Properties of a Previously Unidentified Instrumental Signature in Kepler/K2 That was Confused for AGN Variability

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Abstract

The Kepler satellite potentially provides the highest precision photometry of active galactic nuclei (AGNs) available to investigate short-timescale optical variability. We targeted quasars from the Sloan Digital Sky Survey that lie in the fields of view of the Kepler/K2 campaigns. Based on those observations, we report the discovery and properties of a previously unidentified instrumental signature in K2. Systematic errors in K2, beyond those due to the motion of the detector, plague our AGNs and other faint-target, guest observer science proposals. Weakly illuminated pixels are dominated by low-frequency trends that are both nonastrophysical and correlated from object to object. The instrumental signature lags in time as a function of radius from the center of the detector, crossing channel boundaries. Thus, systematics documented in this investigation are unlikely to be due to Moiré noise, rolling band, or pointing jitter. A critical clue to understanding this instrumental systematic is that different targets observed in the same channels of Campaign 8 (rear facing) and Campaign 16 (forward facing) have nearly identical light curves after time reversal of one of the campaigns. We find evidence of temperature trends that also reverse according to the Sun–spacecraft field orientation and that may dominate the systematics. These temperature variations are larger in K2 than in the nominal Kepler mission and strongly support our hypothesis of temperature-driven focus changes. Further characterization of this signature is crucial for rehabilitating K2 data for use in investigations of AGN light curves.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Quasars (1319); Broad band photometry (184); Space telescopes (1547); Time domain astronomy (2109); Transient sources (1851)

1. Introduction

The Kepler satellite was originally conceived as an exoplanet-finding mission. Its rich archival data (2009–2018) has revolutionized planet discovery and characterization (e.g., Borucki et al. 2010; Kopparapu et al. 2013). Kepler’s second mission, K2, has also impacted many other research fields including asteroseismology, stellar activity, microlensing, white dwarfs, supernovae, active galactic nuclei (AGNs), and more, together comprising ~60% of all publications using K2 data thus far. However, poorly understood instrumental systematics posed a significant impediment to an efficient exploitation of K2’s thousands of light curves. Part of the problem is that noise removal is optimized differently depending on the science objective.

Noise removal takes on one definition for planet transit detection and another for characterization of a faint “unknown” signal, as is the case of AGNs in the short timescale regime (<100 days; optical wavelengths). A planet transit manifests as a strictly periodic signal, characterized by a peak at the orbital frequency in the power spectral density (PSD) of a light curve. In contrast, AGNs exhibit intrinsically “noisy” fluctuations that are best characterized by the entire shape of the empirical power spectrum. The problem of cleaning data of instrumental noise at nearly all observed frequencies is critical to enabling science that relies on the entire PSD, which is the case for aperiodic or stochastic variability.

K2 data provide the most evenly sampled high-cadence (30 minutes) observations for a large sample of AGNs in the optical (over 4000 targets). If these data are properly mitigated for systematics, the observed sample may be studied jointly with data from the Zwicky Transit Factory (Bellm et al. 2019) and the Deep Drilling Fields of the Vera Rubin Observatory (Ivezic et al. 2008) to probe supermassive black hole (SMBH) physics on timescales of days to months. The physics in this regime are extremely valuable to constraining the corona–accretion-disk relationship (e.g., Giustini & Proga 2019) across the broad spectral taxonomy of AGNs (blazars, BL LACs, Seyfert Is, Seyfert IIs, radio-quiet quasars, radio-loud quasars, weak-lined quasars, broad absorption-line quasars, and more).

Characterizing the short-timescale variability properties of AGNs offers the promise of yielding deeper insights into the accretion physics of SMBHs and can potentially constrain physical scales. Most importantly, Kepler/K2’s extremely regular 30 minute cadence and sensitivity (to quasars) will remain unmatched for the foreseeable decade. Between Mushtizky et al. (2011), Wehrle et al. (2013), Edelson et al. (2014), Revalski et al. (2014), Chen & Wang (2015), Kasliwal et al. (2015), Shaya et al. (2015), Dobrotka et al. (2017), and Smith et al. (2018a), 21 Kepler AGNs have already revolutionized our understanding of AGN variability, while ~4000 K2 AGNs remain un- or understudied.

The Kepler telescope focused on a fixed 116 square degree field of view (FOV) between Cygnus and Lyra for 4 yr prior to K2. The focal-plane array (FPA) consisted of 42 2200 × 1024 pixel CCDs. Each CCD had a half-maximum bandpass of 435 to 845 nm and was read out through two channels (84 CCD channels also referred to as “module outputs”). The long-cadence data had an

5 https://keplerscience.arc.nasa.gov/publications.html#breakdown-by-subject
6 For focal-plane labeling and signal map per CCD, see Figures 24 and 25 in https://archive.stsci.edu/kepler/manuals/KSCI-19033-001.pdf.
effective cadence of \( \sim 30 \) minutes (Van Cleve & Caldwell 2016). Following the failure of the second of four reaction wheels in May 2013, causing Kepler to be repurposed as the “K2” mission, engineers (Ball Aerospace; McCalmont et al. 2015) devised a way to stabilize pointings using solar radiation pressure and periodic thruster firings. This solution permitted the mission’s observing strategy consisting of 19 subsequent fields along the ecliptic.

Several reprocessing pipelines were developed to correct pointing errors known as arc drift (e.g., Vanderburg & Johnson 2014; Aigrain et al. 2015; Armstrong et al. 2015; Crossfield et al. 2015; Foreman-Mackey et al. 2015; Huang et al. 2015; Libralato et al. 2015; Lund et al. 2015). Custom reprocessing software and recommendations were also published in the literature (Kinemuchi et al. 2012). Although many of these pipelines were optimized specifically for exoplanet transit detection, the majority were highly successful at producing arc-drift-free light curves and enabling science for many types of highly variable astrophysical signals. Many of these reextracted light curves are publicly available on K2-MAST.7,8

Large-sample science that may be possible with data in multiple K2 campaigns requires a streamlined approach that manual custom reprocessing cannot scale to. However, no single prescription to date rehabsilitates K2 data for the study of all types of astrophysical variability. Correlated Kepler/K2 noise systematics may arise from a combination of error sources such as rolling band, Moiré noise, faint blended background sources (Van Cleve & Caldwell 2016), and point-spread function (PSF) changes (Libralato et al. 2015). To characterize systematics, we primarily take advantage of correlations across multiple sources on the same channel. Using all pixels downlinked by K2 (per campaign), we detect features that exhibit dependencies on campaign, channel, magnitude, and distance from the boresight that cause hundreds of targets to be correlated with each other. Low-frequency and red-noise systematics, which are not mitigated by arc-drift corrections (Vanderburg & Johnson 2014; Luger et al. 2018), especially plague AGNs and other faint targets (O’Brien et al. 2018).

