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The K2 Halo Photometry Campaign

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ABSTRACT

While the *Kepler* mission was designed to look at tens of thousands of faint stars ($V \gtrsim 12$), brighter stars which saturate the detector are nevertheless some of the most interesting because of the ease with which they can be observed by other instruments and the wealth of knowledge about them that is already available. By considering the unsaturated scattered light 'halo' around these stars we retrieve precise light curves of most of the brightest stars in *K2* fields from Campaign 6 onwards. This halo campaign reveals stellar variability ubiquitously, including effects of stellar pulsation, rotation, and binarity. Here we describe our pipeline, and present a catalogue of the halo sources, with classifications and parametrizations of their variability and remarks on interesting objects. These light curves are publicly available as a High Level Science Product from the Mikulski Archive for Space Telescopes (MAST).

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1. INTRODUCTION

The *Kepler* Space Telescope was launched with a main goal of determining the frequency of Earth-sized planets around Solar-like stars (Borucki et al. 2010), a goal which it has substantially achieved (e.g. Fressin et al. 2013; Petigura et al. 2013; Foreman-Mackey et al. 2014). In order to explore these populations it was necessary to observe hundreds of thousands of stars, with the consequence that the *Kepler* the exposure time and gain were set to optimally observe eleventh or twelfth-magnitude stars, while bright stars are saturated and these saturated stars were intentionally avoided. In the two-wheeled revival as the *K2* mission, the *Kepler* telescope observed a sequence of ecliptic-plane fields containing many more very-saturated stars. While it is difficult to obtain precise light curves of these stars because of their saturation, they are some of the most-valuable targets to follow up with photon-hungry methods such as interferometry or high-resolution spectroscopy, and they typically have long histories of previous observations.

In order to recover precise photometry of the brightest stars in *K2* , we have developed two main approaches, 'smear' and 'halo' photometry. Smear photometry (Pope et al. 2016) uses collateral calibration data to recover light curves of stars which were not necessarily conventionally targeted. The more precise method of halo photometry, which is the subject of this paper, uses the broad 'halo' of scattered light around a saturated star to recover relative photometry, by constructing a light curve as a linear combination of individual pixel time series and minimizing a Total Variation objective function (TV-min). It has been employed for example on the Pleiades (White et al. 2017) and the brightest-ever star on *Kepler* silicon, Aldebaran (Farr et al. 2018), recovering photometry with a precision nearly that of normally-obtained *K2* observations of unsaturated stars. Unlike smear, this requires downloading data out to a 12–20 pixel radius around each star, and has accordingly only been possible for stars that were specifically targeted with apertures optimized for this method and for a small number of other stars for which this is fortuitously the case.

In this Paper we describe the complete catalog of long-cadence *K2* halo light curves which we have made publicly available. We have employed halo photometry on all stars targeted with appropriate apertures, and have done a preliminary characterization of interesting astrophysical variability. We also document the main changes in the halo data reduction pipeline, `halophot`, with respect to previous releases. These include oscillating red giants, pulsating and quiet main sequence stars, and eclipsing binaries, many of which are among the brightest objects of their type to have been observed with space photometry. We hope that this diverse catalog of light curves will be useful for an equally-diverse range of astrophysical investigations.

2. HALO PHOTOMETRY

We use an extension of the method of halo photometry, first described by White et al. (2017) and with further developments by Farr et al. (2018). Because SAP is not possible, we consider instead the unsaturated pixels p_j at the wings of the broad and complex PSF, and construct a light curve as a linear combination with weights w_j of these time series, so that flux at cadence i is

$$f_i \equiv \sum_j w_j p_{ij}. \tag{1}$$

The weights are chosen to minimize an objective function

$$\Lambda_{k,l} \equiv \frac{\sum_i |f_i - f_{i-l}|^k}{\sum_i f_i}, \tag{2}$$

which is the L_k norm on a 'lagged' finite difference with a lag parameter l. For $k = 1$ and $l = 1$, $\Lambda_{1,1}$ is the standard Total Variation as used in previous halo papers, and can be seen as the L1 norm on the derivative of f or as a discrete approximation to its arc length. The lag parameter l allow for flexibility in modelling systematics occurring at different timescales from cadence-to-cadence, and we investigate its effects below. The order parameter k allows for flexibility in how sensitive we are to normally-distributed versus long-tailed noise. TV is a convex objective function and I think the generalizations are too and $\Lambda_{k,l}$ has analytic derivatives with respect to w_j (calculated with `autograd`; Maclaurin et al. 2015), and it is therefore extremely fast to optimize and converges well on a global solution.

