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# REDUCED LIGHT CURVES FROM CAMPAIGN 1 OF THE K2 MISSION

Andrew Vanderburg[1,2]
Harvard–Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138

## ABSTRACT

We present reduced light curves from Campaign 1 of the two wheeled *Kepler* mission, K2. The *Kepler* spacecraft has been observing different fields along the ecliptic plane since a mechanical failure ended the original *Kepler* mission in May of 2013. K2 offers exciting opportunities to study diverse topics ranging from transiting exoplanets, to asteroseismology and galactic archaeology, to active galactic nuclei variability. However, unlike the original *Kepler* mission, the K2 pipeline does not yet produce light curves, and raw light curves created from pixel level data are dominated by systematic effects due to the spacecraft's reduced pointing precision. We extract light curves for 21647 targets observed by K2 during Campaign 1, and correct for the motion of the spacecraft using a modified version of the technique presented in Vanderburg & Johnson (2014). We measure photometric precision within 55% of *Kepler* for stars with *Kepler* band magnitudes 10 < Kp < 15, and within 35% of *Kepler* for stars with *Kepler* band magnitudes 11 < Kp < 14. We release the data for the community in the form of both downloadable light curves and a simple web interface, available at `https://www.cfa.harvard.edu/~avanderb/k2.html`. This ArXiv only report is meant to serve as data release notes – for a refereed description of the technique, please refer to Vanderburg & Johnson (2014).

## 1. INTRODUCTION

In May of 2013, the second of four reaction wheels used to stabilize the *Kepler* spacecraft failed, leaving the highly successful planet hunting instrument unable to point precisely at its original target field. Because *Kepler*'s ability to find small planets arose from its extremely stable pointing, it was thought that the mechanical failure would end *Kepler*'s ability to find small planets around other stars.

However, Ball Aerospace and the *Kepler* team devised an alternate way to stabilize the spacecraft, using the two remaining reaction wheels and balancing *Kepler*'s solar panels against solar radiation pressure. This scheme, employed in the extended K2 mission, has proven successful in restoring pointing stability sufficient for *Kepler* to continue making high precision photometric observations (Howell et al. 2014).

Although *Kepler*'s pointing is stable enough to continue photometric observations, the increased level of pointing jitter introduces large systematic effects into light curves, degrading the quality of raw photometry by a factor of four (Howell et al. 2014). After the release of 9 days of data taken in February 2014, Vanderburg & Johnson (2014), hereafter VJ14, showed that the quality of K2 photometry could be improved substantially by decorrelating the photometric light curves with the motion of the spacecraft. Using their "self flat fielding" (SFF) approach, VJ14 showed that the quality of K2 photometry could approach that of the original *Kepler* mission. This type of decorrelation with image centroid positions has been used to detect the first two planetary systems discovered by K2, HIP 116454 (Vanderburg et al. 2014), and EPIC 201367065 (Crossfield et al. 2015).

In this report, we apply a similar procedure to produce light curves for 21647 targets observed by K2 during Campaign 1, the first full length science campaign of the K2 mission. We extract light curves from K2 target pixel files, and decorrelate the motion of the spacecraft from the photometry. We release these light curves and various diagnostic information to the community via a simple online interface.

## 2. DATA ACQUISITION

Campaign 1 was the first full length ($\simeq$ 80 days) observing campaign undertaken during the K2 mission. *Kepler* observed the Campaign 1 target field, centered at RA = 11:35:45.51, Dec = +01:25:02.28, from May 30, 2014 until August 21, 2014. There is a three day long mid-campaign data gap. After basic pixel level processing by the *Kepler*/K2 pipeline, target pixel files for 21647 targets were released on the Mikulski Archive for Space Telescopes (MAST) in late December 2014. We downloaded and performed our analysis on target pixel files from Data Release 3, the first release of Campaign 1 data.