Unfortunately, there is no pipeline that sufficiently cleans K2 data for large-sample AGN variability studies. In this work, we discuss possible ways to identify systematics in K2 light curves that have been confused for astrophysical variability in published literature (e.g., Aranzana et al. 2018 for K2 AGNs and Dobrotka et al. 2017 for Kepler AGNs followed by a retraction in Dobrotka et al. 2019). On particular channels, systematics may dominate even at the optimal Kepler magnitude (12th magnitude stars). Finally, we review available light-curve-processing software that may provide suitable starting points for rehabilitating K2 data and we provide recommendations for continued development of reprocessing software that may potentially produce fully usable light-curve PSDs for scientific investigation.

This paper is organized as follows. Section 2 describes K2 AGN light curves that are available in Campaigns 8–19 with an emphasis on targets that overlap with Sloan Digital Sky Survey (SDSS; York et al. 2000) fields. Section 3 discusses known systematics in the first phase of Kepler that were corrected with cotrending basis vectors (CBVs); Section 4 presents our investigation of remaining systematics in K2 and discusses possible approaches for mitigating errors more effectively than CBVs. Section 5 demonstrates the performance of popular reprocessing methods such as the self-flat-fielding (SFF) prescription of Vanderburg & Johnson (2014) and the Everest 2.0 pipeline of Luger et al. (2018). Finally Sections 6 and 7 summarize our AGN science motivations to rehabilitate K2 data and the most important findings in this work.

2. AGN Targets

During the nominal mission, Kepler observed 21 spectroscopically confirmed AGNs and 66 high-probability AGN candidates. A systematic effort was undertaken by several groups to identify bright AGNs in the Kepler FOV. By cross matching observations from ROSAT, 2MASS, and WISE, Edelson & Malkan (2012) identified several AGNs. Radio-loud AGNs were identified using the VLBA (Wehrle et al. 2013). The KSwAGS X-ray survey of the Kepler field, conducted with SWIFT, discovered several candidate AGNs, 13 of which have been spectroscopically verified (Smith et al. 2015). Data for all observations acquired during quarters 0 through 17 are publicly available on the Kepler MAST archive (Data Release 25).

Kepler’s second mission, K2, targeted over 4000 AGNs and AGN candidates for periods of \( \sim 80 \) days, each of which is referred to as a campaign. Our group proposed observations of known quasars beginning with Campaign 8. These quasar targets were selected from the SDSS I/II (Schneider et al. 2010) and SDSS-III quasar catalogs (Pâris et al. 2017). Robust photometric quasar candidates (with positions accurate to \( \sim 50 \) mas) are also drawn from Richards et al. (2004), Bovy et al. (2011), Peters et al. (2015), and Richards et al. (2015), where the Peters et al. catalog specifically targeted quasar candidates due to their variability. Thus, our targets are a heterogeneous K2 sample of known quasars and high-confidence photometric quasar candidates (most with robust photometric redshifts).

In short, we proposed to target all SDSS quasars (and many quasar candidates) that overlapped with the K2 FOV in each campaign starting with Campaign 8. The focus was on objects in SDSS Stripe 82 where \( \sim 100 \) epochs of existing photometry (Annis et al. 2014) can be coupled with K2 photometry to increase the time baseline for investigations of quasar variability. Figure 1 illustrates the magnitude and redshift distribution of SDSS quasars targeted by our group in Campaigns 8, 10, 12, 14, 16, 18, and 19. These targets include objects that are fainter than the typical range of magnitudes included in the standard pipeline processing (e.g., Luger et al. 2018). For each campaign, Table 1 lists the number of observed targets, approximate maximum redshift (column \( z_{\text{max}} \)), and faint limit magnitudes (\( i \) band; column \( \text{imagmax} \) is a metric referenced for quasar science; see Richards et al. 2006). Note that many more targets were proposed than were accepted and the process for sub-selecting the observed targets was not uniform (sometimes favoring bright targets and known quasars, but other times to reduce high spatial density such as in the Stripe 82 area).

For this investigation of instrumental trends we use all raw data available for Campaigns 8–19 (not AGNs exclusively). We also analyze V14 and Everest 2.0 reprocessed light curves for all targets in Campaigns 8 and 16, which are corrected for arc drift and are also background-subtracted.

3. Kepler/K2 Cotrending Basis Vectors

Low-frequency instrumental systematics in the nominal Kepler mission could be removed (to an extent) with CBVs generated by the data calibration module, PDC

7 https://archive.stsci.edu/missions-and-data/k2
8 https://keplerscience.arc.nasa.gov/new-keplerk2-high-level-science-products-available.html
CBVs were calculated for each observing quarter and per channel with a principal component analysis (PCA) of an ensemble of “quiet” stars. PDC-MAP (maximum a posteriori) supplied CBV-corrected light curves with weights derived from the most correlated neighboring sources to individual targets for a predetermined aperture (using a minimum of five vectors).

CBV subtraction was, however, problematic for preserving intrinsic astrophysical variability. Higher-order vectors (3rd or higher) added variance and high-frequency features (Smith et al. 2012). Any coincidental correlations between the intrinsic signal and CBVs was projected onto the model used for correction. CBVs do not mitigate spatially dependent systematics such as (boresight-dependent) focus changes, rolling band, or Moiré noise.

The challenge of error mitigation in the first phase of Kepler was typically approached with custom manual reprocessing or calibration with ground-based data when available (Smith et al. 2018a and Kasliwal et al. 2015, respectively). For AGNs, custom-aperture or PSF photometry was particularly important in order to minimize noise from background sources in crowded regions and from extended host galaxies. Custom-aperture optimization and CBV subtraction was possible with PyKE (Still & Barclay 2012) or similar software but without the advantage of simultaneously fitting neighboring sources as in PDC-MAP that could mitigate issues of over-fitting CBV components.

The compromise of minimizing known and new instrumental noise while preserving the astrophysical signal of interest carried over into Kepler’s second mission, K2. While correcting complex arc-drift systematics became the calibration priority, few publications focused on removing other types of instrumental noise or documenting evidence of Kepler’s natural degradation.

