Variability Properties of Four Million Sources in the TESS Input Catalog Observed with the Kilodegree Extremely Little Telescope Survey

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Abstract

The Kilodegree Extremely Little Telescope (KELT) has been surveying more than 70% of the celestial sphere for nearly a decade. While the primary science goal of the survey is the discovery of transiting, large-radii planets around bright host stars, the survey has collected more than 10^6 images, with a typical cadence between 10–30 minutes, for more than four million sources with apparent visual magnitudes in the approximate range 7 < V < 13. Here, we provide a catalog of 52,741 objects showing significant large-amplitude fluctuations likely caused by stellar variability, as well as 62,229 objects identified with likely stellar rotation periods. The detected variability ranges in rms-amplitude from ~3 mmag to ~2.3 mag, and the detected periods range from ~0.1 to ~2000 days. We provide variability upper limits for all other ~4,000,000 sources. These upper limits are principally a function of stellar brightness, but we achieve typical 1σ sensitivity on 30 min timescales down to ~5 mmag at V ~ 8, and down to ~43 mmag at V ~ 13. We have matched our catalog to the TESS Input catalog and the AAVSO Variable Star Index to precipitate the follow-up and classification of each source. The catalog is maintained as a living database on the Filtergraph visualization portal at the URL https://filtergraph.com/kelt_vars.

Key words: stars: rotation – stars: variables: general – surveys

Supporting material: machine-readable tables

1. Introduction

Technological advancements in the past two decades have led to a dramatic rise in the number of cost-effective, small-aperture, wide-field surveys that monitor large portions of the celestial sphere on a nightly basis. While antecedent astrophysical observing strategies typically involved dozens of observations of a single star per night, contemporary surveys can obtain >100 observations for >10^5 sources on a nightly basis. These surveys have led to a number of discoveries in the fields of transiting exoplanets, supernovae, transient phenomena, and variable stars (Bakos et al. 2004; Pollacco et al. 2006; Pepper et al. 2007; Basri et al. 2011; Pepper et al. 2012; Bakos et al. 2013; Law et al. 2013; Wang et al. 2013; Oelkers et al. 2016a). These surveys have been particularly helpful to advance the techniques used in the reduction and collection of massive amounts of astronomical data on practical timescales.

The first generation of time-series photometric surveys contributed to the discovery, cataloging, and study of nearly every type of known classical variable star, as well as pioneering methods for identifying variable stars used by modern surveys. Perhaps the most well-known is the General Catalog of Variable Stars (Samus’ et al. 2017, GCVS), which has cataloged a variety of bright variable stars distributed across the entire sky since 1948. Additionally, the Optical Gravitational Lensing Experiment catalog of variables (hereafter, OGLE; see Soysański et al. 2017 and references therein) provides nearly one million well characterized periodic variables. The All Sky Automated Survey (Pojmanski 1997, 2002, 2003; Pojmanski & Maciejewski 2004, 2005; Pojmanski et al. 2005, ASAS) and the Northern Sky Variability Survey (Wozniak et al. 2004a, NSVS) contributed to the basic understanding of the fundamental physics behind RR Lyraes (Kinemuchi et al. 2006; Szczygiel et al. 2009), β Cephei-types (Pigulski & Pojmanski 2008), classical Cepheids (Pietrukowicz 2001), long-period variables (Wozniak et al. 2004b), and eclipsing binaries (Pilecki et al. 2007). Additionally, these survey aided in the precovery of numerous variables which would be observed by future space missions (Pigulski & Pojmanski 2008).

Recently, the next generation of high-cadence, time-series photometric surveys have led to the discovery of numerous interesting variable stars such as Blazhko effect RR Lyraes (Wang et al. 2011), an eclipsing binary with a 70 year period (Rodriguez et al. 2016c), Type-II Cepheids in eclipsing systems (Wang et al. 2013; Oelkers et al. 2015), and some yet-to-be explained phenomena (Boyajian et al. 2016). The Transiting Exoplanet Survey Satellite (hereafter, TESS) and Large Synoptic Survey Telescope (hereafter, LSST), which plan to survey nearly the entire celestial sphere, expect to compound these discoveries (Ivezic et al. 2008; Ricker et al. 2014).
The KELT-N survey instrument includes an Apogee AP16E camera with a 4096 × 4096, 9 μm pixel Kodak KAF-16801E front-illuminated CCD. The detector can be thermo-electrically cooled to a temperature of ΔT ~ −30°C relative to ambient, but is set to maintain a constant −20°C. Testing of the CCD showed a dark current of 0.1–0.2 e− pix−1 s−1. The optics include a Mamiya 645 80 mm f/1.9 lens (42 mm effective aperture) and a Kodak Wratten #8 red-pass filter. The pixel scale of the detector is ~23″ pix−1, leading to a total field of view (hereafter, FoV) of 26° × 26°.

The KELT-N telescope has been observing from Winer Observatory in Sonoita Arizona (31°39′56″08 N, Longitude 110°36′06″42 W, elevation 1515.7 m) since 2007. Winer Observatory hosts weather with 60% observable nights, half of which are determined to be photometric.

2.1.2. KELT South

The KELT-S instrument is a near- replica of the KELT-N instrument, but includes an Apogee Alta U16M camera with a 4096 × 4096, 9 μm pixel Kodak KELT-16803 front illuminated CCD. The detector can be thermo-electrically cooled to a temperature of ΔT ~ −70°C relative to ambient, but is set to maintain a constant −20°C. Testing of the CCD showed a dark current of <0.26 e− pix−1 s−1. The optics include a Mamiya 645 80 mm f/1.9 lens (42 mm effective aperture) and a Kodak Wratten #8 red-pass filter. The pixel scale of the detector is ~23″ pix−1, leading to a total FoV of 26° × 26°.

The KELT-S telescope has been observing from South African Astronomical Observatory near Sutherland South Africa (32°22′46″ S, 20°38′48″ E, altitude 1768 m) since 2012. The Sutherland site typically experiences 70% observable nights, with 60% of this time considered photometric. Typical seeing at the site reaches ~0.92″ (see footnote 12).

2.2. KELT Observations

All KELT observations are robotic and do not require real-time human intervention for operations. The telescope control scripts undergo a variety of observability testing prior to the start of normal operations, including checks on air temperature (>−10°C), humidity (<90%), dew point, wind speed (<60 km h−1), precipitation, and clouds. Bias frames and sky flats are taken first, and survey observations begin at astronomical twilight (Pepper et al. 2007, 2012).

Exposures are kept to 150 s (with a typical readout time of 30 s) to optimize the photometric precision of stars with 8 < Vk < 10, where Vk represents the zero-pointed KELT band pass to V magnitude. Each telescope typically targets a number of fields on any given night, if the field is above 1.5 airmasses and typically further than 45–55° of the Moon (for KELT-S and KELT-N respectively). If a field is observable, it can be expected to receive at least 10–15 observations per night, but possibly as many as 30–50 depending on the location.

