The Kepler IRIS Catalog: Image Subtraction Light Curves for 9150 Stars in and around the Open Clusters NGC 6791 and NGC 6819

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Abstract

The four-year Kepler mission collected long-cadence images of the open clusters NGC 6791 and NGC 6819, known as “superstamps”. Each superstamp region is a 200 pixel square that captures thousands of cluster members, plus foreground and background stars, of which only the brightest were targeted for long- or short-cadence photometry during the Kepler mission. Using image subtraction photometry, we have produced light curves for every object in the Kepler Input Catalog that falls on the superstamps. The Increased Resolution Image Subtraction (IRIS) catalog includes light curves for 9150 stars, and contains a wealth of new data: 8427 of these stars were not targeted at all by Kepler, and we have increased the number of available quarters of long-cadence data for 382 stars. The catalog is available as a high-level science product on MAST, with both raw photometric data for each quarter and corrected light curves for all available quarters for each star. We also present an introduction to our implementation of image subtraction photometry and the open-source IRIS pipeline, alongside an overview of the data products, systematics, and catalog statistics.

Unified Astronomy Thesaurus concepts: Astronomy databases (83); Astronomy data analysis (1858); Stellar photometry (1620); Open star clusters (1160)

1. Introduction

During the nominal four-year Kepler mission, the telescope observed 150,000 stars in 30 minute long cadence (Jenkins et al. 2010), and 512 per quarter in 1 minute short cadence (Gilliland et al. 2010). Compared to the several million stars in the field, this places a limit on the completeness of statistical studies, with dependencies on factors such as magnitude and binarity (Wolniewicz et al. 2021). The mission downloaded three full-frame images (FFIs) per quarter, accessible via Montet et al. (2017). This sampling cadence is not short enough to recover many kinds of periodicity among stars that were not individually targeted for long- or short-cadence photometry. Areas near the Galactic plane and in stellar clusters were undertargeted because the higher levels of crowding made it harder to isolate individual stars (Batalha et al. 2010). Each targeted star was first downloaded as a series of images, known as a target pixel file (TPF), and a light curve was produced using simple aperture photometry (SAP). There is little we can do to extend the number of targets in the Galactic plane, apart from serendipitous finds in the background of TFs, but the open clusters NGC 6791 and 6819 were targeted by “superstamps”, 200 × 200 px images (delivered as 20 × 100 “sub-stamps”), which covered the clusters at the Kepler long cadence of 30 minutes. Only a fraction of stars within these superstamps were targeted in the usual way, leaving many more still to be analyzed. We use image subtraction photometry, a method suited to crowded fields, to produce light curves for all 9150 Kepler Input Catalog (KIC) targets that fell on the superstamps.

We obtained these light curves using a novel implementation of image subtraction photometry, which we term Increased Resolution Image Subtraction (IRIS). The IRIS pipeline, outlined in Section 2.3, is open source and available on GitHub at https://github.com/astroblo/kepler_iris. In this paper, we present the Kepler IRIS Catalog5, a collection of Kepler long-cadence light curves for 5342 stars in the field of NGC–6791 and 3808 stars for NGC 6819. These include 8427 KIC entries that were not targeted during the nominal Kepler mission. All light curves are freely available as a high-level science product (HLS) on MAST via 10.17909/t9-w8fw-4r14.

With 13’20″ square coverage of each cluster across the superstamps, the majority of cluster members are covered by these data products. Open clusters are prime testing grounds for theories of stellar evolution, as all the stars in a cluster are the same age. The open clusters covered by the Kepler superstamps are two of four open clusters within the Kepler field of view (FOV), alongside NGC 6811 and 6866. All four clusters have been the focus of many studies throughout and beyond the lifetime of the Kepler mission. In this section, we provide an overview of those studies that focused on NGC 6791 and 6819.

NGC 6791 is one of the oldest known open clusters, with an age of 8.2 ± 0.3 Gyr (McKeever et al. 2019), and an unusually high metallicity of +0.313 ± 0.005 dex (Villanova et al. 2018), indicating that it likely formed in the Galactic bulge. NGC 6819 has an age of 2.38 ± 0.05 Gyr (Brewer et al. 2016), making it also one of the older known open clusters. It has a metallicity of +0.10 ± 0.04 dex (Carrera et al. 2019), close to the solar value. Many general studies of NGC 6819 have focused on stellar rotation (Balona et al. 2013), particularly on the application of the period–age–mass relation (Meibom et al. 2011, 2015). Further studies of the cluster have

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5 https://archive.stsci.edu/hlsp/iris
shown the connection between lithium abundance and stellar rotation rates (Deliyannis et al. 2019).