CBVs are available for K2 in the EVEREST 2.0 package (Luger et al. 2018) calculated with the SysRem algorithm (Tamuz et al. 2005) from an arc-drift-corrected light-curve ensemble. While the first- and second-order CBVs do an excellent job at removing the lowest frequency trends, they cannot account for some of the more troubling and recognizable instrumental signatures that we identify in our AGNs and other variable star samples. For both Kepler and K2 data, CBVs removed the lowest frequency systematics very well, but residual instrumental trends are at best mixed with variance by the PCA-detrending approach. Theoretically, PCA cannot account for any local spatial dependence within a CCD (channel) or for time-dependent systematics across the focal plane such as temperature-dependent effects. There is a critical need for other calibration algorithms in order to fully exploit the rich K2 archive.

4. Correlated AGN Light Curves

The first evidence that we encountered for the presence of residual systematics in K2 data after arc-drift removal came from visually identifying strong correlations between independent target light curves. Inspection of AGN light curves from K2 indicated that certain patterns were commonly seen, despite the fact that all AGN light curves are expected to be unique. Further investigation shows that those common patterns reveal strong systematic effects in the data.

To illustrate the problem, here we compare some simulated light curves that, by design, lack features correlated in time, with some K2 light curves that clearly exhibit correlated features. In Figure 2, we illustrate the AGN variability that we expected to observe with K2. Following Moreno et al. (2019), each column is generated with a simple stochastic model (damped random walk, hereafter DRW) corresponding to characteristic timescales \( \tau_{\text{decay}} = 10, 25, \) and 50 days, respectively. Although the light curves in each column have the same underlying parameters, each is unique and there are not obvious correlations between the different light curves in terms of the locations of the peaks and valleys.

In contrast, in Figure 3 we plot light curves identified using an agglomerative clustering analysis that detects high correlation in the K2 AGN sample used for scientific analysis by Aranzaña et al. (2018). A visualization of the raw and smooth AGN light curves reveals trends that exhibit multiple peaks and troughs in phase across several sources. Such patterns are not expected between unique AGNs and indicate that systematics are completely dominating these light curves. Simply put, any matching variability patterns have nothing to do with the astrophysical targets.

The groups represented in Figure 3 plot light curves from clusters with the strongest covariance. In the right-most panel, we plot cluster members that exhibit a mixture of astrophysical signal and instrumental trends. Although this clustering analysis was executed on full postage stamp raw light curves, rerunning the analysis with K2 SFF (Vanderburg & Johnson 2014) from...
Figure 2. Expected AGN variability (simulated). Columns (left to right) show example light curves with increasing characteristic intrinsic timescales $\tau_{\text{decay}} = 10, 25,$ and 50 days. These simulated light curves include a constant photometric noise of 5% and constant variability amplitude. The black curve outlines a smoothed trend through each light curve to show that relatively low frequency trends do not correlate even within columns for "objects" having the same characteristic timescales. We do not expect AGNs to vary synchronously, except if that trend is due to correlated noise in the CCD.

Figure 3. Examples of full postage stamp AGN light curves from K2, Campaign 1, referenced in Aranzana et al. (2018). The light curves of Vanderburg & Johnson (2014) retain similar patterns that can be detected by the same clustering algorithm. The three different colors highlight just a few of the many “types” of systematic trends that cause independent AGNs to be correlated with each other.
MAST that are background-subtracted also reveals the same correlated behavior that we attribute to instrumental systematics. Such correlations are strong evidence that faint-object K2 light curves show patterns that are instrumental, not astrophysical, in origin. These systematics are not removed by any currently used analysis pipeline.

We measured systematic noise to be $<1\%$ percent for AGNs close to 16th magnitude and $5\%$–$8\%$ for AGNs with magnitudes fainter than 19 (for further details of these estimates, see Section 4.4). These trends remain even in calibrated, background-subtracted light curves (see VJ14 and the Everest 2.0 light curves in Section 5). The amplitudes of the trends are typically in the range of 50–200 counts in faint and bright light curves (that are background-subtracted, such as the Everest light curves in Section 5). The fractional fluctuation expected for typical AGN variability is $5\%$–$50\%$ with a median value of $\sim20\%$ on timescales of years (MacLeod et al. 2012). Short-timescale AGN variability, less than 100 days, has not been well studied for statistical samples but recent analyses measure variability of $5\%$–$20\%$ in the short-timescale regime (J. Moreno et al., in preparation). This work aims to characterize K2 systematics that cause targets to be correlated with each other and that are not mitigated by typical background subtraction or detrending with currently available K2 CBVs so that they are not mistaken for astrophysical variability.

4.1. Channel Dependence and Spacecraft Orientation

As a next step in our analysis, we test for channel dependence of the instrumental systematics in K2 light curves. In Figure 4, we show median light curves (normalized flux) per channel for Campaign 8 (orange) and time reversed for Campaign 16 (purple). Features resembling an “M” or “W” (or other complex patterns) that are synchronized in time reveal channel-dependent systematics that dominate over the astrophysical variability of the sources.

For a given channel in Campaign 8 or 16, we calculate the curves plotted in Figure 4 as follows:

1. We calculate all the light curves for objects within the 13–20 magnitude range on that channel, using all of the pixels in each object’s postage stamp (also interpolating any missing/spurious cadences).
2. We normalize the individual light curves by subtracting the mean flux of the object and dividing by the standard deviation. This normalization was done to ensure that the median light curves would not be disproportionately affected by brighter objects.
3. For each channel, we take the median value across all the light-curve ensembles, evaluated at each cadence.9

Using the total postage stamp for a large range of source magnitudes ensures that the systematics from the background pixels will dominate at each cadence. Additionally, using all 13–20 magnitude light curves in C8 and C16 shows how widespread these systematics are.

Note the strong correlations after time reversal between targets that are unique to the fields corresponding to Campaign 8 (rear facing) and Campaign 16 (forward facing). This observation is perhaps the most crucial clue to understanding the correlated noise shown in Figure 3. It strongly suggests that the underlying problem relates to the relative Sun–spacecraft-field orientation which would have been approximately the same on day 1 of Campaign 8 as on the last day of Campaign 16 and vice versa. It further means that these systematics are unlikely to be due to Moiré rolling band, dust particles, etc.—unless those are somehow dependent on the Sun–spacecraft-field orientation and are largely repeatable. Instead it is strongly suggestive of temperature-dependent focus changes (that are further subject to differences between the channels). This pattern may explain the observation by Armstrong et al. (2015) and Aigrain et al. (2015) regarding the need to split campaigns into separate time segments on either side of the time when the spacecraft was perpendicular to the Sun (see Howell et al. 2014 Figure 2 for a visualization of the geometry).