12 The seeing conditions are not a factor in observation quality, given the large KELT pixel scale of 23″ pix−1.
of the Moon (Siverd et al. 2012; Kuhn et al. 2016). Figure 1 shows each KELT field and their locations on the celestial sphere. The KELT fields used in this analysis are described in Table 1 and may be subject to change for other analysis or future updates to the catalog.

2.3. KELT Photometry

2.3.1. Image Processing and Flux Extraction

KELT-N images are pre-processed by undergoing dark subtraction, bias subtraction, and flat fielding. The images are flat-fielded using a master flat created from thousands of sky-flats, which have been individually bias-subtracted, dark-subtracted, and gradient-corrected. KELT-N also creates a new master bias and master dark frame for each observing night. The images are also 2D-calibrated using their night-specific master calibrations (Siverd et al. 2012).

KELT-S images are pre-processed by undergoing dark subtraction and flat fielding. The process uses a master dark and master flat-field. The master dark frame was created from hundreds of dark frames taken at the start of survey operations. The master flat frame was created using hundreds of sky-flats, which have been individually bias-subtracted, dark-subtracted, and gradient-corrected (Pepper et al. 2012; Kuhn et al. 2016).

The KELT photometric pipeline uses a heavily modified version of the ISIS difference imaging routine (Alard & Lupton 1998; Alard 2000; Siverd et al. 2012; Kuhn et al. 2016). The reference frame for each field was created through an iterative rejection process to construct a frame using only high-quality images taken at low airmass13 and low background signal.

The kernel used in the subtraction routine is constructed from a series of Gaussian functions and blurs the reference frame to match the seeing conditions in each of the science images. The two frames are subtracted and the residual flux is measured on the subtracted images using PSF-weighted aperture photometry. The reference flux is extracted using PSF photometry from the standalone DAOPHOT II program,
Figure 3. The variability metrics used to identify stars with large amplitude changes relative to the ensemble set of light curves in each orientation of KELT-N10. For clarity, only the results for the W orientation are shown. In practice, the star must pass all four metrics in both the E and W orientations to be considered variable. The red lines denote the cutoffs in each panel, and the blue dots or arrows represent the value of the star shown in the bottom panel. Top left: the eta metric. Top right: the $\Delta_{90}$ metric. Middle left: the Welch–Stetson J metric. Middle right: the Welch–Stetson L metric. Bottom: combined E (gray points) and W (black points) orientation light curves for the variable object 2MASS J16353003+3036125. Typical photometric error is shown at the top right of the panel.

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then is matched to the ISIS output with an aperture correction (Stetson 1987; Siverd et al. 2012; Kuhn et al. 2016). Finally, the raw flux is converted to magnitude and the light curves are $3\sigma$ clipped to remove outlier data points. Each light curve is fully reproduced from the photometry files when a new KELT observing season is completed (Siverd et al. 2012; Kuhn et al. 2016).

The KELT telescopes use a German Equatorial mount, and the observations described in Section 2.2 involve a meridian flip (near 0 hr angle) as the field passes from east to west of the meridian. This means all KELT fields will have images that need to be rotated 180° relative to one another. Rather than rotate the images during pre-processing, each field is divided into two data sets, East and West (hereafter, E and W) because the telescope optics are not exactly axi-symmetric (Pepper et al. 2007, 2012).

### 2.3.2. Noise

The careful documentation of possible sources of uncertainty is necessary to claim the detection of astrophysical signals. Flat-fielding errors, sub-optimal image alignments, poor subtractions, and sub-optimal observing conditions can create possible sources of contamination in photometry. While the KELT data goes through a rigorous set of data quality checks, these checks do not remove all of the sources of uncertainty.

We compared the KELT photometric scatter to the noise limits expected from typical sources of astrophysical uncertainty: the photon count from a star, typical sky background levels, and the scintillation limit. We modeled the statistical uncertainty as:

$$\sigma^2 = I_N^2 + (A \cdot I_{sky})^2 + \sigma_a^2,$$

where $I_N$ and $I_{sky}$ are the photon counts from the star and sky, respectively. Here, $A$ is the area of the photometric aperture, and $\sigma_a$ is the scintillation limit defined by Young (1967) and Hartman et al. (2005) as:

$$\sigma_a = S_0 d^{-2} X^4 e^{-8m (2t_{ex})^{-1}},$$

where $S_0$ is 0.1 when the diameter is defined in cm, $d$ is the diameter of the telescope in cm, $h$ is the altitude of the observatory, $X$ is the airmass, and $t_{ex}$ is the exposure time in s.

We approximate the expected noise using the values for KELT-N at Winer Observatory: $d = 4.2$ cm, $h = 1515$ m, $2 > X > 1$, and $t_{ex} = 150$ s. We find the scintillation limit to be $\approx 2$–6 mmag, depending on airmass. We measured the root-mean-square (hereafter, rms) of the magnitude of each light curve for the KELT-N05 field and compared those values with the noise model as a check of KELT’s basic photometric quality, as shown in Figure 2. We find satisfactory agreement with the simple model described above, with the KELT system achieving typical eta of $1–2\times$ the scintillation limit for stars with $V_K < 10$.

### 3. Searching for Variability and Periodicity

We objectively determine a KELT object’s variability with two methods, following the work of Wang et al. (2013), Oelkers et al. (2015, 2016b). First, we employ four variability metrics designed to identify moderate-to-large scale variability, which could be aperiodic or subtly occur over the large KELT baseline ($>\approx 5$ years), such as a steady decrease or increase in magnitude due to long-term variation. Second, we impose four periodicity requirements designed to identify small-to-large scale variability that repeats on periodic timescales and is not consistent with frequencies of common KELT systematics.

These metrics are used to discover variable and periodic objects in the KELT survey on a per field basis and assume, in general, that most stars will be “constant” and not variable. Each metric is calculated on a per star basis and the values are compared with either the entire sample or a subset of each sample with similar magnitude ($\pm 0.5$ mag). We find that, by employing these metrics in this way, we greatly reduce contamination by systematics (due to poor subtractions or observing conditions) because “constant” stars in the same field, with similar magnitudes, should have similar dispersions even if affected by systematics. Additionally, we emphasize that these metrics are empirical in nature, and while they reasonably identify true variable stars and eliminate false positives, the specific selection criteria described in Sections 3.1 and 3.2 are ultimately subjective, not statistical, and may need to be updated for other data sets.

As previously mentioned, KELT has two orientations per field: E and W. We searched each field orientation independently and compared the results for objects in both orientations. If the star had a light curve in both orientations but was only determined to be variable in one, the star was rejected as a variable. This was done under the assumption that if a star is an *bona fide* variable, it should show similar variations in both the E and W orientations because true astrophysical variability will be independent of the telescope’s position relative to the meridian.