Red giants are a particular focus of Kepler open cluster studies: with well-characterized oscillations, their seismic parameters can be used in the asteroseismic scaling relations to provide mass and radius estimates, and hence cluster age and distance estimates (Basu et al. 2011). Additionally, with an understanding of the red giant populations in each cluster, red giant seismic parameters have been used to confirm cluster memberships (Stello et al. 2011) and study red giant evolution (Corsaro et al. 2012). Red giant seismology in the Kepler open clusters has also been used to examine the role of metallicity in cluster evolution (Hekker et al. 2011) and to test the asteroseismic scaling relations (Stello et al. 2010; Miglio et al. 2012). In NGC 6791, Miglio et al. (2012) used red giants to find that there is no extreme mass loss on the red giant branch, noting that NGC 6819 is too young to exhibit significant mass loss. Studies of the younger red giant population in NGC 6819 have used seismology to distinguish between red giant branch and red clump stars (Handberg et al. 2017), and focused on individual stars of interest, such as the lithium-rich red giant KIC 4937011 (Anthony-Twarog et al. 2013; Carlberg et al. 2015). Showing that there are still more members to be found, Komucyeya et al. (2018) identified a new red giant in NGC 6819, namely KIC 5112840.

Kepler’s light curves for NGC 6791 and NGC 6819 have yielded studies of many other stellar oscillators. NGC 6791 is old enough to have white dwarfs: Kalirai et al. (2007) showed that the white dwarfs in NGC 6791 did not evolve via the helium flash mechanism, but rather as the result of mass loss on the extreme horizontal branch, which suggests that mass loss is more efficient in higher-metallicity environments. García-Berro et al. (2011) went on to show that the white dwarf population of the cluster is largely the result of binary mergers. NGC 6791 is also host to a notable pulsating subdwarf B (sdB) star, KIC 2438324 (Pablo et al. 2011); a further two sdB stars were identified using Kepler data and analyzed by Reed et al. (2012). NGC 6819 contains several γ Doradus and δ Scuti stars (Talamantes et al. 2010; Balona et al. 2013). A notable classical pulsator in NGC 6791 is the γ Doradus binary KIC 2438249, which Li et al. (2020) analyzed using prerelease data from this study.

There has also been a wide range of research into binary star systems in the Kepler open clusters. In particular, eclipsing binary (EB) modeling provides reliable masses and radii; this allows us to determine stellar age, and in turn cluster age. In NGC 6791, Grundahl et al. (2008) used ground-based data to study the detached EB KIC 2437452, providing cluster age and distance measurements. Brogaard et al. (2011) introduced three new EB models in the cluster, which they used to calibrate age and He abundance measurements; of these stars, Hoyman et al. (2019) went on to model the EB KIC 2438061 using Kepler data, proving a distance estimate to the cluster, though their mass estimates differ from Brogaard et al. (2011). NGC 6819 has proved host to a greater number of binaries than expected, as shown in the preliminary studies for this data release (Colman 2020), which we will discuss in greater detail in Section 3.3. Before Kepler, there have been studies of binaries in NGC 6819 from the WIYN Open Cluster Survey (WOCS; Talamantes et al. 2010; Milliman et al. 2014). Using Kepler time-series data, there has been increased focus on individual binaries to provide age and distance estimates, including the EB KIC 5024447 (Sandquist et al. 2013), spectroscopic binaries KIC 5113146 and KIC 5111815 (Soydugan et al. 2020), and the triple systems KIC 5113053 (Jeffries et al. 2013) and KIC 5023948 (Brewer et al. 2016). Many binaries in both clusters have also been identified as blue stragglers (e.g., Hole et al. 2009; Brogaard et al. 2018). In recent work, Vaidya et al. (2020) identified 75 blue stragglers in NGC 6791 and 29 in NGC 6819, while Gao (2020) found 49 blue stragglers in NGC 6791.

As this broad range of results shows, the Kepler mission was uniquely suited to collecting large volumes of time-series data for members of the open clusters in the FOV. However, the crowding in these regions placed limits on the completeness of photometric coverage across the open clusters. With this data release, we provide light curves for all KIC targets in NGC 6791 and 6819, including both cluster members and nonmembers, opening up new avenues of time-domain study for both cluster analysis and general usage, such as the search for oscillating stars and exoplanets in the Kepler field.