This method differs from smear photometry (Pope et al. 2016), which uses collateral 'smear' data to obtain a 1-D spatial profile with $\sim 1/1000$ of the flux on each CCD. While this has also been used for photometry of very bright stars, the 'halo' method has the advantage of averaging over many more realizations of the K2 pointing systematics and permitting more significant calibration, achieving a generally higher photometric prevision.

While the halo procedure produces in most cases a fairly clean light curve, there are nevertheless residual systematic errors related to spacecraft motion. In order to correct these, we employ the K2SC code (Aigrain et al. 2015, 2016), which simultaneously models a light curve as a 3D Gaussian Process (GP) in time and predicted position (the K2 standard data product POS_CORR) in pixels (x, y). The model prediction in time for fixed position is then a nonparametric model of the stellar variability, and the prediction in space evaluated for fixed time represents the pointing systematics and is subtracted from the input fluxes to obtain a final corrected flux, which is the time series we use and recommend for science. The target pixel files for C91, C92, and C101 include no position information, and there are no halo apertures for C112. As a result K2SC-corrected data are not available for these targets.

3. SAMPLE

The full sample of stars for which halo apertures were obtained is listed in Tables 1–6, broken down by Campaign. While some very bright stars were observed with conventional apertures as part of these programs, simple aperture photometry is satisfactory on these targets and we exclude them from the present discussion and data release, which is oriented strictly towards targets only observable with halo photometry. We make an exception for Spica, which was observed in Campaign 6 without a halo aperture but in Campaign 17 with a halo aperture. In Campaign 6 it was assigned a normal aperture by mistake and simple aperture photometry performed extremely poorly, so we have processed it with the halo pipeline. The stars in Campaign 18 were also on-silicon in Campaign 5, but were not assigned apertures suitable for halo photometry in C5. A possible further extension of the present work would be to recover C5 light curves for these objects using either or both of smear or modified halo photometry.

Seven stars in Campaign 13 and one in Campaign 16 were not only assigned long-cadence halo apertures, but also downloaded at short cadence. For these targets we have provided both long and short cadence reductions.

Some of the objects here have been previously published, but we here provide the first public data releases for the Pleiades' Seven Sisters (White et al. 2017), Aldebaran (Farr et al. 2018), ι Lib (Buysschaert et al. 2018), and ϵ Tau (Arentoft et al. 2019), as well as ρ Leo with halo photometry but without using the TV-min method (Aerts et al. 2018).