## 3. DATA PROCESSING

We processed the Campaign 1 target pixel files using a slightly modified version of the algorithm presented in Vanderburg (2014), which itself is a descendant of the algorithm of VJ14. In brief, VJ14 performed aperture photometry on the K2 target pixel files and measured image centroid positions as a proxy for the motion of the spacecraft. They then excluded thruster firing events and other data points marked by the *Kepler* pipeline as having suboptimal quality. Critically, they measured a one-dimensional correlation between the flux measured from each target and the position of the image on the detector. After measuring the correlation (which they called the "self-flat-field" or SFF), they fit it with a piecewise linear function and divided it from the raw light curve, yielding higher quality photometry.

Vanderburg (2014) modified the technique of VJ14 in several ways. First, they broke up the full light curve into shorter "divisions", during which time, the motion of stars on *Kepler*'s detector could be approximated as a

[1] avanderburg@cfa.harvard.edu
[2] NSF Graduate Research Fellow

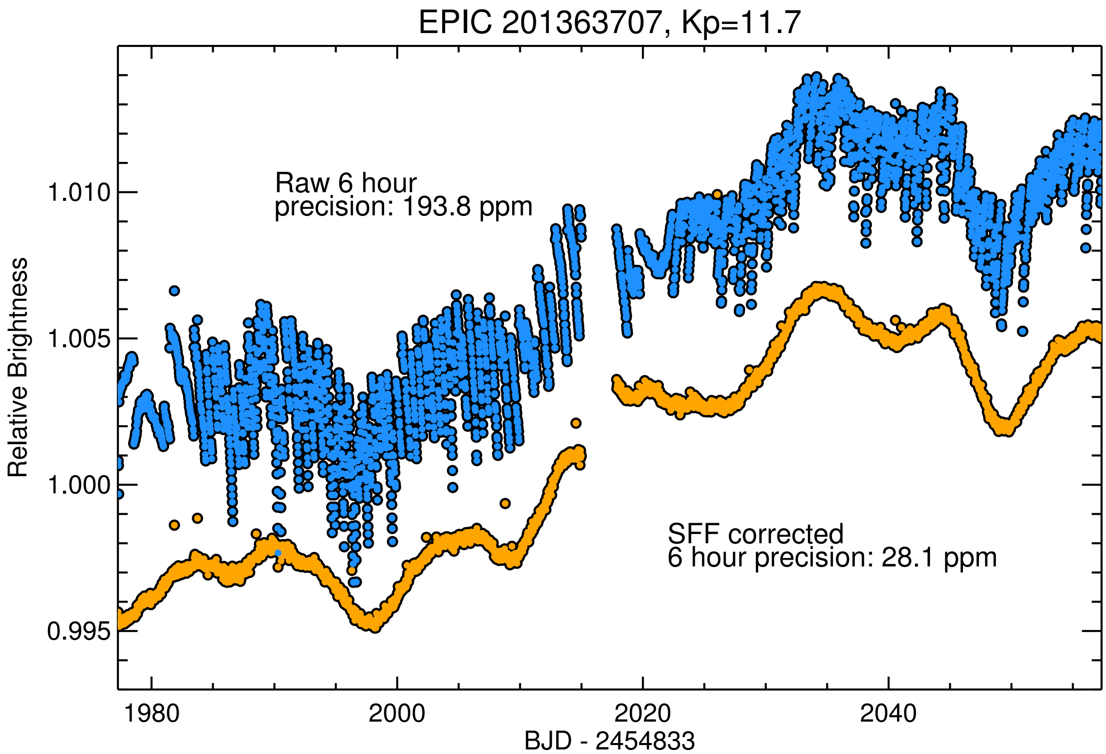


FIG. 1.— Raw light curve (top) and SFF corrected light curve (bottom). The SFF correction significantly improves photometric precision while retaining long timescale stellar variability.

one dimensional path along the chip, and performed the SFF correction on each division separately. They were still able to recover long term stellar brightness variations by iteratively fitting a spline to the entire light curve while simultaneously deriving the SFF correction for each division. Vanderburg (2014) also took a more agnostic approach to aperture selection than VJ14, and extracted light curves for 20 different apertures (10 circular apertures and 10 apertures shaped like the *Kepler* Pixel Response Function, PRF), and selected the one that resulted in the best photometric precision. Finally, unlike VJ14, Vanderburg (2014) chose one star with in particular with particularly precise centroid measurements to infer the spacecraft's motion, instead of using centroids measured from each individual star's image.