2. Methods

2.1. Kepler Photometry

The basic method for CCD photometry is aperture photometry, which involves selecting an aperture of pixels surrounding each target and adding the photon counts in those pixels (potentially with weighting) to calculate flux. The method can also involve defining an annulus around the aperture to estimate the background flux, which can be subtracted from each frame prior to photometry to create a more accurate time series. The main benefits of SAP are that it is easy to implement and fast to process; most complications in its implementation arise from defining the aperture. The SAP time series provided by Kepler used apertures informed by the point-spread function (PSF) and target brightness. The Kepler PSF changed across the telescope’s FOV, and, as such, it was modeled for each target individually. This led to apertures of varying sizes, as described by Bryson et al. (2010). There is also an official Kepler data product of detrended time series (Stumpe et al. 2012; Smith et al. 2012; Thompson et al. 2016), using the subtraction of cotrending basis vectors (CBVs) to remove systematics and trends from spacecraft pointing and jitter. The CBVs were calculated to fit the most common systematic trends in the data, in particular long-term trends that arise from pointing drift. This method is called presearch data conditioning (PDC) because it occurs prior to the search for transits in Kepler data. Its implementation follows after the background-subtraction step of SAP: even with an accurate aperture, SAP retains systematics from the pointing of the telescope which collected the data.

SAP and PDC-SAP are the default methods of time-series data delivery for Kepler and K2 targets, and produce high-quality data for a majority of stellar targets. Using the Kepler target pixel files (TPFs), one can also perform custom photometry on any targeted star. This has been a particular imperative for K2 data, which are harder to detrend due to the 6 hr pointing drift. There are multiple sets of K2 time-series data available from different pipelines (e.g., Vanderburg & Johnson 2014; Lund et al. 2015), all hosted on MAST. There are also superstamp images available for open clusters in K2 (Cody et al. 2018), presenting further opportunities for custom photometry. FFIs and calibration data provide opportunities for
innovative approaches to obtain time-series data for bright targets (Pope et al. 2016; White et al. 2017; Pope et al. 2019), where SAP is less effective due to pixel bloom and smearing, and nontargeted stars.

As well as bright stars, SAP is less effective for faint targets and crowded targets. In particular, when there is minimal separation between neighboring targets, or indeed multiple stellar signals contributing to one pixel’s flux, a different approach is required. In the following sections, we will discuss image subtraction photometry as an alternative to SAP, and our implementation for performing custom image subtraction photometry on the Kepler superstamps.

2.2. Image Subtraction Photometry

To extract light curves from the NGC 6791 and 6819 superstamps, we used image subtraction photometry. Throughout the literature, this method is also known as difference imaging, or differential image analysis; we refer to the method as image subtraction to distinguish from the false-positive vetting procedure known as difference imaging (Bryson et al. 2013). Image subtraction was introduced by Tomaney & Crotts (1996), and refined into today’s widely used algorithm by Alard & Lupton (1998). Image subtraction was proposed as a method to offset poor seeing in ground-based telescopes. Alard & Lupton created a reference image from an average of the 20 frames with the best seeing, after realigning each frame in the time series so that the target is centered on the same point. Following this, they used a kernel convolution to match the PSFs between each frame in the time series and the reference image, and then subtracted the reference image from each frame. This is the key step in the process: subtracting a reference image, which acts as an average, removes all nonvariable signal in the time series. Following subtraction, Alard & Lupton performed aperture photometry on each image, reconstructing any variable signal into a time series. This makes image subtraction an ideal method for studying stellar variability and probing crowded fields.

Since the introduction of the image subtraction method for photometry, its primary use has been on ground-based data. However, various image subtraction algorithms have been developed for use on Kepler and Transiting Exoplanet Survey Satellite (TESS) pixel data. The most common is the FITS photometric package (Pál 2012), which includes utilities that have been used by Soares-Furtado et al. (2017) and Wallace et al. (2019) on K2 cluster data, and by Bouma et al. (2019) in the search for exoplanets in TESS open clusters. There is also the DIA pipeline (Oelkers & Stassun 2018), which is designed to perform image subtraction photometry on TESS data. Another method that has been used for crowded-field photometry in Kepler is the causal pixel modeling method (Wang et al. 2017; Hattori et al. 2021), an approach to aperture photometry that defines an image background based on random pixels selected in the star’s vicinity.

In this study, we introduce a new method for image subtraction photometry on space-based time-series image data. Our implementation differs from previous methods in that we do not perform the convolution step for image realignment. We create a reference frame by taking an arithmetic mean of all frames in the time series, following a process of realignment to ensure that the target is centered on the same point in all frames. Alignment is a key issue when dealing with images from spacecraft, since we need to account for pointing drift.