4.2. Rolling Band

Rolling band can be a significant source of additive alias noise that depends on channel, local-detector electronics-board temperature, amplifier temperature, and excitation by bright sources (Van Cleve & Bryson 2017). The rolling band may add as much as 20 flux counts per pixel10 and has been measured to propagate across pixels on the timescale of hours (Cleve et al. 2016) which was critically important to Kepler's original mission. It is also possible that increases in flux due to rolling band may occur on timescales of days to weeks which are much more detrimental to the K2 mission, heavily obscuring the signal of faint or extragalactic targets. In the case of AGNs, 20 counts of noise per pixel would completely obscure the astrophysical signal if all of the source variability is in the range of 100 flux counts. Examples of such ranges exist among the 21 confirmed AGNs of the original Kepler mission (see Figure 12 in Smith et al. 2018b). Any additive instrumental signature that temporally modulates the flux of a distant AGN by a few tens of counts per pixel could entirely dominate the shape of the K2 light curve.

The channels outlined in red in Figure 4 are flagged for worst rolling band (Campaign 0 release notes; Van Cleve & Bryson 2017); however, these channels are not necessarily the most dominated by the type of systematics that we aim to characterize. Since rolling band flags were generated at commissioning, it is possible that noise characterization was only exploited at timescales most likely to compromise the original mission (detection of planet transits) and that low-frequency modes of the rolling band are poorly characterized across each CCD. Additionally, channels may not have degraded uniformly and temperature changes may follow very different trends in the K2 mission than they did during prelaunch commissioning. Thus, channels that are unflagged may still be strongly affected by rolling band.

Regardless of timescale, hours or weeks, much of the rolling band should be mitigated by careful background subtraction as per handbook recommendation (Van Cleve & Bryson 2017). Rolling band is characteristically responsible for a flux increase that propagates across CCD rows. Although raw light curves without background subtraction are used in Figures 3 and 4 to maximize systematics, we report that rerunning the analysis for both figures using VJ14 reprocessed light curves and Everest light curves, which employ both aperture-photometry optimization and background subtraction (see Vanderburg & Johnson 2014 and Luger et al. 2016, Section 3.1, for details of photometry), results in nearly identical trends. The low-frequency patterns seen in Figures 3

9 Python scripts and notebooks to reproduce or modify figures from this article are available at https://github.com/trybutry/agn_everest.

10 https://keplerscience.arc.nasa.gov/new-in-lightcurve-identifying-time-variable-background-noise.html
and 4 are not sufficiently mitigated by a regular background subtraction and appear to be an altogether different type of noise that turned up post-launch. One of the most revealing characteristics of the noise under investigation is a temporal and spatial dependence that crosses channel boundaries and is coupled to the Sun–spacecraft orientation.

4.3. Spatial Dependence

There are a number of arguments against rolling band being the main cause of systematic noise in our AGN sample. The main argument is that we find a spatial dependence relative to the boresight rather than along the read-out direction of the CCDs. We also note a time dependence of that spatial dependence, which we focus on in this section. In Figure 5, we gather a set of noise-dominated light curves from channel 55 for Campaigns 8 and 16. The light curves are ordered by decreasing pixel row index (Y). The sequence of dip features (starting with three such dips in the top panel) shifts by a few days with decreasing pixel row index (ending with only two dip features in the bottom panel).
panel). Such a dependence may appear to be consistent with “rolling band” despite channel 55 not being identified as having high rolling-band noise. However, the timescale of the shift is days, not hours (although examples exist of what is thought to be rolling band on such timescales), and the same shifting pattern is seen in reverse in Campaign 16 light curves. Furthermore, we find evidence (below) that the time drift in the pattern crosses channel boundaries.

The time dependence of dip features with boresight distance is smoothed out in the big-picture view of systematics provided in Figure 4. The median light curves of Figure 4 can be seen as a vertical collapse of the light curves in Figure 5. To measure the time shift of peak and dip sequences such as “N-,” “M-,” or “W-” shaped features, we use a wavelet algorithm to time the occurrence of several local minima per light curve, which we demonstrate with the estimates of $t_{\text{max}}$ and $t_{\text{min}}$ in Figure 6 for channel 33. Flux minima or dips due to astrophysical signal are expected to occur randomly in time, whereas any one or more minima that occur at about the same time for several light curves reveal an instrumental origin.

To demonstrate the method used to visualize the time drift per channel and across channel boundaries, in Figure 6, we examine a slightly simpler pattern on channel 33 consisting of one peak and dip pair (rather than the more complex dip sequence of channel 55 that was shown in Figure 5). We estimate the time of occurrence for the events when a peak and dip pair occurred in the latter half of Campaign 8 for all point sources (CH 33) fainter than 16th Kepler magnitude, totaling 136 sources.

The top panel of Figure 6 is a recreation of the median light curve of channel 33 from Figure 4 along with two additional light curves showing the 25th and 75th percentiles using the 136 faint-magnitude objects. These three curves provide a visualization of the peak/dip pair feature and evidence of a time shift. The mean time difference between the peak and the dip events is 11.8 days. The standard deviation is 1.4 days (136 sources) which is low enough to suggest that the same feature is being tracked across the sample. The bottom two panels show the time of the peak and dip, $t_{\text{max}}$ and $t_{\text{min}}$, respectively, as a function of pixel row (purple) and column (gray). Each source light curve is smoothed with a running mean filter to minimize the influence of outlier flux values prior to peak and dip detection. The y-axis and x-axis range for both bottom panels are equal and show similar slope trends if the peak and dip are shifting together. The peak-dip feature indeed shifts as a function of pixel row and column on this channel. The width of the peak also exhibits more variance than the width of the dip and may account for a large fraction of the spread seen in the bottom left panel. In the following analysis, we use this same method to visualize global spatial dependence across the focal plane by transforming row and column pixel coordinates to radius (boresight distance). The diversity of patterns from channel to channel, for example, the number, width, and amplitude of peaks and dips, makes it more difficult to measure the time dependence and spatial dependence. Therefore, we rely heavily on density or clustered groups to reveal continuity across channel boundaries.

To test if the timings of sequential dips (for example a “W” feature) exhibit a spatial dependence from channel to channel, we plot the times, $t_{\text{min}}$, for the last two dip features per light curve as a function of radius from the FOV center. Tracking one dip alone would not be sufficient to tell which dip event is measured. Figures 7 and 8 show timings of the dip features for light curves observed in modules 11 (which includes channels 33–36 as seen in Figures 4), 12, 13, 14, and 15 (channels 49–52), which span the full diameter of the focal plane, and perpendicular modules 8 (channels 21–24), 13, 18, and 23 (channels 77–80; short of a full diameter due to failed module 3). We account for the CCD rotations and read-out directions of the four channels in each module according to rotations noted in Figure 24 of Van Cleve & Caldwell (2016) and we track radius in units of pixel coordinates.