To reduce light curves from Campaign 1, we make a few minor modifications to the pipeline used by Vanderburg (2014). First, we treat the data taken before and after the mid-campaign data gap separately. This can introduce offsets between the two halves of the campaign, similar to the type seen in data taken during the original *Kepler* mission. Like Vanderburg (2014), we choose one star, namely EPIC 201611708, to infer the spacecraft's motion. Finally, we modified our aperture selection routines for stars brighter than Kp = 9.5. These stars are saturated and can exhibit large bleed trails. Instead of defining apertures for these bright stars using the measured *Kepler* pixel response function, we define apertures by selecting contiguous regions of illuminated pixels. This approach to shaping the apertures of very bright stars improves our ability to capture all of the signal in the bleed trails, and substantially improves photometric precision for these bright stars.

We show an example light curve before and after SFF processing in Figure 1. The SFF processing improves photometric precision (as defined by VJ14) by a factor of almost 7 in this case.

## 4. CHARACTERISTICS OF CAMPAIGN 1 PHOTOMETRY

### 4.1. *Photometric Precision*

We extracted and corrected light curves for 21647 targets observed by K2 in Campaign 1. Like VJ14, we found that the SFF algorithm works best for dwarf stars, and can produce poor results for stars with rapid or high levels of photometric variability.

We measured the photometric precision of every light curve and assessed the ensemble's precision compared to previous K2 campaigns and the original *Kepler* mission. Like VJ14, we measured photometric precision based on observations of cool dwarf stars, which have less astrophysical noise than giants and hot stars. We isolated dwarf stars observed by K2 during Campaign 1 by selecting stars proposed by two Guest Observer proposals: GO-01054 (PI Sanchis-Ojeda) and GO-1053 (PI Montet). These two proposals focus on exoplanet detection and therefore proposed almost exclusively dwarf stars. We summarize the precision of Campaign 1 data compared to the precision of *Kepler* data and K2 data from Campaign 0 and the engineering test in Table 4.1, and we plot the photometric precision versus *Kepler* band magnitude in Figure 2.

We find that for bright (Kp $<$ 15) stars, the data from Campaign 1 have excellent photometric precision, significantly better than data from Campaign 0, and an incremental improvement in precision compared to the K2 engineering test. We measure photometric precision within