Figure 1. 5 × 5 cutout example showing KIC 2437745, an ellipsoidal binary in NGC 6791.

Our implementation of the algorithm uses a process of resampling and realignment to correct for this. The resampling step uses bilinear interpolation to redistribute flux into a subpixel structure—leading to the term “increased resolution image subtraction” (IRIS)—and the realignment step involves a further interpolation, this time using a centroid measurement to redistribute the flux accordingly. We present a detailed outline of this method in the following section.

2.3. The IRIS Algorithm

We performed image subtraction photometry on one quarter of Kepler superstamp data at a time. We will cover the specifics of the practical application of this algorithm on Kepler superstamp data in Sections 2.6 and 2.7. The steps are as follows:

1. Beginning with Kepler superstamp data, we cut out a 5 × 5 pixel postage stamp centered on the target star, as in Figure 1. This puts our data in a format akin to a Kepler TPF—that is, a time series of pixel images, here termed “frames”. We found the image centroid in pixel coordinates, calculated within a 3 × 3 pixel square around the target. We calculated the centroid using the equation for the first moment of an image,

\[
\frac{\sum x_i f_i}{\sum x_i},
\]

where \( x_i \) are the pixel coordinates along the x-axis and \( f_i \) are the flux values in the corresponding pixels. We used a similar equation for the y-axis.

In general, we found that the centroid shift for a Kepler target is typically several hundredths of a pixel. Although small, this is significant, and consistent across all targets within the superstamps. We will discuss the centroiding process in greater detail in Section 2.4.

2. We prepared the two-dimensional time-series data for photometry by resampling each frame to have a large
number of pixels per 4″ Kepler pixel, as in the left panel of Figure 2. Resampling allows for easier redistribution of flux according to the measured centroid. We included an interpolation at this stage to create a true distribution of fluxes across the new, finer-resolution image. By inspecting the quality of light curves at various resampling factors, we found that a factor of 20 was sufficient for high-quality photometric data.

We performed the resampling using scipy’s rectangular bivariate spline interpolation functionality (Virtanen et al. 2020). We used bilinear interpolation across both image axes. In general, cubic interpolation methods are preferred, as the cubic function is assumed to give a better fit. Bilinear interpolation is slightly less computationally intensive than bicubic interpolation; however, its main advantage in this study is that bicubic interpolation results in flux dilution due to a signal-overshooting effect, meaning that bicubic interpolation leaves the interpolated image with a blurred look. Bilinear interpolation is better at preserving flux values, and retains a certain level of detail that bicubic does not, which is useful for understanding the structure of signal sources. Additionally, the scipy implementation of bicubic interpolation results in pronounced edge effects at the borders of the 5 × 5 postage stamp. We show an example of this in the right panel of Figure 2.

3. Again using interpolation, we shifted each frame in the time series to move the measured centroid to the center of the postage stamp. We then took the average of all the realigned frames to use as our reference frame. We calculated the range of fluxes in the average frame, and selected the pixels with fluxes in the bottom 5% of that range to determine a value for the background flux. We subtracted this background from each frame.

4. Next, before performing the photometry, we defined an aperture around our target. Image subtraction isolates and measures variability, but in the case where multiple-variable sources are nearby in a crowded field, it is necessary to limit the aperture to avoid the blending of multiple signals. The apertures we used are two-dimensional arrays with the dimensions of the average frame, with pixel values from 0 to 1, indicating weighting. We will cover aperture selection in more detail in Section 2.5.

5. Finally, we subtracted the reference frame from each individual frame. This removed any nonvariable flux that may have been in the aperture and accentuated any variable signal. We show the result of this subtraction for one frame in Figure 3. Then, we added together the flux from each individual pixel, weighted by the aperture mask, making a single point in our time-series data. The unit of these points is an arbitrary flux count, proportional to the square of the resampling factor and the original electrons per second count in each pixel prior to resampling and realignment. We repeated the subtraction and subsequent aperture photometry process for each frame. Finally, we added the aperture sum to each point in the time series, giving the time-series point a flux value. Figure 4 shows the uncorrected time series for the example star used throughout this section.

We implemented this algorithm in Python, using AstroPy for the FITS file handling (Robitaille et al. 2013; Price-Whelan et al. 2018), Pandas for database handling (Reback et al. 2021), NumPy for array handling (Harris et al. 2020), SciPy for interpolation (Virtanen et al. 2020), and Lightkurve for data management (Barentsen et al. 2021). The code used to produce the IRIS light curves can be found at https://github.com/astrobel/kepler_iris.