#### 3.1. Variability Testing

First, we identify stars where the dispersion in their light curves is larger than is expected for stars of similar magnitude in the KELT band-pass. For this analysis, we use two metrics: the eta and $\Delta_{90}$. The eta metric identifies the magnitude range for $68\%$ of the data points in each light curve, and the $\Delta_{90}$ metric identifies the magnitude range for $90\%$ of the data points in each light curve (Wang et al. 2013). We compute the upper $p < 0.05$ envelopes of both statistics as a function of

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14 If a star only had a light curve in one field but passed the tests below, it was included in the variable data set but appropriately flagged (see Section 3.3).
Figure 5. The periodicity requirements used to identify stars with *bona fide* astrophysical periodicity. The blue arrows are used to denote the representative periodic star 2MASS J17390451-0447289 ($P \sim 313.408$ days) that passes each requirement. Top row: histograms of the top five peak periods for all stars, regardless of whether they pass the periodicity requirements in Section 3.2, for the W (left) and E (right) orientations of KELT-S13. The alias cutoff for an approximate calendar year ($360 \pm 40$ days) is shown as a hashed red region. Periods to the right of this line are likely aliases of the calendar year. Middle row: the normalized L-S power for every stellar period recovered in the KELT-S13 analysis within $\sim 313 \pm 3.1$ days (1% of the candidate period). The candidate period’s normalized power is shown to be larger than both the average power and the 0.1 power requirement. Bottom row: the phase-folded light curve for 2MASS J17390451-0447289 in the W (left) and E (right) orientations. The star has been folded on twice the period and plotted for clarity. The star is clearly periodic, with the amplitude of the periodicity changing between cycles, which may indicate the true period is twice that of our detected period. Typical photometric error and the recovered period in each field orientation is shown at the top right of these panels.
magnitude, and assume any object lying above these limits is a bona fide variable. Neither metric is calculated using error weighting, but because we wanted the envelopes to be based on "constant" stars, we applied a 3σ iterative clipping to the \eta and D90 metric values in each magnitude range, prior to calculating the envelope.

Next, we compute the Welch–Stetson J and L metrics (Stetson 1996). These two metrics are useful in identifying significant, correlated variations between subsequent data points and the sampling rate of KELT: typically 10–30 minutes. These metrics are expected to produce a distribution centered at or near zero, with a one-sided tail. Stars in this tail represent significant deviations likely not to be caused by systematics. We compute the \( p < 0.003 \) cutoff of this tail in both \( J \) and \( L \) to select variable objects.

We initially remove objects with \( J, L > 10 \) and do a 3σ iterative clipping to determine the mean and standard deviation of the \( J \) and \( L \) distributions, because we are interested in our metric cutoffs being based on "constant" stars (see footnote 15). This clipping allows us to calculate the distribution properties of \( J \) and \( L \) using a population of stars that show minimal deviation between subsequent data points.

Additionally, we found the \( J \) statistic to be much more sensitive to systematics caused by detector saturation. This caused some objects to have very large \( J \) values and small-to-moderate relative \( L \) values. Therefore, we made a final requirement that the ratio of \( J \)-to-\( L \) must not be greater than 1.5.

Figure 3 shows the four variability metrics recovering a variable star in \( W \) orientation of KELT-N10. The \( E \) and \( W \) light curves of the passing variable object 2MASS J16353003+3036125 are also shown.

3.2. Periodicity Testing

We identify stars with significant periodic signals using the ASTROPY implementation of Lomb–Scargle (Lomb 1976; Scargle 1982). We searched each light curve for the top five periods, ranked by power, between 0.1 days and the total number of baseline days in a given KELT \( E \) or \( W \) field orientation. Periods were independently searched between the \( E \) and \( W \) orientations to help eliminate spurious signals. Again, we assume a bona fide astrophysical period will be independent of telescope position. We required each period to pass the four requirements below before we accepted the period as valid.

First, we required any candidate period to match within 1% of the period in the other field orientation. For example, if the \( E \) light curve had a period of one day, then the \( W \) period must also have a period between 0.99 and 1.01 days. If the \( E \) period is 100 days, then the \( W \) period must be between 99 and 101 days, and so on. If a star had a light curve in only the \( E \) or \( W \) data, this step is skipped but the star was appropriately flagged (see Section 3.3).

Second, we required the period to be unique. We computed the \( \Delta \eta \) and \( D90 \) metric values in each magnitude range, prior to calculating the envelope.
can be identical to a period identified by Lomb–Scargle in the Fourier spectrum of a different star in the same field-orientation. While we remove the most common observing aliases known in the KELT data (see below), each combination of field and orientation has a unique set of image timestamps—and thus a unique spectral window function. As a result, the aliasing pattern varies from field to field. By requiring the periods to be unique, we help to alleviate this tension. However, if two stars showed identical periods in a given field and the stars were blended (within five KELT pixels of one another), we considered the period valid for both stars—but again, the stars are flagged (see Section 3.3).

Third, we excluded periods near the following KELT aliases: the most common diurnal aliases (0.10 ± 0.003 days, 0.125 ± 0.002 days, 0.1425 ± 0.0025 days, 0.1665 ± 0.0015 days, 0.2 ± 0.005 days, 0.25 ± 0.025 days, 0.33 ± 0.01 days, 0.5 ± 0.025 days, and 1 ± 0.05 days); the lunar month, 29 ± 3 days; roughly a third of a year 120 ± 10 days; roughly half a year, 180 ± 20 days; and roughly a calendar year, 360 ± 40 days. Because many aliased peaks can be disguised as harmonics and/or sub-harmonics, we also checked if $P/2$, $P/3$, $2P$, or $3P$ would fail the alias check; if so, we removed the period, as suggested by previous studies (VanderPlas 2017). The regions of exclusion due to observing alias contamination are shown visually in Figure 4.

Fourth, we placed a limit on the normalized power and only accepted periods with powers larger than 0.1 as candidate astrophysical signals. Next, we identified all periods from all stars in a given KELT field orientation within the period range $P - (P \times 0.01) < P < P + (P \times 0.01)$, where $P$ is the candidate period. We then calculated the mean power of these periods and compared this mean power to the power of the candidate period. We required the candidate period’s power to be larger than the mean power. This metric was included to remove some spurious periods that were caused by aliases of signals other than the sidereal day, lunar month, and calendar year, but were found in multiple stars. This metric also helped to remove stars that were blended with nearby, bona fide periodic stars, because the blended star’s power was typically much lower than the power of the periodic star.

Any period that satisfied these four requirements was considered to be genuine. Additionally, we consider a star to be multi-periodic if we could identify more than one period in a given light curve that satisfied the above requirements. Figure 5 shows the implementation of these four requirements for the representative periodic object 2MASS J17390451-0447289 from the KELT field S13.