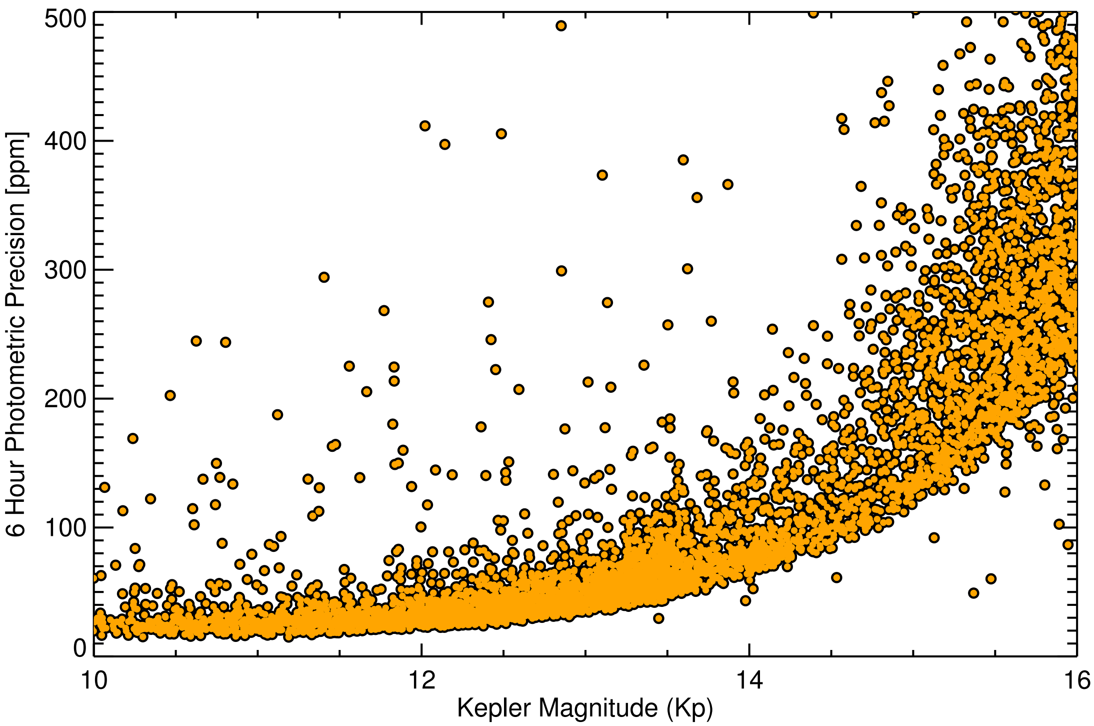


FIG. 2.— Six hour photometric precision as a function of Kepler magnitude. Here, we plot only dwarf stars from the Guest Observer proposals GO-1053 and GO-1054.

55% of *Kepler* for stars with 10 < Kp < 15, and within 35% of *Kepler* for stars with 11 < Kp < 14. We attribute the increased precision compared to Campaign 0 to the lessened effect of source crowding and contamination in Campaign 1, and to differences in target selection between the two campaigns. Campaign 0 was pointed near the plane of the Milky Way, so there is a high density of bright stars. We qualitatively illustrate the difference in source density between the two campaigns in Figure 3. Crowding can hurt photometric precision both because apertures can be contaminated with noisy sources, and also by introducing larger systematic errors due to pointing jitter from sources entering and exiting photometric apertures. In Campaign 1, the density of stars is comparatively low, and similar issues are much more rare. We also attribute the improvement in photometric precision to differences in the type of dwarf stars observed between the two campaigns. In Campaign 0, many of the bright dwarf stars were relatively hot, F-type stars, while in Campaign 1, more of the bright dwarf star targets were G- and K-type stars (R. Sanchis-Ojeda 2015, private communication). The hotter F-type stars have lower surface gravity, and therefore higher levels of short timescale photometric variability (or flicker), which hurts photometric precision (Bastien et al. 2013). Finally, observing near the plane of the galaxy increases the risk of giant and stars being accidentally included in proposals to observe dwarf stars. Giant stars also have higher levels of short timescale photometric variability.

We find that the photometric precision of faint (Kp > 15) stars appears to be worse in Campaign 1 than in Campaign 0. We attribute this to contamination of apertures in Campaign 0 with nearby bright stars, which overwhelm the signal of the faint target stars. We believe that the photometric precision we report for Campaign 1 is more representative of the precision one can expect to attain for faint stars with K2.

TABLE 1
MEDIAN 6 HOUR PHOTOMETRIC PRECISION

| $K_p$ | ET K2 | C0 K2 | C1 K2 | *Kepler* |
|---|---|---|---|---|
| 10-11 | 31 | 38 | 27 | 18 |
| 11-12 | 33 | 37 | 29 | 22 |
| 12-13 | 40 | 59 | 39 | 30 |
| 13-14 | – | 90 | 62 | 47 |
| 14-15 | 164 | 141 | 125 | 81 |
| 15-16 | – | 228 | 266 | 147 |

NOTE. — These photometric precision measurements represent (in parts per million) the median 6 hour precision (as defined by VJ14) of all dwarf stars observed by K2 during the engineering test (ET), Campaign 0 (C0) and Campaign 1 (C1). *Kepler*'s photometric precision was calculated from the PDCSAP_FLUX data in the *Kepler* light curve files.

## 5. DATA PRODUCTS

We have made our data products available to the community in the same format and with the same online interface and online diagnostics as we did in Vanderburg (2014) for Campaign 0 light curves. We restate descriptions of our data products and interface for completeness.