2.4. Cluster Centroids

The image subtraction algorithm presented by Alard & Lupton (1998) uses a kernel convolution method to account for imperfect seeing from ground-based data. As Kepler is a space telescope, this step is not necessary. However, we still need to ensure alignment between the reference frame and each individual frame. The benchmark image subtraction algorithm for Kepler and TESS data, FITS (Pál 2012), retains the convolution step to perform this realignment, although it does not involve resampling. Alongside resampling, we introduce a centroiding process, which allows us to use interpolation to...
redistribute flux on a finer pixel grid. The overall change in centroid position at each cadence over one quarter can be as much as 20% of a Kepler pixel. For the process of realignment, we take image centroid measurements in 3 × 3 pixel squares centered on the target, and convert them from pixel coordinates into distances from the middle of the 5 × 5 postage stamp. The centroid displacement between any two cadences is typically several hundredths of a pixel along each axis; therefore, to precisely realign each frame without interpolation, we would need to resample by a factor of 100. However, the computational time involved in this would be untenable as part of a pipeline designed to run on thousands of stars. We found that interpolation on a grid resampled by a factor of 20 yields high-quality results within an acceptable computational time.

In practice, we did not need to perform the centroid calculation for each target. Calculating the centroid of a star in a crowded FOV is unreliable because there are so many nearby sources of flux, many of which may be brighter than the target star and cause an incorrect measurement of the target centroid. To deal with these cases, we calculated an ensemble centroid for each cluster. We chose the 100 brightest targets in each cluster, discarding any stars which were missing quarters due to being near the edge of the superstamp, and stars where the 3 × 3 pixel centroiding region covered multiple 20 × 100 stamps. The distributions of these stars across the superstamps are shown in Figure 5. We calculated the centroid measurements throughout each quarter for each of these stars, and created the ensemble centroid from an average at each cadence. Similar to the process of centroiding for individual targets, we then converted the ensemble centroid measurement into a pixel distance by subtracting the median. Note that centroid patterns repeat every four quarters, due to the orientation of the Kepler telescope, meaning that the cluster is once again falling on the same CCDs. Note also that the patterns differ between the clusters: while systematics are similar enough that an ensemble centroid measurement is reliable within one 200 × 200 pixel.
isolation measure, which we used to scale weighted Gaussian apertures for photometry.

One advantage of the ensemble centroid is in computation time: the centroid calculation is the most time-intensive stage of the code, owing to the fact that it deals with individual pixels in tens of thousands of frames for each star. We reduced the computation time from \( \sim 20 \) minutes per star with centroid calculation to \( \sim 4 \) minutes per star with the precalculated ensemble centroid. As we will show in Section 3.3, the ensemble centroid also proves to be better for faint and/or crowded targets, where a direct centroid measurement is easily skewed by nearby contaminants. Finally, we note that, since an ensemble centroid measurement is more computationally efficient, it will likely be highly useful for broader applications of the IRIS algorithm to large volumes of space-based data, such as TESS photometry.

For the remainder of this paper, we refer to the use of the ensemble centroid (EC) measurements for the IRIS algorithm as EC-IRIS, and the use of individual target centroid (TC) measurements as TC-IRIS.

2.5. Aperture Selection

The apertures we used for this pipeline are weighted two-dimensional Gaussian functions with the dimensions of the resampled \( 5 \times 5 \) postage stamp. We adjusted the width of the Gaussian based on magnitude and crowding, which we represented with an isolation parameter. To obtain this parameter, we estimated magnitudes for each target using the unmasked and not-yet-resampled \( 5 \times 5 \) postage stamp as our aperture, and then compared these to the catalog values of the Kepler bandpass magnitude (Kp), calculated for every star in the KIC using high-resolution ground-based photometry, and augmented with data from a range of all-sky surveys (Brown et al. 2011). To obtain the postage-stamp magnitude \( (M_{5,5}) \), we summed the flux in each quarter and compared to a reference star, then took an average across all quarters. We calculated the flux for each quarter using

\[
M_{5,5} = M_{\text{ref}} - 2.5 \log_{10} \left( \frac{F}{F_{\text{ref}}} \right).
\]

(2)

We chose one isolated, bright target in each cluster to act as a reference star. The reference star for NGC 6791 was KIC 2436824, with Kp = 14.515 and \( F_{\text{ref}} = 29,292 \) counts, and for NGC 6819 we used KIC 5111949, with Kp = 12.791 and \( F_{\text{ref}} = 106,088 \) counts. Both stars are red giants.