3.3. Identifying Possible Contamination from Non-Astrophysical Sources

While we take care to select objects most likely to be bona fide variables, the catalog is not free from spurious members. We have created a set of six catalogs flags designed to educate the reader that a given variable could be contaminated by common KELT systematics. These catalog flags are described as:

1. EDGE: If a star was closer than 200 pixels to the edge of the CCD, the EDGE flag is set to 1.
2. POINTS: If the total number of data points for any light curve is less than $N < \mu_N - 1\sigma_N$, where $N$ is the number of data points in the light curve, $\mu_N$ is the mean number of data points of all light curves in the E/W orientation, and $\sigma_N$ is the standard deviation of the mean number of data points per field, the POINTS flag is set to 1.
3. BLEND: If the centroid of a stars was within 5 pix (1/9) of the centroid of another star brighter by more than 1.5 magnitudes, the BLEND flag is set to 1.
4. PROXIMITY: If a candidate variable is within 5 pix (1/9) of another candidate variable, which is brighter by more than 1.5 magnitudes, the PROXIMITY flag is set to 1.
5. ALIAS: If at least three of the top five peaks in the Lomb–Scargle power spectrum are aliases of the sidereal day, lunar month or calendar year the ALIAS flag is set to 1.
6. SINGLE: If a star has only one light curve (either E or W but not both) and passed either all variability metrics or all periodicity requirements, the SINGLE flag is set to 1.
4. Results

4.1. Variable and Periodic Sources in KELT

We identify 52,741 stars as variable or periodic using the metrics and requirements above. From this list, 35,060 stars passed all variability metrics, 21,362 stars passed all periodicity requirements, and 3618 stars passed both the variability metrics and periodicity requirements. The 15,072 stars passing the variability metrics, the 21,362 stars passing all periodicity requirements, and 3618 stars passed both the variability metrics and periodicity requirements above. From this list, 35,060 stars passed all requirements. The 15,072 stars passing the variability metrics, the 21,362 stars passing all periodicity requirements, and 3618 stars passed both the variability metrics and periodicity requirements above. From this list, 35,060 stars passed all requirements.

Figure 7. This bias is expected because the variability metrics require relatively large amplitude variation to pass each metric. We determine the variable star rate ($V_r$) in the Milky Way Galaxy as a function of Galactic latitude ($b$) by dividing the number of variables found in each field ($N_V$) by the total number of stars in a given field ($N_{tot}$), as shown by: $V_r = N_V / N_{tot}$. We find the variable star rate correlates with absolute Galactic latitude, as shown in Figure 8. We find the variable star rate to be as much as 3% at low Galactic latitudes ($|b| < 20^\circ$), to a rate of 1% at higher Galactic latitudes ($|b| > 20^\circ$). These rates are consistent with the variable star rates determined by previous studies (Wang et al. 2013; Díaz et al. 2016; Oelkers et al. 2016a, 2016b).

Figures 9 and 10 shows example light curves for 18 stars passing the variability metrics from various KELT fields, while Figures 11 and 12 show example light curves for 18 stars passing the periodicity metrics from various KELT fields. The full catalog.

Table 1

| Field Name | North/South | Approximate Field Center $\alpha$ (hh:mm.m) | $\delta$ (dd:mm) | Julian Date Start | Star Count | Variables Identified |
|------------|-------------|--------------------------------------------|-----------------|------------------|------------|----------------------|
| N01        | North       | 00:06:0                                    | +31:40          | 2454034          | 66592      | 652                  |
| N02        | North       | 02:01:8                                    | +31:40          | 2454034          | 85828      | 362                  |
| N03        | North       | 03:38:2                                    | +31:40          | 2454034          | 98259      | 721                  |
| N04        | North       | 05:54:0                                    | +31:40          | 2454035          | 172816     | 1874                 |
| N05        | North       | 07:50:4                                    | +31:40          | 2454035          | 95805      | 748                  |
| N06        | North       | 09:46:2                                    | +31:40          | 2454035          | 49412      | 320                  |
| N07        | North       | 11:42:6                                    | +31:40          | 2454035          | 23254      | 292                  |
| N08        | North       | 13:38:4                                    | +31:40          | 2454049          | 38660      | 271                  |
| N09        | North       | 15:34:8                                    | +31:40          | 2454124          | 49723      | 385                  |
| N10        | North       | 17:30:6                                    | +31:40          | 2454154          | 66233      | 1197                 |
| N11        | North       | 19:27:0                                    | +31:40          | 2454250          | 165927     | 2620                 |
| N12        | North       | 21:22:8                                    | +31:40          | 2454259          | 162204     | 2401                 |
| N13        | North       | 23:19:2                                    | +31:40          | 2454034          | 56788      | 765                  |
| N16        | North       | 00:03:0                                    | +57:00          | 2456068          | 145870     | 1913                 |
| N17        | North       | 02:43:2                                    | +57:00          | 2455973          | 139849     | 433                  |
| N20        | North       | 10:43:2                                    | +57:00          | 2455976          | 57248      | 258                  |
| N23        | North       | 18:43:2                                    | +57:00          | 2455978          | 134183     | 884                  |
| N24        | North       | 21:23:4                                    | +57:00          | 2456009          | 131756     | 2417                 |
| S05        | South       | 06:07:8                                    | +03:00          | 2455256          | 169498     | 1717                 |
| S12        | South       | 16:52:2                                    | +03:00          | 2455268          | 145044     | 1142                 |
| S13        | South       | 18:24:0                                    | +03:00          | 2455275          | 163723     | 2823                 |
| S14        | South       | 19:55:8                                    | +03:00          | 2455298          | 215161     | 4577                 |
| S17        | South       | 00:00:0                                    | −53:00          | 2455378          | 39670      | 512                  |
| S18        | South       | 01:31:8                                    | −53:00          | 2455378          | 44482      | 490                  |
| S19        | South       | 03:04:2                                    | −53:00          | 2455256          | 46246      | 242                  |
| S20        | South       | 04:36:0                                    | −53:00          | 2455256          | 68403      | 511                  |
| S21        | South       | 06:07:8                                    | −53:00          | 2455256          | 97360      | 1125                 |
| S22        | South       | 09:12:0                                    | −20:00          | 2455256          | 154456     | 1643                 |
| S23        | South       | 10:43:8                                    | −20:00          | 2455268          | 92255      | 246                  |
| S24        | South       | 12:16:2                                    | −30:00          | 2455268          | 102385     | 805                  |
| S25        | South       | 13:48:0                                    | −30:00          | 2455268          | 102303     | 1148                 |
| S26        | South       | 15:19:8                                    | −20:00          | 2455268          | 120235     | 1125                 |
| S27        | South       | 19:55:8                                    | −53:00          | 2452455          | 111056     | 1497                 |
| S29        | South       | 23:00:0                                    | −53:00          | 2452455          | 51019      | 671                  |
| S32        | South       | 00:04:1                                    | −29:50          | 2455803          | 66383      | 375                  |
| S34        | South       | 08:16:0                                    | −54:00          | 2455200          | 178687     | 2372                 |
| S36        | South       | 17:24:0                                    | −53:00          | 2456428          | 219968     | 5967                 |
| S37        | South       | 15:07:2                                    | −53:00          | 2456451          | 132493     | 2329                 |
| S38        | South       | 12:50:4                                    | −53:00          | 2456647          | 208826     | 2981                 |

Note. The coordinates of each field are an approximation of each field center. The star counts and Julian Dates of the fields represent the data in this work and vary for future reductions.
including the cross-matches described below, has been made available through the Filtergraph visualization portal (Burger et al. 2013) at the URL https://filtergraph.com/kelt_vars. Through this portal, the public can access all variability information determined for the star, the cross-matches with the TESS Input Catalog and AAVSO Variable Star Index (see Sections 4.3 and 4.4 for more details), and a basic light curve image for the W and E light curves. Additionally, we provide the catalog in normal table format, with Table 2 detailing the catalog and astrometric information for each variable, Table 3 detailing the magnitude information for each variable, and Table 4 detailing the variability metrics and catalog flags for each variable.