Our reduced light curves available at the following URL: `https://www.cfa.harvard.edu/~avanderb/k2.html`. This page contains links to compressed files with all of our reduced light curves, so that users can easily download the entire dataset. We release the light curves as comma separated value (CSV) files with two

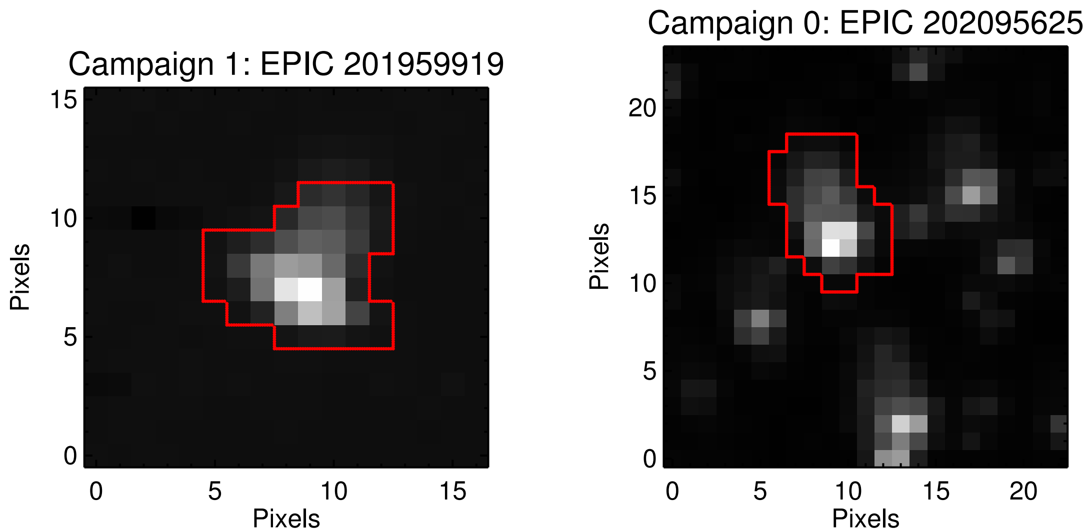


FIG. 3.— An example aperture from Campaign 1 compared with that from Campaign 0. The color scaling is roughly the same for both apertures, and the red outlines indicate the photometric apertures used in processing. Both of the apertures selected here are shaped based on the *Kepler* PRF. Campaign 0 was pointed near the Milky Way, and had a very high density of bright stars. Crowding was more of an issue in Campaign 0 than in Campaign 1, which was pointed near the north galactic cap.

formats. The first is a simple format with only two columns in each CSV file: the time of the observation and the SFF corrected light curve. In the simple files, thruster firing events have been automatically excluded. The second, more comprehensive format is a CSV file with columns for time, raw uncorrected flux, corrected flux, arclength (a measure of image centroid position as defined in VJ14), the measured flat field correction, and a flag indicating thruster fires. The additional information in the larger files makes it possible for users to re-derive the SFF correction under different assumptions and conditions.

In addition to the compressed files containing the entire dataset, we provide an online interface to quickly view and download individual light curves. We maintain a list of all of the Guest Observer targets observed during Campaign 1 at the following URL: `https://www.cfa.harvard.edu/~avanderb/allk2c1obs.html`. This webpage links to webpages for each individual target. Each target webpage includes links to both light curve CSV files for that particular object, as well as a plots of the raw and corrected light curve, the SFF correction as a function of image centroid position, the background flux in the target pixels, the position of the target in relation to the rest of the K2 Campaign 1 targets, and an image of the target pixels and the photometric aperture. Screenshots of the webpage for one particular target are shown in Figure 4.

## 6. SUMMARY

We have extracted light curves from data taken by the *Kepler* spacecraft during Campaign 1 of the K2 mission. We corrected the light curves for systematic effects due to the motion of the spacecraft using the technique of Vanderburg & Johnson (2014), and released the light curves to the community. The light curves we produce from Campaign 1 data have excellent photometric precision, better than that measured for light curves from Campaign 0 and the K2 engineering test. We attribute the improved photometric precision to the the fact that the density of stars in Field 1 is significantly less than the density of stars in Field 0, and that the typical dwarf stars observed in Campaign 1 were cooler dwarfs than in Campaign 0. We make our data available for download, and provide a simple interface for quickly looking at light curves online.

