit $\times10^{32}$ erg
kepler-22	LC	6.5
kepler-22	SC	4.4
kepler-61	LC	3.1
kepler-61	SC	2.2
kepler-62	LC	4.5
kepler-62	SC	3.2
kepler-174	LC	5.4
kepler-174	SC	4.1
kepler-186	LC	1.4
kepler-186	SC	1.0
kepler-283	LC	7.6
kepler-296	LC	2.8
kepler-298	LC	7.9
kepler-298	SC	5.6
kepler-438	LC	1.6
kepler-440	LC	4.0
kepler-442	LC	5.6
kepler-443	LC	24.0
KOI-4427	LC	6.9

Habitability

- **Flares are associated with an increased likelihood of coronal mass ejections (CMEs). These can strip planetary atmospheres, potentially impacting habitability. They can also change atmospheric chemistry, altering possible biomarkers.**
- **The effects of CMEs are strongly dependent on the protection of planetary magnetospheres. We estimate magnetosphere standoff distances for Earth-like magnetospheres on these planets.**
- **This calculation involves balancing the magnetic pressure from the planet against stellar wind ram and magnetic pressures at the orbital distance of the planet. See [3] for details of how these are estimated.**
- **The resulting standoff distances are in all cases similar in size to the Earth’s. However, if only a weak field (or none) is generated, they will shrink or vanish altogether.**

References

[1] Handberg & Lund 2014, MNRAS 445, 2698
[3] Armstrong et al 2015 (MNRAS, submitted)
[2] Mathur et al 2013, A&A, 562, A124
[4] Shibayama et al 2013, ApJ, 209, 5