4.2. Variability Upper Limits for All Remaining Sources

The catalog described in Section 4.1 was created to identify the most variable objects observed by KELT, which may also be observed by large-scale photometric surveys in the future, such as the upcoming TESS mission. This method of pre-identifying variable objects via KELT, prior to mission start, has been shown to work well for the K2 mission (Ansdell et al. 2017; Rodriguez et al. 2017a, 2017b). However, we expect the catalog will not identify every variable object because either: (1) the statistics we applied were too strict for some variable objects to be recovered, even if they show considerable large amplitude variations; or (2) the star’s variability occurred below the typical KELT precision for a given star and could not be objectively differentiated from the expected system noise (see Figure 2). Given that KELT has observed an additional four million objects, we believe we can use the remaining KELT catalog to provide additional variability information that may be useful for community members wishing to identify variable objects through their own independent metrics.

Therefore, we provide an upper limit for the variability for the remaining objects observed by the KELT survey. Table 5 provides the eta metric on timescales of 30 min (similar to the expected 30 min full-frame images provided by the TESS mission (Ricker et al. 2014)), 2 hr, and 1 day. This catalog extension aims to provide the astronomical community with complete upper limits of all stars, not just those showing the most significant variability. We emphasize that these statistics should only be interpreted as upper limits and will vary significantly with the star’s KELT magnitude.

4.3. Variability Properties of Stars in the TESS Input Catalog

TESS and KELT share many similarities in their design. Both telescopes have modest apertures (<10 cm) and wide FoV ($26^\circ \times 26^\circ$). While efficient at surveying large
portions of the celestial hemisphere quickly, this optical design leads to crowded sources and can make pinpointing the source of variability cumbersome. Our variable catalog can lessen the burden of some variability detection by acting as pre-covery for many sources TESS is expected to observe.

We matched any star with a 2MASS identification in the KELT variable catalog to the fifth version of the TESS Input Catalog (hereafter, TIC). The TIC is an ambitious catalog that attempts to create a nearly uniform list of stellar parameters, such as effective temperature, mass, and radius, for more than 470 million stars, and is the primary source of target selection for the upcoming TESS mission (Ricker et al. 2014; Stassun et al. 2017). We provide the TIC identification as part of our library, and adopt the stellar parameters provided by the TIC when available.

4.3.1. Searching for Large Amplitude Variability Among the Top TESS Two-minute Target Candidates

We also compared our variable catalog with the specialized transiting Candidate Target List (tCTL) of the TIC. This list identifies the stars most suitable for searching for transit-like signals and provides a prioritized list of stars that may be included in the final list of 400,000 targets to receive two-minute cadence during the TESS mission (Stassun et al. 2017). Because the detection of transit-like signatures is simplified when a light curve is quiescent, it would be preferable for stars in the final 400,000 member target list to show minimal stellar variations.

We found 493 objects identified in our catalog to be within the top ∼400,000 tCTL candidate members, with 3,339 being in the top 2,500,000 targets. While the increased cadence observations of these variables could help diagnose the origin of their variability, future versions of the tCTL may benefit from a variability measure included in calculations of the star’s priority, if the primary goal of the two-minute science targets is the detection of transiting Earth-sized planets. However, given the current number of identified variable stars in the tCTL is <1%, we do not expect variable stars to heavily contaminate this highly cultivated list.

4.3.2. A Focused Search for Rotation Periods of TESS Target Candidates in KELT Light Curves

Following the approach of Stassun et al. (1999), we also executed a search for periodic signals most likely to come from the rotation period of the star for a specific subset of KELT stars: those identified as high-priority dwarfs expected to be
observed in the TESS two-minute cadence (Stassun et al. 2017). This search was designed to test the feasibility of recovering a rotation period from future TESS light curves, given that the basic designs of both systems are comparable in terms of expected pixel scale, crowding, and blending effects.

For these stars, we combined the E and W light curves into a single light curve and post-processed the data using the Trend-Filtering Algorithm (Kovács et al. 2005) to remove common detector systematics. We searched for rotation signals in the combined light curves using a modified version of the Lomb–Scargle period finder algorithm (Lomb 1976; Scargle 1982). We searched for periods between a minimum period of 0.5 days and a maximum period of 50 days using 2000 frequency steps. Additionally, we masked periods between 0.5–0.505 and 0.97–1.04 days to avoid the most common detector aliases associated with the solar and sidereal day. We then selected the highest peak of the power spectrum as the candidate period.

Next, we executed a bootstrap analysis, using 1000 Monte-Carlo iterations, where the dates of the observations were not changed but the magnitude values of light curve were randomly scrambled (see Henderson & Stassun 2012). We recalculated the Lomb–Scargle power spectrum for each iteration and recorded the maximum peak power. If, after 1000 iterations, a maximum power of the bootstrap analysis was found to be larger than the power of the candidate period, the period was rejected as a false positive.

We identified 62,229 stars with possible rotation periods, as defined in our search. Table 6 provides basic stellar parameters from the TIC and the rotation period information for each star. Of these stars, 2,110 were also found in the searches described in Sections 3.1 and 3.2. However, the remaining ∼60,000 stars were found to have rotation periods that were not identified as part of these ensemble searches, and ∼10,000 periods from the ensemble search were not found as part of the rotation search.

These periods were likely not recovered in the ensemble period search for the following reasons. First, the ensemble period search was for 0.1 < P < max(baseline) days, whereas the rotation search was limited to 0.5 < P < 50 days. The difference in the period range searched also resulted in some difference in the number and spacing of frequencies searched. Second, the ensemble search considered the E and W
light curves separately, in order to ensure the robust identification of truly significant variability, while the rotation search used the combined light curves to increase the rotation period signal. Because rotation periods are typically low-amplitude, it is possible the ensemble search did not have enough power for the signal to reach the threshold of 0.1 in normalized power. Third, the ensemble search used the raw photometry, whereas the rotation search used detrended photometry. Finally, the ensemble search greatly expanded the masked period regions and required unique periods, while the rotation search used a bootstrap analysis to determine the likelihood the period was genuine. More fundamentally, the ensemble analysis was intended to identify large-amplitude variations that meet stringent criteria for significance, whereas the rotation-focused analysis was designed to identify periodic signals that could, in some cases, be detected at amplitudes below that required by the rms, $D_{90}$, or Welch–Stetson $J$ and $L$ metrics.