Figures 7 and 8 reveal a time dependence and radial dependence for systematics that do in fact cross channel boundaries. Transitioning colors indicate these channel boundaries as well as channel numbers above and below each color. Parallel channels on the same module are plotted in the same color (refer to Figure 4 for channel number, module number, and channel-specific dip feature). On some channels (or at some radii), this approach results in more than two clusters. Since clusters reveal synchronous dips in the light curves of multiple targets, it is possible that the depths of these dips vary across the light-curve sample such that for a subset of light curves, the first two dips were the most prominent “W” shape and for other light curves, the last two dips were the most prominent “W” shape. Additionally, in Figure 8, the reduction in variance at the largest radii appears to correlate with a narrowing of dip features which makes it easier for the algorithm to find the minimum than for broader/shallower dips. Some channels also appear to have up to three or four clusters which reflects diversity in the depth/width and number of dips of the instrumental signatures on any module. However uncertain the source of the instrumental signature, it is empirically clear that the signature crosses channel boundaries and cannot be rolling-band noise.

4.4. Magnitude Dependence

Since it is possible that the systematics are additive and thereby more dominant in faint sources with low counts, we explored a magnitude dependence at the pixel level and the target level. The majority of bright K2 stellar sources reside in the magnitude range $12 < K_p < 15$, AGNs reside in the magnitude range $15 < K_p < 21$, and background pixels generally have magnitudes $K_p > 18$ depending on the size of the postage stamp and the extent of the PSF. Faint background sources $\sim$19th magnitude may also reside in every pixel (Van Cleve & Caldwell 2016).

In Figure 9, we selected a worst-case example, channel 55 (see Figure 4) from Campaign 8, to investigate the typical distribution of pixel illumination, measured in magnitudes. To convert from flux to magnitudes we use the equation, $K_\text{Mag} = -2.5 \log(\text{flux}/1.74e5) + 12$. We show the distribution of Kepler magnitudes for individual pixels in order to quantify the percentage of “empty” pixels that may be used to characterize instrumental trends in each CCD background. The left panel of Figure 9 includes an inset with example postage stamps at a snapshot in time, demonstrating that the postage stamps contain very few truly empty pixels that can be used to compute local backgrounds. The raw magnitude distribution of pixels in the inset is also shown in the right panel by the purple bins. Pixels in these four postage stamps range from 21–22.2 Kepler magnitudes. Although nearly 40%–50% of pixels are fainter than the faintest pixels in these four postage stamps, these faint sources likely have no background pixels and their PSFs may even jitter out of the cutout boundaries.

To examine how systematic effects reveal themselves differently as a function of target magnitude, we compute and stack full

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11 See https://keplerscience.arc.nasa.gov/the-kepler-space-telescope.html.
Figure 5. Campaigns 8 (left) and 16 (right) channel 55 objects ordered by their Y position on the CCD. “X” is the pixel column and “Y” is the pixel row. The red line marks the position of the central dip in the light curve of the first object. There is a position- (but not magnitude-) dependent phase shift of about 10 days in the systematics.
The peak we plot these percentile light curves in units of fractional change of pixel row greater than 5% while on better channels, such as 62 located at the magnitude targets have larger fractional changes than brighter channel 55 peak feature appearing in multiple light curves in channel 33. Top: The median light 25th, 50th, 75th, and 85th percentile at each epoch. In Figure 10, Pixel row and column dependence of a time-shifted peak and dip feature. Bottom: Timing of the peak \( t_{\text{peak}} \) and dip \( t_{\text{dip}} \) as a function of pixel row (purple) and column (gray) for 136 faint sources on channel 33. The peak–dip feature shifts as a function of pixel row and column, but this trend is a broader function of radius from the center of the FOV as we will illustrate in the following figures.

We display the results of a related analysis for module 16 in Figure 11 for a better view of the module dependence in the top right panel of Figure 11 across magnitude bins. It is likely that pixels in brighter magnitude bins (percentiles 60–80) are spatially coupled in some way, possibly by belonging to the same source or system of stars seen by pixels in relatively close spatial proximity on the CCD. Postage stamp flux light curves and select the 5th, 10th, 15th, 25th, 50th, 75th, and 85th percentile at each epoch. In Figure 10, we plot these percentile light curves in units of fractional change and label each with its corresponding mean (target) magnitude for channel 55 (left panel; edge of focal plane) and channel 62 (right panel; center of focal plane). Figure 10 reveals that fainter-magnitude targets have larger fractional changes than brighter targets, especially on bad channels. Channel 55 shows that targets with Kepler magnitudes fainter than 18th exhibit amplitudes greater than 5% while on better channels, such as 62 located at the center of the FPA, faint targets exhibit fractional changes at \( \sim 2\% \) or better.

We display the results of a related analysis for module 16 in Figure 11 and for all modules and channels (from Campaigns 8 and 16) in Figure 12 where correlated systematics can be seen across the K2 FOV. In these visualizations, we have stacked 500 (magnitude-binned) median light curves generated from “empty” pixels (the faintest 80% shown in Figure 9) to produce intensity maps for the entire CCD array for Campaigns 8 and 16 using the method developed by O’Brien et al. (2018). A zoomed-in example of a module (16) is shown in Figure 11 for a better view of detail. Nonrandom structure in these intensity maps shows pixel correlations across time (along the x-axis) as a function of magnitude (y-axis in each channel) in the channel background. We applied flux smoothing and whitening (transformed to having a mean of zero and a variance equal to one) in order to uniformly compare the strength of systematics across magnitudes and channels. We use a divergent purple-to-orange color map to represent trends above and below the median flux value, respectively. Saturated colors from purple to orange indicate a decreasing trend in each magnitude-binned light curve as seen in Campaign 8. For example, shifting dips show up as the orange Florida shape (channel 15) or striping feature (channel 55) in the left-most upper block in Figure 12. Trends in Campaign 16 are seen to be reversed in time as compared to Campaign 8 for corresponding channels.