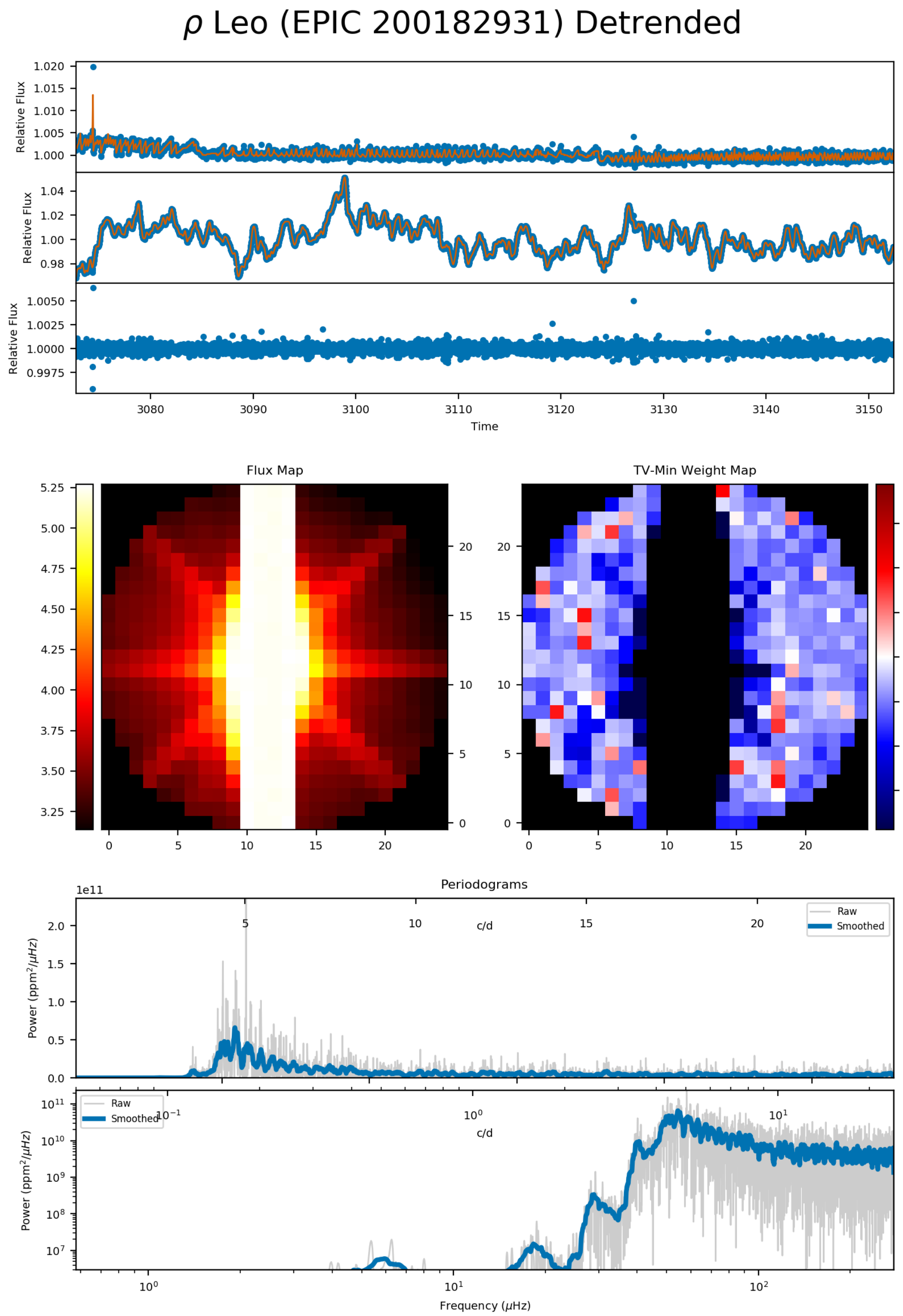
4. DISCUSSION

5. CONCLUSIONS

Some of the objects presented here are the subject of more detailed work in preparation, namely Spica (Buzasi et al., in prep.) and the Hyades giants (White et al., in prep.). In addition to this, we aim to separately publish asteroseismic catalogues of the red giants (Yu et al., in prep.) and main-sequence stars (Greklek-McKeon et al., in prep.).

The sample of K2 bright stars presented here only includes those with halo apertures, but while some others are available conventionally, many were not assigned target pixels and were not downloaded at all. Smear photometry has been used to recover the brightest otherwise-unobserved stars in nominal *Kepler* (Pope et al., in prep.), and this can also be done in K2, although in the latter case the sample is much smaller due to competition with halo apertures and the systematics correction is more difficult. A natural extension of both pieces of work would be to produce smear light curves of all bright stars without halo apertures in K2, which would finally make the *Kepler* extended mission magnitude-complete at the bright end.

The halo method naturally extends to other contexts where simple aperture photometry is not possible, such as for saturated stars observed by the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015). Although the saturation limit is brighter ($T_{mag} \sim 6$) and this problem accordingly affects fewer stars and less badly, there are situations such as for α Centauri or β Hydri where the bleed column reaches the



edge of the chip and a SAP light curve is irrecoverable. We expect that TV-min halo photometry will therefore be valuable in ensuring that TESS can observe even the very brightest stars.

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Table 1. Stars in Campaigns 7-8 observed with halo photometry in K2.

Name	EPIC	Spectral Type	V mag	Campaign	Comments
Alcyone	200007767	B7III	2.986	4	White et al. (2017)
Atlas	200007768		3.763	4	White et al. (2017)
Electra	200007769	B6IIIe	3.851	4	White et al. (2017)
Maia	200007770	B8III	4.305	4	White et al. (2017)
Merope	200007771	B6IVe	4.305	4	White et al. (2017)
Taygeta	200007772	B6IV	4.448	4	White et al. (2017)
Pleione	200007773	B8Vne	5.192	4	White et al. (2017)
γ Tau	200007765	G9.5IIIabCN0.5	3.474	4	
δ1 Tau	200007766	G9.5IIICN0.5	3.585	4	
Ascella	200062593	A2.5Va	2.585	7	
Albaldah	200062592	F2II-III	2.88	7	
τ Sgr	200062591	K1.5IIIb	3.31	7	
ξ2 Sgr	200062590	G8/K0II/III	3.51	7	
o Sgr	200062589	G9IIIb	3.77	7	
52 Sgr	200062585	B8/9V	4.598	7	
Ainalrami	200062588	K1II	4.845	7	
ψ Sgr	200062584	K0/1III+A/F	4.85	7	
43 Sgr	200062587	G8II-III	4.878	7	
ν2 Sgr	200062586	K3-II-III:CN1Ba1	4.98	7	
ϵ Psc	200068392	G9IIIbFe-2	4.28	8	
Revati	200068393	A7IV	5.187	8	
80 Psc	200068394	F2V	5.5	8	
42 Cet	200068399	G8IV+A(8)	5.87	8	
33 Cet	200068395	K4/5III	5.942	8	
60 Psc	200068396	G8III	5.961	8	15 Vega measurements HD4526
73 Psc	200068397	K5III	6.007	8	17 Vega measurements HD 6386
WW Psc	200068398	M2.5III	6.14	8	
HR 243	200068400	G8/K0II/III	6.368	8	
HR 161	200068401	K3III	6.407	8	

Table 2. Stars in Campaign 9 observed with halo photometry in K2.