We found that this process systematically underestimated the magnitudes for fainter stars—that is, our calculated Kp was systematically brighter—because the \( 5 \times 5 \) aperture captured additional flux from neighboring stars. This information was used to measure a target’s isolation in any given \( 5 \times 5 \) postage stamp. Once we obtained \( M_{5,5} \) for each target, we calculated an isolation measure, I, using

\[
I = \frac{1}{2.5Kp - M_{5,5}}.
\]

(3)

where 2.5 is an approximation for \( 10^{0.4} \), which is sufficient for the application of the isolation measure. By subtracting \( M_{5,5} \) from the catalog Kp, converting to a brightness ratio and then inverting this value, we ensure that \( I > 1 \) when \( M_{5,5} > \text{Kp} \), and \( 0 < I < 1 \) when \( M_{5,5} < \text{Kp} \). In other words, \( I < 1 \) indicates that we have underestimated the target’s brightness, and therefore that we must use a smaller aperture to reduce the effects of crowding.

The basic aperture for photometry was a normalized two-dimensional Gaussian weighted pixel aperture, with a variance (or \( \sigma \)) of 1 Kepler pixel. We scaled the aperture by multiplying \( \sigma \) by an adjusted isolation measure. For this process, we placed two constraints on I: first, we set all targets with \( M_{5,5} > \text{Kp} \) to \( I = 1 \). We found that too large an aperture introduced excess noise to the resulting light curves, often at the expense of signal. As such, we found that the standard aperture as described above was sufficient for all fairly isolated stars, no matter their magnitude. For targets with \( M_{5,5} < \text{Kp} \) we...
implemented a second constraint, scaling \( I \) to lie within the range \( 0.25 < I < 1 \). This avoided producing too-small apertures for extremely crowded stars, such as those with \( M_{5.5} \) – \( K_p > 2 \). Figure 6 shows \( M_{5.5} \) versus \( K_p \) for all targets across both clusters, color coded by adjusted isolation measure.

Following the creation of an aperture, we multiplied each subtracted frame in the time series by the Gaussian aperture, which scaled the fluxes according to pixel weighting. For crowded targets with \( M_{5.5} < K_p \), the adjusted aperture decreased the weighting on pixels subject to contamination. Due to the logarithmic nature of magnitudes and hence the isolation measure, the base aperture did not change perceptibly for targets where \( M_{5.5} \) was close to \( K_p \). Only 810 targets in NGC 6791 (\( \sim 15\% \)) and 166 targets in NGC 6819 (\( \sim 4\% \)) were processed with no change to the base \( \sigma = 1 \) Kepler pixel aperture; as is expected in open clusters, the remaining stars were subject to brightness contamination due to crowding, and processed with smaller apertures. The relatively larger percentage of \( \sigma = 1 \) Kepler pixel apertures used for targets in NGC 6791 is due to lower levels of crowding in that cluster.

2.6. Target Selection

We used the KIC (Brown et al. 2011) as our base catalog. From the MAST target search, we obtained a list of all targets in a 14′ radius of the central coordinates of each cluster, in order to perform image subtraction photometry on every possible target in the NGC 6791 and NGC 6819 superstamps. We only retained stars that lie within the superstamps (which are 200 Kepler pixels square, or 13′20″). Due to shifts between quarters of up to five pixels, targets toward the edges of the superstamps may only appear for a subset of all quarters.

This process resulted in 5342 targets in the field of NGC 6791 and 3808 targets for NGC 6819. There are 17 quarters of superstamp data for NGC 6791, and 14 for NGC 6819. Of the targets included in this data release, 91% of NGC 6791 targets fall on the superstamps for all 17 quarters, and 93% of NGC 6819 targets have 14 quarters of data. We also compared data availability in these regions to targets which have Kepler long-cadence data: 310 targets for NGC 6791 (\( \sim 6\% \)) and 413 for NGC 6819 (\( \sim 11\% \)) were targeted during the Kepler mission. Of these, only 155 targets for NGC 6791 and 186 for NGC 6819 have the maximum available number of quarters; many also include quarter 0, the commissioning quarter, for which there are no superstamp data. Many of these targeted stars are not cluster members. Our overall corpus of light curves covers 9150 targets in the Kepler IRIS data release, of which 8427 were not targeted for long-cadence photometry during the Kepler mission. We also provide light curves with more quarters for 382 Kepler long-cadence targets.