In all campaigns (not shown here), modules 14, 15, 19, and 20 are least affected by systematics (i.e., intensity maps contain the most white), whereas modules 6, 11, and 16 (on the left edge of Figure 12) exhibit the strongest intensity systematics. Scanning each intensity map from the top down, the direction of increasing magnitude (dimmer pixel illumination), we observe structure corresponding to peaks (purple) and dips (orange) in median light curves. Strikingly, all of this correlation or structure comes from pixels with magnitudes of 19–30 which are used for local background subtraction. We attempted to use these magnitude-binned background light curves to correct various stellar and AGN light curves, but it was unclear how to evaluate an optimal fit without suffering the same failings of a PCA approach. Additionally, our detrending attempts consistently revealed that light curves were not in phase with their corresponding magnitude-bin median light curve. Light curves were more correlated to and in phase with their local neighbors. Although each magnitude bin averages together local spatial information within a channel, thus losing spatial information, there is a persistent time dependence in Figures 11 and 12 that resembles phase-shifting features discussed in the previous section on spatial dependence. For example, the phase shift between light curves in channel 55, shown in Figure 5, resembles the time dependence in Figure 10 as well as the time dependence in the top right panel of Figure 11 across magnitude bins. It is likely that pixels in brighter magnitude bins (percentiles 60–80) are spatially coupled in some way, possibly by belonging to the same source or system of stars seen by pixels in relatively close spatial proximity on the CCD. A general boresight distance dependence can also be noted in Figure 12 since three inner modules exhibit a trend that is opposite of the rest of the modules in the array. Modules 12, 13, and 18 exhibit a negative slope, purple to orange in Campaign 8, while all other modules have a positive trend, orange to purple. The slopes reverse in Campaign 16 for inner and outer modules. Smaller scale features (orange marks) on module 16, channel 55, also become mirrored between Campaigns 8 and 16. Some initial boresight PSF dependence is captured in these visualizations such that inner channels might contain a cleaner population of background pixels and outer channels likely include more pixels from irregular PSFs. The main takeaway, however, is that pixels from separate postage stamps and from separate channels that should observe unstructured background are correlated despite channel boundaries. Magnitude slicing emphasizes that this systematic affects faint sources the most since they typically have smaller postage stamps and from separate channels that should observe background subtraction. Background pixels in a small postage stamp can collect counts from the source going out of focus as it breathes in response to temperature changes resulting directly from the Sun–spacecraft orientation.

4.5. Spacecraft Temperature Variations

The Sun–spacecraft orientation would have largely resulted in the telescope experiencing seasons of fluctuating incident
light from the Sun and fluctuating heat from reaction wheel speeds (in response to changes in solar radiation pressure). To test our hypothesis that these systematic trends are the symptom of temperature-dependent focus changes, we examined temperature data for K2 Campaigns 8 and 16 and reviewed analyses of reaction wheel speeds and pixel response function (PRF) widths included in the ancillary engineering data release report (KSCI-19150-001). Both our analysis of publicly available temperature data and analyses in the data report provide strong

Figure 7. Timing a sequence of two dip features in the light curves of point sources fainter than 16th Kepler magnitude for all channels in modules 11, 12, 13, and 14. The scatter plots depict the epochs of two dip features per target as a function of radius from the FOV center. Channels are colored such that the gradient from light to dark indicates increasing radius. For example, navy points on the left are channels 33 and 36 and on the right are channels 51 and 52. The lack of randomness indicates that the detected minima/dips are systematic and form trends that cross channel boundaries. The channels tested correspond to horizontal (x-axis) modules across the FOV diagram in Figure 4.

Figure 8. Same analysis as in Figure 7 but for vertical (y-axis) modules 8, 13, 18, and 23 shown in Figure 4. Failed module 3 (channels 5–8) is shaded in gray. Time dependence and radial dependence of these systematics show the least variance at the outermost radius.

12 Report available at https://archive.stsci.edu/files/live/sites/mast/files/home/missions-and-data/kepler/_documents/KSCI-19150-001.pdf.
evidence that the systematics characterized by trend reversal in Campaigns 8 and 16 (or more broadly by the Sun–spacecraft orientation of each campaign) is causally linked to temperature-driven focus changes.

We examined two temperature measurements from ancillary engineering data products for the K2 mission and found that Campaign 8 (forward facing) and Campaign 16 (rear facing) have inverted temperature profiles (KSCI-19150-001). In Figure 13, we plot TH2LVAT data for a sensor located between the spacecraft and the primary mirror and TH2PMAT data for a sensor located underneath the primary mirror. The data release document reports that the peak-to-peak change in TH2LVAT is four times larger in the K2 mission than in the nominal Kepler mission. This large increase in peak-to-peak change could explain why these systematics only become a dominant problem in the K2 mission.

11 The Astronomical Journal, 162:232 (18pp), 2021 December Moreno et al.

13 Data available at https://archive.stsci.edu/missions-and-data/kepler/kepler-bulk-downloads.
Focus variations can cause empty pixels in a postage stamp to also observe photons from the source and become less appropriate for estimation of the background. High pointing jitter from operating with only two out of four reaction wheels also complicates flux extraction and background estimation with the constraint of a fixed-size postage stamp. Reaction wheel speeds used in the K2 mission are reported to nearly double from speeds used during the Kepler mission. Lastly, trend reversals between forward-facing and rear-facing campaigns are also visible in the speed data for reaction wheels #1 and #3 (Figure 5 in the data report).

Commissioning data from the Kepler mission shows strong correlations between PRF widths and both sensor temperatures (Figure 6 in KSCI-19150-001). The characteristic mirroring or time reversal associated with Sun–spacecraft orientation and the instrumental trends under investigation is the smoking gun.
These temperature profiles and analyses of reaction wheel speeds and PSF widths in the report provide strong evidence for our focus-change hypothesis for all patterns that become inverted from Campaign 8 to Campaign 16 (Figure 5) or that register high correlation after time reversal in Figure 4.

4.6. Optimizing the Aperture

Aperture photometry is a technique that assumes a useful shape such as a square or circle rather than a PSF model to collect and sum observed counts. After estimating the total counts from all pixels within some defined area, an estimate of the background can be subtracted to compute the flux of the source. An optimal aperture captures as much of the signal (as close to 100% of the true PSF) as possible to maximize S/N. Fainter sources typically require larger apertures. However, as the number of pixels increases, the PSF wings of a faint source have increasingly larger errors. These considerations are particularly relevant for AGNs in crowded fields and local (low-luminosity) AGNs that do not significantly outshine their host galaxy. In such cases, flux extraction of the faint AGN becomes prohibitively more difficult since the outer wings of the PSF are convolved with the extended galaxy profile. The K2 systematics discussed in the previous subsection present a tertiary motivation for PSF modeling or developing a careful aperture optimization scheme.

Careful frame-by-frame PSF photometry may be a way to mitigate time-dependent focus changes in K2 light curves. Empirically, we find that the aperture size highly influences the strength of the instrumental signature under investigation. Typically for AGNs, we would want very small apertures to reduce blended background sources in dense fields. We demonstrate the issue with this approach in Figure 14 using the lightkurve package (Lightkurve Collaboration et al. 2018).  