Name	EPIC	Spectral Type	V mag	Campaign	Comments
HR 6766	200069361	G7:IIIbCN-1CH-3.5HK+1	4.56	9	
HR 6842	200069360	K3II	4.627	9	
4 Sgr	200069357	A0	4.724	9	
11 Sgr	200069358	K0III	4.98	9	
7 Sgr	200069362	F2II-III	5.34	9	
15 Sgr	200069359	O9.7Iab	5.37	9	
HR 6838	200069363	K2III	5.75	9	
Y Sgr	200069364	F8II	5.75	9	Cepheid
HR 6716	200069365	B0Iab/b	5.77	9	
HR 6681	200069366	A0V	5.929	9	
9 Sgr	200069368	O4V((f))z	5.97	9	
16 Sgr	200069367	O9.5III	6.02	9	
HR 6825	200069369	ApSi	6.15	9	
63 Oph	200069370	O8II((f))	6.2	9	
HR 6679	200069373	A1V	6.469	9	
HD 165784	200069371	A2Iab	6.58	9	
HD 161083	200069374	F0V	6.58	9	
5 Sgr	200069372	K0III	6.64	9	
HD 167576	200069378	K1III	6.66	9	
HR 6773	200069380	B3/5IV	6.71	9	
HD 163296	200071159	A1Vep	6.85	9	
HD 165052	200069379	O5.5:Vz+O8:V	6.87	9	
17 Sgr	200069375	G8/K0III	6.886	9	
HD 169966	200069376	G8/K0III	6.97	9	
HD 162030	200069377	K1III	7.02	9	

Table 3. Stars in Campaigns 10-12 observed with halo photometry in K2.

Name	EPIC	Spectral Type	V mag	Campaign	Comments
Porrima	200084004	F1V+F0mF2V	2.74	10	
Zaniah	200084005	A2IV	3.9	10	
21 Vir	200084006	B9V	5.48	10	
FW Vir	200084007	M3+IIICa0.5	5.71	10	
HR 4837	200084008	G8III	5.918	10	
HR 4591	200084009	K1III	6.316	10	
HR 4613	200084010	G8/K0III	6.364	10	
HD 107794	200084011	K0III	6.46	10	
θ Oph	200128906	OB	3.26	11	
44 Oph	200128907	kA5hA9mF1III	4.153	11	
45 Oph	200128908	F5III-IV	4.269	11	
51 Oph	200128909	A0V	4.81	11	
36 Oph	200129035	K2V+K1V	5.03	11	
o Oph	200128910		5.2	11	
26 Oph	200129034	F3V	5.731	11	
HR 6472	200128911	K0III	5.83	11	
HR 6366	200128913	Fm dD	5.911	11	
HR 6365	200128912	K0III	5.977	11	
191 Oph	200128914	K0III	6.171	11	
κ Psc	200164167	A2VpSrCrSi	4.94	12	
83 Aqr	200164168	F0V	5.47	12	
24 Psc	200164169	K0II/III	5.94	12	
HR 8759	200164170	G5II/III	5.933	12	
14 Psc	200164171	A2II	5.87	12	
HR 8921	200164172	K4/5III	6.191	12	
81 Aqr	200164173	K4III	6.215	12	
HR 8897	200164174	K4III	6.34	12	

Table 4. Stars in Campaign 13 observed with halo photometry in K2.