2.7. Running the Pipeline

We ran the pipeline on these stars using high-performance computing facilities at the University of Sydney, using GNU Parallel (Tange 2015) to decrease runtime. We processed each star with both the EC-IRIS and TC-IRIS pipelines, and one custom SAP pipeline. This SAP pipeline was designed to closely mimic standard Kepler SAP, but included resampling (without realignment) for fair comparison between data in apertures of the same dimensions.

The only Kepler quality flag we took into consideration was for manually excluded cadences, bit 9 (Thompson et al. 2016). The QUALITY column in the Kepler open cluster substamps covers quality issues across all 20 × 100 pixels, which leads to a quality flag for almost every cadence; additionally, some stars lie on the corners of these 20 × 100 substamps, creating further complications when we consider that quality flags ought to be drawn from all data used. We implemented a filter to remove only cadences with the “manual exclusion” flag, which indicates that the detector was uniformly affected by quality issues. Notably, this removed artefacts due to the coronal mass ejections (CMEs) in quarters 12 and 14 from our data.

3. Results

3.1. Light-curve Processing and Classification

The first step in processing the light curves that result from the IRIS pipeline was cropping out safe modes and other few-cadence low-quality events, using a list of events supplied by the Sydney pipeline for Kepler photometry (Huber et al. 2009). As mentioned in Section 2.7, we removed the CME events prior to photometry; beyond these manual exclusions and the Sydney pipeline exclusions, some of the remaining cadences may be subject to quality issues, such as cosmic ray incidences and sudden pixel sensitivity dropout events.

After the pipeline conducted photometry for each star, we performed light-curve corrections to remove systematics. First, we applied a high-pass filter by smoothing with a Gaussian of width 100 cadences, followed by a 3σ outlier clipping process. We performed the filter and clipping procedure in three iterations to each individual quarter. Normally, one would divide the light curve by the Gaussian curve used for filtering, and this would guarantee normalization. However, in crowded fields, the contribution of photon noise from contaminating stars is additive, meaning that a subtractive filter is more appropriate. The contaminating flux changes between quarters due to the differences in pixel sensitivity across different CCD modules. This led to significant variation in the scatter between time-series points across different quarters, which introduced noise into the periodogram calculation. After subtracting a Gaussian curve from each quarter to account for both contamination and scatter, we calculated a mean flux. We then divided each quarter by the mean of those means, leading to more uniform light curves, such as the one shown in Figure 7 for KIC 2437745, the example star from Section 2.3. This method worked well for the majority of stars; there are some targets with persistent systematics (see Section 3.2), where custom corrections may need to be performed before further analysis.

For each target, we examined the image subtraction light curves for evidence of periodicity by computing a Lomb–Scargle periodogram (Lomb 1976), as implemented by Astropy (Robitaille et al. 2013; Price-Whelan et al. 2018). For purposes of categorization, we classified stars as either variable or nonvariable based on the presence of significant peaks in the amplitude spectrum. One issue is the possibility of multiple variable signals, or the signal of a nearby bright contaminant, within one aperture. To manually check for contamination, we produced a periodogram of the light curves in each individual pixel of a star’s 5 × 5 postage stamp (see Bryson et al. 2013; Colman et al. 2017). The majority of stars in our sample are faint enough that contamination must be present if the overall
photometric signal is stronger in any pixel other than the central pixel of the 5 × 5 postage stamp. Due to the high completeness of this study, in most cases it was possible to identify the contaminant among the light curves of nearby targets in the data set, confirming the pixel periodogram analysis method as highly reliable. There were only a small number of cases across the sample where two KIC targets occupied the same pixel and we detected a signal that could come from one or both of the targets. In these and other ambiguous cases, we classified the target as variable.

3.2. Systematics

A significant minority of these light curves display a ∼3 day signal which appears to be correlated with spacecraft motion. We have no firm explanation as to what causes this signal. There is no change in the signal with position on the detector, target brightness or isolation, or any intrinsic stellar properties. The presence of the signal is related to noise levels: the ∼3 day signal has a lower amplitude when it appears in targets which exhibit higher levels of shot noise. We have confirmed that this signal is also present in the Kepler pipeline data for the same targets. Figure 8 shows KIC 5023743, a star with Kepler long-cadence data available, where both light curves display the unknown ∼3 day signal. By percentage, the signal is more common among our light curves than in the Kepler long-cadence data set; this is consistent with the higher density of field sampling in our data set when compared with the sampling of stars targeted during the Kepler mission.