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Facilities: Kepler

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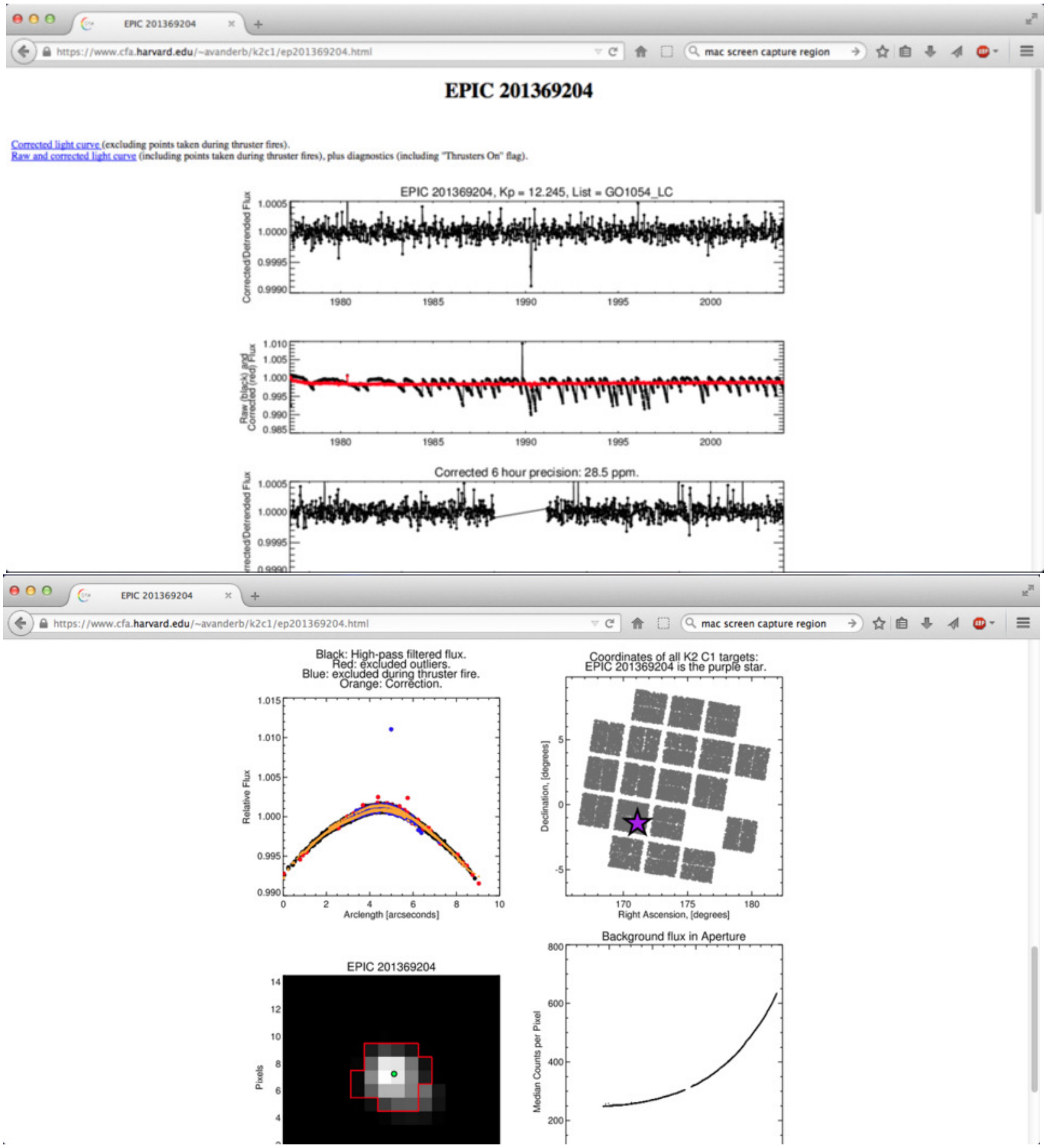


Fig. 4.— Top: Screenshot of part of a webpage for an individual target showing links to light curve files and a light curve plot. Bottom: Screenshot of the same webpage showing diagnostic plots.

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