We observe a tradeoff between arc-drift correction performance and the inclusion of complex systematics that are difficult to detrend. In Figure 14, we compare four pixel-moving aperture light curves for four unique targets (columns) to full postage stamp light curves (little arc drift but maximal error contributed by more pixels). In the first row of Figure 14, we plot full postage stamp light curves for pairs of objects with mirrored systematics in Campaigns 8 and 16. In the second row, we show the four pixel-moving aperture for each object. Finally, in the third row, we show the SFF-corrected moving aperture light curves. The smaller aperture minimizes the inclusion of instrumental trend, as seen in the second row, but the light curve is still dominated by the effects of arc drift, even after the application of the SFF correction in the third row.

PSF modeling may be a crucial part of the error mitigation process for faint targets at the largest distance from the center of the FOV. However, it is unclear how dramatic PSF changes may be throughout a campaign and if they are radially dependent given the initial focus on nonuniformities. It is also possible that the PSF may go out of focus to the point that the signal of interest spreads beyond the edges of a postage stamp. There is no easy way, to our knowledge, to deal with these cases.

5. K2 Reprocessing Pipelines

Two of the most successful and popular arc-drift-corrected K2 data sets available through MAST are the SFF method of Vanderburg & Johnson (2014) (henceforth VJ14) and the pixel level decorrelation (PLD) method implemented in EVEREST by Lugger et al. (2018). Both of these methods have also been implemented in the lightkurve package (Lightkurve Collaboration et al. 2018). In this section, we present and discuss SSF and EVEREST 2.0 public light curves, showing that these data products are successfully free of arc drift, but still require instrumental noise removal at low- to mid-range frequencies prior to employing time series analyses such as estimating power spectra.

The SFF method corrects for systematics correlated with centroid arc length (drift) by fitting a third order B-spline to position offsets recorded across the light curve. VJ14 light curves are plotted in the second row of Figure 15 (for multiple Kepler magnitudes). For comparison, raw light curves are shown in the first row. The VJ14 pipeline first defines an optimal stationary aperture by fitting a section of pixels around the target centroid where radius is a function of magnitude. A median background is estimated from excluded pixels and subtracted from the optimal aperture light curve. VJ14 SFF data products include multiple circular and PRF-based apertures that are available in MAST. In Figure 15, we apply each processing method to the full postage stamp aperture light curves for the purpose of emphasizing differences due to the arc-drift correction algorithms in each processing chain rather than differences due to aperture selection or optimization. K2 SFF light curves are continuum-normalized and no flux errors are available. A flexible implementation of the SSF method is available in the lightkurve package.

PLD (Deming et al. 2015) is another highly successful method for arc-drift removal (Lugger et al. 2018). PLD is a Taylor series expansion of fractional flux changes in individual pixels and pixel products intended to model covariances in flux variations (across pixels) resulting from instrumental motion. In EVEREST 1.0, PLD is calculated from pixels within each individual target postage stamp. In EVEREST 2.0, PLD weights are computed from an ensemble of neighboring stars.
on the same channel (limited to bright stars in the magnitude range of $11 < K_p < 13$) and thus is referred to as the neighboring PLD. EVEREST 2.0 also makes use of a Matern 3/2 Gaussian process (GP) kernel to account for systematic covariance between cadences when fitting the noise model. The PSD of a Matern 3/2 kernel has an exact closed-form representation, with power-law slope $-4$ in the limit of high frequencies and constant for low frequencies, with a knee set by the natural frequency tuning parameter $\omega_0$ (Foreman-Mackey et al. 2017). The choice of a Matern 3/2 in EVEREST may therefore imprint an artificial power-law slope into the observed PSD. We experimentally verified that these power-law slopes appear in finite sample sizes by drawing random sequences from Gaussian process kernels with known input $\omega_0$ and time sampling comparable to the K2 light curves.\textsuperscript{15} EVEREST 2.0 light curves are plotted in the fourth row of Figure 15.

Naive use of the Matern 3/2 kernel results in a light curve with added variability at low frequencies (red noise). In Figure 16, we show an example raw light curve with little variability for which use of the Matern 3/2 kernel results in added power at low frequencies. In the left panels, we see the raw light curve with arc drift (top) and the EVEREST 2.0 light curve (bottom) available through MAST. In the right panels, we plot the PSD estimated with the Lomb–Scargle periodogram and a power-law model fit above and below the noise floor. The PSD slope of the raw light curve resembles white noise with a slope approximating zero, while the PSD of the EVEREST 2.0 reprocessed light curve exhibits a slope equal to that expected for AGN variability (PSD $\propto f^{-2}$), but this variability is not real.

In the case of AGNs and low-frequency stellar variables such as M dwarfs, artificial power is added by the use of the Matern 3/2 kernel. In Figure 17, we show the slope of the power spectrum in EVEREST 2.0 light curves as a function of Kepler magnitude. Nearly all of the targets, represented by density contours, in Figure 17, need to be reprocessed with the EVEREST 2.0 package or lightkurve PLD routine with the Matern 3/2 amplitude parameter set to zero (or GP modeling toggled off) in order to benefit from the n-PLD method; see also Saunders et al. (2019) who performed an assessment of the impact of different detrending algorithms on the PSD and determined that PLD with a careful choice of kernel is a promising method for recovering signals that can be modeled by a DRW (PSD $\propto \nu^{-2}$). While the DRW is well established as a useful model to characterize AGN variability at long timescales (years), it is unclear whether DRWs are suitable for the timescale regime probed by K2.

For AGN short-timescale variability (and K2 data in particular), we are most interested in estimating the high-frequency slope of the empirical PSD. GP processes require a priori knowledge of an appropriate model (kernel) for the astrophysical signal which typically corresponds to implicit PSD slopes. However, Kepler/K2 observes a unique timescale regime that has never been studied or surveyed before for a complete AGN sample. Additionally, a rehabilitated Kepler/K2 data set of 30 minute cadence provides a unique and valuable large sample for validating the accuracy and usefulness of popular and novel statistical models used in variability studies to constrain physical models of accretion disks. Thus, there is a strong desire to rehabilitate the light curves of AGNs observed during the K2 campaigns as discussed in the next section.

6. Why Rehabilitate K2 Data?

Kepler/K2 AGNs may offer significant insights to the overall understanding of AGN variability acquired from investigations of ground-based light curves. PSD (and structure function; SF) features at timescales less than 50 days have been debated in multiple investigations of ground-based light curves.