Name	EPIC	Spectral Type	V mag	Campaign	Comments
Aldebaran	200173843	K5+III	0.86	13	Farr et al. (2018)
θ2 Tau	200173845	A7III	3.41	13	SC
ϵ Tau	200173844	G9.5IIICN0.5	3.53	13	Arentoft et al. (2019)
θ1 Tau	200173846	G9IIIFe-0.5	3.84	13	
κ1 Tau	200173847	A7IV-V	4.201	13	SC
δ3 Tau	200173849	A2IV-Vs	4.25	13	C4
τ Tau	200173850	B3V	4.258	13	
υ Tau	200173848	A8Vn	4.282	13	SC
ρ Tau	200173851	A8V	4.65	13	SC
11 Ori	200173853	A1VpSiCr	4.661	13	
HR 1427	200173855	A6IV	4.764	13	SC
15 Ori	200173854	F2IV	4.82	13	
75 Tau	200173852	K1IIIb	4.969	13	
97 Tau	200173857	A7IV-V	5.085	13	SC
HR 1684	200173856	K5III	5.163	13	
κ2 Tau	200173859	F0Vn	5.264	13	SC
56 Tau	200173861	A0VpSi	5.346	13	
81 Tau	200173860	Am	5.454	13	
53 Tau	200173864	B9Vsp	5.482	13	
HR 1585	200173858	K1III	5.49	13	
80 Tau	200173866	F0V	5.552	13	
51 Tau	200173865	F0V	5.631	13	
HR 1403	200173867	Am	5.711	13	
89 Tau	200173868	F0V	5.776	13	
HR 1576	200173871	B9V	5.776	13	
98 Tau	200173870	A0V	5.785	13	
99 Tau	200173862	K0III	5.806	13	
105 Tau	200173869	B2Ve	5.92	13	
HR 1554	200173874	F2IVn	5.961	13	
HR 1385	200173875	F4V	5.965	13	C4
HR 1741	200173873	K0III	6.107	13	
HR 1633	200173872	K0	6.188	13	
HR 1755	200173876	K0III	6.205	13	

Table 5. Stars in Campaigns 14-15 observed with halo photometry in K2.

Name	EPIC	Spectral Type	V mag	Campaign	Comments
ρ Leo	200182931	B1Iab	3.87	14	Aerts et al. (2018)
58 Leo	200182925	K0.5IIIFe-0.5	4.838	14	
48 Leo	200182926	G8.5IIIFe-1	5.07	14	
53 Leo	200182928	A2V	5.312	14	
65 Leo	200182927	K0III	5.52	14	
35 Sex	200182929	K2II-III+K1II-III	5.79	14	
43 Leo	200182930	K3III	6.08	14	
Dschubba	200194910	B0.3IV	2.32	15	
Zubenelhakrabi	200194911	G8.5III	3.91	15	
ι1 Lib	200194912	B9IVpSi	4.54	15	Buysschaert et al. (2018)
41 Lib	200194913	G8III/IV	5.359	15	
ζ4 Lib	200194914	B3V	5.499	15	
HR 5762	200194915	A2IV	5.52	15	
HR 5806	200194916	K0III	5.79	15	
ζ3 Lib	200194917	K0III	5.806	15	
HR 5810	200194918	K0III	5.816	15	
ι2 Lib	200194919	A2V	6.066	15	Buysschaert et al. (2018)
HR 5620	200194920	K0III	6.14	15	
28 Lib	200194921	G8II/III	6.17	15	
HD 138810	200194958	K1(III)(+G)	7.02	15	

Table 6. Stars in Campaigns 16-18 observed with halo photometry in K2.

Name	EPIC	Spectral Type	V mag	Campaign	Comments
Asellus Australis	200200356	K0+IIIb	3.94	16	
Acubens	200200357	kA7VmF0/2III/IVSr	4.249	16	
ξ Cnc	200200358	G8.5IIIFe-0.5CH-1	5.149	16	
$o1$ Cnc	200200360	A5III	5.22	16	
η Cnc	200200359	K3III	5.325	16, 18	
45 Cnc	200200728	A3III:+G7III	5.65	16	SC
$o2$ Cnc	200200361	F0IV	5.677	16	
50 Cnc	200200363	A1Vp	5.885	16, 18	
Spica	200213067	B1V	0.97	17	
82 Vir	200213053	M1+III	5.01	17	
76 Vir	200213054	G8III	5.21	17	
68 Vir	200213055	K5III	5.25	17	
80 Vir	200213056	K0III	5.706	17	
HR 5106	200213057	A0V	5.932	17	
HR 5059	200213058	A8V	5.965	17	
γ Cnc	200233186	A1IV	4.652	18	C5
ζ Cnc	200233643	F8V+G0V	4.67	18	C5
60 Cnc	200233188	K5III	5.44	18	C5, C16
49 Cnc	200233189	A1VpHgMnSiEu	5.66	18	C5
HR 3264	200233190	K1III	5.798	18	C5
29 Cnc	200233192	A5V	5.948	18	C5
HR 3222	200233193	G8III	6.047	18	C5
21 Cnc	200233196	M2III	6.08	18	C5
25 Cnc	200233644	F5IIIm?	6.1	18	C5
HR 3558	200233195	K1III	6.146	18	C5
HR 3541	200233194	C-N4.5	6.4	18	C5