4.4. Cross-match with the AAVSO Variable Star Index

The American Association of Variable Star Observers (hereafter, AAVSO) has created and cultivated the Variable Star Index (hereafter, VSX) since 2006 (Watson 2006). The VSX combines basic variability and astrometric information for more than 400,000 variable stars discovered by both amateur and professional astronomers. We matched our catalog to the VSX, selecting the nearest variable within 30", and found 19,313 matches.

We compared the absolute difference between a given variable star’s magnitude at maximum and minimum, as reported by the VSX, to serve as the variable star’s variable amplitude. We then compared this to our own proxy for variable amplitude, the $D_{90}$ metric, as shown in the top panel of Figure 13. While 726 (or 12\%) of stars with reported maximum and minimum magnitude values appear to have similar amplitudes in both catalogs, we find the majority of the stars VSX show larger amplitudes than reported in our catalog. This could be because the $D_{90}$ metric is expected to underestimate the true variable amplitude (because it is only the 90th percentile magnitude range) but also because the KELT magnitude filter is a reddish, broad passband that may be dampening the variable amplitude, which typically peaks in the blue part of the electromagnetic spectrum.

We also compared our recovered periods and those listed in the VSX, as shown in the bottom panel of Figure 13. We find that 3,564 (or 56\%) of the periodic stars in both the VSX and our catalog have similar periods or are aliases of the VSX period ($P/2$, $P/3$, $2P$, $3P$). Additionally, many of the periods recovered by our methods appear to be beat frequencies of the VSX period or vice versa (shown as the parabolic features in the bottom panel of Figure 12. Same as Figure 11, but for nine southern KELT fields.)
Figure 13 (Long et al. 2016; VanderPlas 2017), helping to confirm these sources are likely true periodic variables.

4.5. Using Other Catalogs to Infer the Characteristics of KELT Variables

We can infer basic characteristics of the KELT variable data set using the information provided by the TIC. We select KELT periodic stars with periods <100 days and valid parallax information. We next make a Hertzsprung-Russell diagram by transforming the observed $K_S$ magnitude into an absolute $K_S$ magnitude, and then calculate the $V - K_S$ color.

We find stars on the giant branch tend to have much slower rotation periods than stars on the main sequence (Figure 14, top panel). This is expected for rotation periods of giant stars, as stars tend to spin down as they age (van Saders & Pinsonneault 2013; Tayar et al. 2015). Stars at the low-mass end of the main sequence also show longer rotation periods than their higher-mass counterparts, which could indicate the Kraft break and would be expected for a typical field population (Kraft 1967). There are a few objects along the giant branch with short periods; these are likely pulsators, such as RR Lyrae, or objects within short-period eclipsing binary star systems. Phased light curves for three objects, from three parts of the HR diagram, can be seen in the bottom panels of Figure 14.

Similarly, we created an HR diagram for stars that pass the variable metrics, as shown in the top panel of Figure 15. We color this HR diagram heatmap according to the sum of the Welch–Stetson $J$ and $L$ metrics. Here, we find the sums tend to be larger (>10) for objects identified as giants and sub-giants. Time-series light curves for three stars, from three separate regions of the HR diagram, are shown in the bottom part of Figure 15.

The Welch–Stetson $J$ and $L$ metrics were designed to identify objects that show variable behavior, which is heavily correlated with time (i.e., objects with periodic and/or continuous variability) (Stetson 1996). The large metric values for stars on the giant branch could indicate correlated and continuous stellar variability increases with age (as expected for stars in the instability strips) or the detection of possible seismic oscillations, which can occur on timescales of 10–100 days. The smaller combined $J$ and $L$ values for dwarf stars also indicates the variability detected in these stars could be due to spot variation and rotation, or a sudden solitary variability, such as a stellar flare, rather than the large-amplitude, continuous pulsations found in their giant counterparts.

5. Discussion

5.1. Additional Applications of the KELT Variability and Periodicity Catalog

The long KELT baseline (5–9 years) also provides an opportunity to study the long-term evolution of variable star behavior. Observations with KELT and other long-baseline surveys, such as KEPLER (Borucki et al. 2010), OGLE (Udalski et al. 2015) and WASP (Pollacco et al. 2006), have shown many variable objects tend to modify their variability as a function of time. Therefore, long-baseline observations can provide scientific insight into previously unknown stellar astrophysics and phenomena.

Three variables with evolving behavior, which could have been missed without the baseline of KELT, are shown in Figure 16. The top panel shows 2MASS J05095273+3700158,
Table 3
Magnitude Information for KELT Variables