\textsuperscript{15} \url{https://github.com/BrownDwarf/probabilisticAGN}
Short-timescale AGN variability is difficult to disentangle from the effects of gappy, irregular cadences using methods such as the Lomb–Scargle periodogram and SFs. K2 will be able to reveal if the AGN PSD slope in the high-frequency regime differs significantly from the low-frequency regime constrained with ground-based surveys.

The simplest stochastic model for simulating optical AGN variability is the damped random walk (DRW). The DRW is, however, an inflexible model with a fixed PSD power-law shape ($\text{PSD} \propto \nu^{-2}$). Empirical PSD and SF analyses of Kepler AGNs from the mission’s first phase showed a range of PSD shapes (curvature and slope transitions; Mushotzky et al. 2011; Kasliwal et al. 2015, 2017; Smith et al. 2018a). Rehabilitating K2 light curves would provide the opportunity to characterize the high-frequency PSD slope for a large statistical sample of AGNs. In Figure 18, we show 4000 AGNs observed in Campaigns 8, 10, 12, 14, 16, 18, and 19 over-plotted on the Kepler CCD array. The (relatively) high-frequency regime of AGN PSDs can be investigated as a function of luminosity, black-hole mass, and accretion rate. The characteristic frequency or timescale for a slope transition may also be related to physical scales or black-hole mass as is the case for AGN X-ray variability (Utley et al. 2002). Recently, Simm et al. (2016), Caplar et al. (2017), Zinn et al. (2017), Smith et al. (2018a) and Moreno et al. (2021, in preparation) find evidence of a range of behaviors in the high-frequency regime of AGN PSDs estimated with multiple methods and in multiple data sets. These findings imply that the DRW is not a universal model of AGN variability, but we do not necessarily understand what model is a more useful characterization.

Should a procedure for rehabilitating light curves for faint K2 targets become feasible, Figure 18 provides key guidance with regard to the location and potential light-curve quality of all the SDSS quasars that were targeted by our team. The coloring of the channels, light blue to pink, corresponds to the median absolute deviation (MAD) calculated for median light curves shown in Figure 4. Channels with the highest MAD static (pink) have the largest amplitude instrumental signatures and may need to be altogether avoided. Clearly the targets are not uniformly distributed just as the channels are not all of uniform photometric quality. AGNs appearing in channels outlined in cyan (light) blue may be the best choices for further investigation, while those AGNs appearing in channels outlined in purple and magenta may be beyond repair.

7. Summary

Kepler/K2 has the potential to enable large-sample science programs for AGNs, stars, and extragalactic time-domain
phenomena. These large-sample programs are currently devastated by systematics that persist even after pointing errors known as arc drift are corrected. The systematics may be similar to trends observed in the first phase of Kepler such as rolling band, Moiré noise, faint blended background sources, and changes in PSF. For variability studies requiring the full light-curve PSD, there is no way to measure the performance tradeoff of removing instrumental trends and scattering the astrophysical signal. CBVs (or PCA components), which were popular for detrending Kepler light curves, suffer this particular failing because they do not orthogonally account for magnitude or spatial information which we have shown to contribute significantly to the shape of the systematics. Careful error mitigation is even more critical to enable science for K2 programs at

Figure 16. EVEREST 2.0 applied to a quiet star. The top left panel is the raw light curve, using all of the pixels on the postage stamp as the aperture. The bottom left panel is the light curve resulting from the PLD method and a Matern 3/2 Gaussian process applied using the same aperture. The right panels are the corresponding PSDs. The black dotted line represents the PSD slope of a damped random walk (DRW or red noise). The Matern 3/2 kernel adds in variability that results in a PSD slope that artificially mimics a DRW.

Figure 17. PSD logarithmic slopes as a function of magnitude for non-AGN objects in Campaign 8 before (left panel; raw, full postage stamp light-curve PSDs) and after (right panel) EVEREST 2.0 reprocessing using the Matern 3/2 kernel. Here we see that a naive use of the Matern 3/2 kernel artificially steepens the PSD slopes of 9483 non-AGN targets (from various guest observer proposals) to the value of −2 which corresponds to red noise spectra. An incorrect GP model selected for AGNs will similarly produce an artificial PSD slope.
magnitudes and light-curve cadence that are unmatched by other telescopes.

We note two particularly useful characteristics of the systematics for readers interested in rehabilitating these data. First, there is a tradeoff between arc drift and the instrumental trends that we wish to remove. Arc drift is easier to remove and in some cases not present in larger-aperture definitions. However, the inclusion of more pixels in the aperture leads to stronger, more complex instrumental trends. Second, there appear to be some modules that are significantly less affected by systematics according to empty pixels as shown in Figure 12. Modules 14, 15, 19, and 20 may provide the best data quality, whereas modules 6, 11, and 16 exemplify the worst. This module quality, and by extension data quality, is independent of campaign or telescope orientation.

The mirroring between Campaigns 8 and 16 (Figure 4) is seen in both light curves (with local background subtraction) and temperature data, which suggests that focus changes may

Figure 18. The approximate locations of AGNs relative to the K2 field of view. The transformations used to overlay matching fields from different campaigns contributed slight rotation errors to the positions of AGNs. The coloring of the channels is based on the median absolute deviation (MAD) of the median channel light curves (after subtracting a linear trend). The MAD values are calculated from the smoothed median channel light curves shown in Figure 4. The red outline indicates a bad module. Module 4 failed after Campaign 10. The cluster of objects in Campaign 19 are in SDSS “stripe 82” (York et al. 2000).
be responsible for spatially dependent instrumental trends. The direction of the trend depends on whether the spacecraft was forward facing or rear facing, but the slope and amplitude of systematic features are consistently larger in poorer quality channels regardless of the spacecraft orientation.

An ideal reprocessing pipeline would consider campaign, module/channel number, magnitude, similar magnitude neighbors, aperture optimization, local background subtraction, arc-drift correction, and distance from the boresight. The lightkurve package provides most of the functionality to get started.

The Kepler/K2 observations are a powerful legacy data set for investigations of variable objects. The statistical criteria for doing AGN variability studies are rather different from the requirements for exoplanet discovery, for which the experiment was designed, thus some of the problems we identify above are particularly challenging. More precise characterization and amelioration of these systematic effects are beyond the scope of this work and, we believe, require in-depth investigation by teams experienced in optical instrumentation. Nevertheless, we anticipate that the effort required to clean Kepler/K2 light curves of the systematics we describe above will not only pay worthwhile dividends for AGN science but also expand the parameter space of exoplanet detections that lie at even lower signal-to-noise than has been achieved to date.

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