| 2MASS ID   | $V_\text{K}$ | $T$  | $B$  | $V$  | $g$  | $r$  | $i$  | $J$  | $H$  | $K_S$ | $W_1$ | $W_2$ | $W_3$ | $W_4$ |
|------------|--------------|------|------|------|------|------|------|------|------|-------|-------|-------|-------|-------|
| J00000082+2558023 | 11.056 | 10.710 | 11.673 | 11.204 | 11.416 | 11.099 | 11.277 | 10.249 | 10.047 | 10.021 | 9.970 | 9.998 | 10.110 | 8.168 |
| J00000690+2014145 | 7.434 | 6.361 | ... | ... | 4.026 | 3.079 | 2.562 | 0.652 | 0.964 | 2.072 | 1.579 | 1.023 | 0.579 | 0.379 |
| J00000657+2553112 | 7.796 | 5.520 | 11.528 | 10.377 | 11.310 | 99.999 | 99.999 | 2.225 | 1.317 | 0.915 | ... | ... | ... | ... |
| J00001686+2636285 | 10.273 | 9.193 | 13.258 | 11.712 | 12.405 | 11.907 | 99.999 | 7.346 | 3.079 | 2.562 | 0.652 | 0.964 | 2.072 | 1.579 |
| J00001766+2555323 | 11.495 | 12.661 | 14.569 | 13.777 | 14.074 | 13.224 | 13.137 | 11.823 | 11.399 | 11.269 | 11.189 | 11.301 | 11.119 | 8.615 |
| J00003558+2639495 | 13.081 | 12.819 | 13.657 | 13.337 | 13.440 | 13.235 | 12.344 | 12.224 | 12.116 | 11.963 | 11.959 | 11.692 | 9.003 | ... |
| J00010148+1937371 | 12.704 | 12.426 | 13.682 | 13.050 | 13.349 | 12.869 | 12.734 | 11.852 | 11.547 | 11.540 | 11.540 | 9.003 | 8.666 | 8.229 |
| J00010244+3830145 | 9.021 | 6.669 | 12.918 | 11.157 | 12.167 | 10.246 | 7.783 | 3.542 | 2.630 | 2.083 | −0.506 | 0.077 | 0.737 | 0.229 |
| J00012877+3147256 | 9.544 | 8.024 | 12.996 | 11.401 | 12.147 | 10.604 | 8.511 | 5.719 | 4.796 | 4.486 | 4.238 | 3.902 | 3.645 | 3.011 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| J00032115+4047086 | 9.318 | 7.573 | 13.048 | 11.282 | 12.260 | 10.412 | 7.564 | 4.899 | 3.826 | 3.344 | 3.224 | 2.023 | 2.225 | 1.489 |
| J00032141+3831068 | 12.434 | 11.687 | 13.881 | 12.736 | 13.280 | 12.363 | 11.982 | 10.697 | 10.119 | 9.952 | 9.870 | 9.925 | 9.771 | 8.969 |
| J00032799+3047161 | 13.314 | 12.744 | 14.024 | 13.379 | 13.645 | 13.201 | 13.055 | 12.167 | 11.950 | 11.859 | 11.784 | 11.791 | 11.579 | 9.899 |
| J00033731+3506290 | 9.686 | 8.095 | 12.736 | 11.129 | 11.849 | 10.437 | 8.580 | 5.985 | 5.134 | 4.791 | 4.651 | 4.555 | 4.480 | 4.217 |
| J00034949+3153160 | 12.572 | 11.972 | 13.112 | 12.598 | 12.799 | 12.438 | 12.210 | 11.797 | 11.610 | 11.121 | 11.145 | 11.046 | 8.598 | ... |
| J00035473+4006068 | 11.788 | 11.461 | 12.815 | 12.144 | 12.441 | 11.955 | 11.795 | 10.836 | 10.536 | 10.483 | 10.452 | 10.488 | 10.455 | 8.989 |
| J00040465+3814184 | 12.470 | 11.797 | 13.241 | 12.532 | 12.858 | 12.324 | 12.125 | 11.071 | 10.691 | 10.568 | 10.588 | 10.603 | 10.592 | 8.750 |
| J00040750+1946581 | 12.498 | 11.876 | 13.006 | 12.418 | 12.678 | 12.255 | 12.068 | 11.312 | 11.009 | 10.936 | 10.850 | 10.866 | 10.786 | 8.574 |
| J00040792+4010437 | 10.650 | 10.158 | 12.208 | 11.128 | 11.643 | 10.792 | 10.421 | 9.223 | 8.643 | 8.518 | 8.422 | 8.526 | 8.418 | 8.568 |
| J00040905+3418094 | 10.759 | 9.047 | 13.903 | 12.258 | 13.007 | 11.538 | 9.572 | 6.842 | 5.967 | 5.637 | 5.557 | 5.476 | 5.224 | 4.962 |

Note. This is only a part of the full table to be released online. The most up-to-date version of this table, including updates from new versions of the TIC, additional KELT observations, and/or improved selection metrics, is available for download at the Filtergraph portal https://filtergraph.com/kelt_vars.

(This table is available in its entirety in machine-readable form.)
Table 4
Variability Information for KELT Variables

| 2MASS ID          | $V_K$  | rms  | $\Delta_{90}$ | $J_S$  | $L_S$  | Period (days) | Power | $A_P$ | Variability Flags | Quality Flags |
|-------------------|--------|------|---------------|--------|--------|---------------|-------|-------|-------------------|---------------|
|                   |        |      |               |        |        |               |       |       | Variable | Periodic | Multi-P | Alias | Blend | Prox. | Points | Edge | Single |
| J00000082+2558023 | 11.056 | 0.136| 0.424         | 7.705  | 5.682  | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00000690+2014145 | 7.434  | 0.117| 0.380         | 47.588 | 34.013 | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00006575+2553112 | 7.796  | 0.615| 1.782         | 277.130| 207.578| ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00016866+2636285 | 10.273 | 0.236| 0.820         | 15.561 | 10.755 | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00017666+2555323 | 11.495 | 0.951| 3.004         | 41.226 | 28.022 | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00035585+2639495 | 13.081 | 0.217| 0.696         | 1.455  | 1.041  | 1.309913     | 0.526 | 2.620 | 1        | 1          | 1       | 0     | 0     | 0     | 0     | 0     |
| J00010148+1937371 | 12.704 | 0.145| 0.440         | 1.149  | 0.777  | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 1     |
| J00010244+3830145 | 9.021  | 0.199| 0.628         | 59.084 | 45.950 | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00012877+3147256 | 9.544  | 0.158| 0.564         | 22.433 | 15.298 | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00021115+4047086 | 9.318  | 0.170| 0.582         | 34.176 | 25.764 | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00032141+3831068 | 12.434 | 0.265| 0.212         | 0.579  | 0.403  | 5.929420     | 0.445 | 4.650 | 0        | 1          | 1       | 0     | 0     | 0     | 0     | 0     |
| J00032799+3047161 | 13.314 | 0.151| 0.479         | 0.691  | 0.504  | 0.191503     | 0.639 | 3.130 | 0        | 1          | 1       | 0     | 0     | 0     | 0     | 0     |
| J00033731+3508290 | 9.686  | 0.068| 0.221         | 9.185  | 6.720  | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00034949+3153160 | 12.572 | 0.062| 0.200         | 0.538  | 0.386  | 0.219036     | 0.464 | 4.570 | 0        | 1          | 1       | 0     | 0     | 0     | 0     | 0     |
| J00035473+4006608 | 11.788 | 0.220| 0.685         | 4.456  | 3.286  | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00040465+3814184 | 12.470 | 0.097| 0.328         | 0.924  | 0.614  | 0.201513     | 0.455 | 5.070 | 0        | 1          | 0       | 0     | 0     | 0     | 0     | 0     |
| J00040750+1946581 | 12.498 | 0.107| 0.338         | 0.771  | 0.547  | 0.208178     | 0.543 | 2.650 | 0        | 1          | 1       | 0     | 0     | 0     | 0     | 1     |
| J00040792+4010437 | 10.650 | 0.088| 0.281         | 4.960  | 3.449  | 316.582275   | 0.689 | 7.640 | 0        | 1          | 0       | 1     | 0     | 0     | 0     | 0     |
| J00040905+3418094 | 10.759 | 0.117| 0.370         | 7.930  | 5.661  | ...           | 0.000 | 0.000 | 1        | 0          | 0       | 0     | 0     | 0     | 0     | 0     |

Note. This is only a part of the full table to be released online. The most up-to-date version of this table, including updates from new versions of the TIC, additional KELT observations, and/or improved selection metrics, is available for download at the Filtergraph portal https://filtergraph.com/kelt_vars.
(This table is available in its entirety in machine-readable form.)
also known as HD 33152. The star shows long-term variability, with a large (∼0.5 mag) increase in magnitude between 2,455,000–2,456,000 days, consistent with being a possible long-period Be star (previously identified in Labadie-Bartz et al. 2017), with the magnitude returning to its initial brightness near 2,457,000 days. Interestingly, this object appears to show large amplitude (0.1–0.4 mag) outbursts consistently during its brightening. The identification of these outbursts indicates the KELT survey could participate in a search for similar stellar flares and outbursts in other stars. Such a search could help to constrain flare rates for early-type dwarfs, which have been excluded from previous stellar flare studies that focused on late-type dwarfs in SDSS photometry, {	extit{Kepler} light curves, and photometry from the Chinese Small...
The middle panel of Figure 16 shows the recovery of the DErk object 2MASS J04181078+2591574, also known as V409 Tau (Rodriguez et al. 2015). The object is identified as a classical T-Tauri star, and has been shown to be occulted by a protoplanetary disk on an interval of nearly 600 days. Since the publication of Rodriguez et al. (2015), the star has shown yet another dimming event of similar duration (∼500–800 days).

The bottom panel of Figure 16 shows 2MASS J15303924+3547043, also known as ST Boo. Our match with the VSX shows this star was previously identified as an RR Lyrae-type variable with a primary period of 0.622 days. When the time-series light curve of this variable is plotted, clear period doubling and amplitude modulation can be seen, indicative of the Blazhko effect (Blazhko 1907). In recent years, the cause of the Blazhko effect has been better constrained (nearly 50% of RRab stars show the modulation; e.g., Jurcsik et al. 2009), but the star’s relatively bright V magnitude at minimum, ≈11.35, short pulsation period of 0.622 days, and typical Blazhko modulation in <100 days still make it an excellent candidate for further study.

5.2. Caveats and Future Directions

Here, we discuss three important limitations of the KELT Variability Catalog in its current form, and discuss possible future directions to address these limitations. The first is the use of heuristic methods to identify variable objects, the second is the non-detection of most detached eclipsing binaries, and the third is the likelihood of faint contaminants in the KELT photometry.

The selection criteria used in this work clearly demonstrate the difficulties and current limitations of objectively identifying variable stars in large photometric data sets. While our metrics are based on the reasonable assumption that variability will inflate the dispersion of the light curve, the distributions of each metric are clearly non-Gaussian (see Figure 3). This limits the interpretation of stars that deviate from the main population using typical sigma-based cutoffs. Although we increased the number of metrics in an attempt to alleviate this tension, doing so can ultimately increase the likelihood a star may appear variable due to random sampling error. One way to resolve this issue would be through the use of a neural-net classification. However, there is a current lack of variability training sets.
available that can properly compensate for the varieties of detector red-noise found in ground-based surveys (Pashchenko et al. 2017). Additionally, variable classification is badly imbalanced (there are many more “constant” stars than variable objects in a given data set), which complicates the use of machine-learning techniques. The primary reason we have released the data set through Filtergraph is to provide the astronomical community with a tool for studying and creating a variability training set useful for future study, as well as to allow users to impose their own selection metrics or data-cleaning methods.

The periodicity search methods that we have used in this work (Lomb–Scargle based) are not optimized for detection of eclipsing binaries (EBs), especially detached EBs. We expect that we probably have detected contact EBs in our periodic sample because those light curves are more approximately sinusoidal in nature, but Lomb–Scargle based period-search methods are not optimized for detached EBs whose light curves are characterized by short-duration, punctuated drops in brightness; moreover, they generally involve two eclipses per cycle of different depths. We are planning a focused search for EBs as the subject of a separate KELT paper. Even so, any and all EBs in our light curves—even if not yet recognized as such—do have their general variability properties measured and reported in this paper.

Figure 14. Top: a heatmap, colored by average period, of an H-R diagram of KELT stars with valid rotation periods less than 50 days and parallaxes provided by the TIC from the analysis described in Section 4.3.2. The V magnitude in this figure is the Johnson V magnitude reported in the TIC, and not $V_\text{K}$. Stars with the longest periods are found along the giant branch, as is expected. The figure has been broken into three regions. Region 1: the giant branch, Region 2: sub-giant stars, Region 3: dwarf stars. Bottom: three representative light curves of periodic stars, one from each of the three regions in the top panel. The solid red lines are the best-fit sine curve to each phased light curve. Each light curve has been phased on the period recovered for the star and binned into 400 data points. Representative error bars can be found at the bottom right of each panel. The stars have had their E and W orientation light curves combined and detrended for these figures and the analysis.
As mentioned in Section 2, a KELT pixel is 23” on a side. This means many of the detected KELT sources are blended with fainter (or in some cases, brighter) neighbors. That blending can cause astrophysical variability from the target star to be diluted, or the signal from a variable blended neighbor can contaminate the signal from the target star. In this analysis, we match the stars in our variable and rotation catalogs to the TIC using a positional match between the 2MASS catalog (Skrutskie et al. 2006) and the base KELT catalog, selecting the nearest 2MASS object within 0.3 of the KELT source. Because both the TIC and 2MASS have higher spatial resolution than the KELT catalog, multiple TIC point sources will typically occupy any given KELT pixel. Therefore, future analysis of the KELT data set, when matched to other, higher spatial resolution photometric catalogs, may benefit from an updated matching scheme that incorporates position, magnitude, and color, rather than position alone.

6. Summary

We have presented an in-depth search for variable and periodic sources in the KELT data set. We identify 52,741 stars with large-amplitude modulations and/or periodic signals likely due to stellar variability using four variability metrics (rms, $\Delta_{90}$, Welch–Stetson J and L) and by forcing each period to meet four requirements. Of these variable objects, 18,907 have all quality flags set to 0, meaning they are unlikely to be contaminated by any detector systematics, aliasing, or crowding/blending due to KELT’s wide FoV.

We have matched our catalog to the TIC and VSX. Additionally, we identified candidate rotation periods for 62,229 high-priority dwarfs, which may be observed with the mission’s two-minute cadence. Finally, we provided variability upper limits for all other $\sim$4,000,000 sources observed by KELT and in the TIC.

Figure 15. Top: a heatmap, colored by the sum of the Welch–Stetson $J$ and $L$ metrics, of an H-R diagram for stars in the KELT variable data set with valid parallaxes provided by the TIC. The $V$ magnitude in this figure is the Johnson $V$ magnitude reported in the TIC, and not $V_K$. Bottom: three representative light curves of variable stars in the top panel, one for each of the three regions. Each light curve has been binned into 30 minute intervals. Representative error bars can be found at the bottom right of each panel. The stars have had their E and W orientation light curves combined for these figures.
The full variable catalog has been uploaded to the Filtergraph data visualization portal at the URL https://filtergraph.com/kelt_vars. The portal can be used to access the variability and periodicity information described in Sections 3.1 and 3.2, stellar parameters obtained by the cross-matches listed in Sections 4.3 and 4.4, and a light curve figure for each variable star for visual inspection. This portal is meant to be a living database and will be updated for new TIC versions, updated KELT observations, and any improvements to the variability selection metrics. Basic Python code used to calculate the variability and periodicity metrics is available through the GITHUB URL https://github.com/ryanoelkers/var_tests.

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