Additionally, some targets in NGC 6791 show a spurious signal in quarters 1 and 2 due to the influence of variable guide stars. For the majority of the Kepler mission, the guide stars used for instrumental calibration were chosen to be nonvariable; however, as documented in the Kepler Data Characteristics Handbook (Van Cleve & Caldwell 2016), there were two variable stars used for calibration in quarters 0–2. One of these variable guide stars is an intrinsic variable with a period of 2.9 days, or ∼3.99 μHz, and lies close to the NGC 6791 superstamps. This signal shows up in a small fraction of our NGC 6791 light curves. For studies of these data involving short period targets, we recommend the omission of quarters 1 and 2. We also note that, despite the similar periodicity, this is unrelated to the unknown ∼3 day systematic described above.

Eight targets in NGC 6819 exhibit steep, irregular trends in their uncorrected light curves, with no uniformity across quarters. These variations occur across several orders of magnitude, and appear as either flare-like in shape, or as dramatic dips in brightness. We show two examples in Figure 9. In each case, the target lies in the close vicinity of one of two bright targets: KIC 5024470 (Kp = 10.083) and KIC 5025003 (Kp = 8.367). The targets and their contaminating star are listed in Table 1. As this is a pixel-level issue, we are unable to correct for this as part of the IRIS pipeline and basic light-curve corrections. Nevertheless, the light curves are included in our data release for users to perform their own corrections.
Figure 8. Quarter 9 EC-IRIS (top panel) and Kepler SAP (bottom panel) data for KIC 5023743, a target which exhibits the spurious $\sim$3 day signal described in Section 3.2. Note that the signal is present in both our light curve and a Kepler SAP light curve, but appears to be higher amplitude in our data. This is due to the differing apertures; EC-IRIS apertures were optimized for faint targets.

Figure 9. Top: KIC 5024943. Bottom: KIC 5025005. Both stars exhibit uneven variations in flux due to their proximity to a bright target. Dashed lines represent quarter boundaries.
3.3. Pipeline Statistics and Method Comparison

Due to the limitations of the light-curve corrections used and the unfeasibility of an one-size-fits-all corrections approach for this large data set, we probably underestimate the number of low-frequency (or long-period) variable targets. With that in mind, we identified variability in 239 of 5342 targets in the field of NGC 6791, and in 254 of 3808 targets in the field of NGC 6819. The preponderance of variability in the field of NGC 6791 is noteworthy, as is the fact that this statistic is comparable to the 245 variables found in Colman (2020), where we studied a subset of these stars, 1286 targets determined to be members of NGC 6819 (Drury 2020). This suggests that NGC 6819 is host to an unusually large number of variable stars, or conversely that NGC 6791 may have a low number of variable stars.

Using the periodograms for each target, we measured the median of the amplitude spectrum between 250 and 280 μHz as a representative noise measure for each star, where ∼283 μHz is the Nyquist frequency for long-cadence Kepler data. We expected to find relatively few cases of variability above 250 μHz in this data set, and comparatively many solar-like oscillators, which likely display a low-frequency red noise profile due to granulation. Because of this we consider the higher frequencies a fair estimate of photon noise. We then used the noise measure to calculate a signal-to-noise (S/N) ratio, where the signal amplitude was taken as the highest amplitude present in the spectrum. Note that, despite the aperture sizes scaled to minimize excessive contamination by nearby targets, this method includes light curves subject to contamination, as described in Section 3.1. Additionally, we see some crowded targets with artificially low noise due to high shot noise introduced at the final step of the image subtraction algorithm, the addition of the average flux. However, we have also managed to maximize the S/N ratios for these targets by our careful aperture choice, so we see almost no dilution in signal amplitudes below a strict lower limit that is a function of magnitude. Figure 10 shows noise and S/N versus magnitude for both clusters.

Table 1

| KIC | R.A.   | Decl. | Kp   | Contaminant |
|-----|--------|-------|------|-------------|
| 5024943 | 295.38915 | 40.1768 | 14.854 | 5024470 |
| 5024964 | 295.392906 | 40.164344 | 16.716 | |
| 5024979 | 295.395495 | 40.16895 | 17.291 | |
| 5025005 | 295.3999995 | 40.167944 | 17.55 | 5025003 |
| 5025024 | 295.40397 | 40.156006 | 16.663 | |
| 5025051 | 295.408611 | 40.146194 | 18.079 | |
| 5025063 | 295.4099295 | 40.15199 | 17.375 | |
| 5025073 | 295.412547 | 40.146044 | 17.67 | |

Figure 10. Top panels: noise vs. Kp plots for both clusters. Bottom panels: signal-to-noise (S/N) vs. Kp. NGC 6791 is on the left and NGC 6819 is on the right. All plots use noise and S/N measures as outlined in Section 3.3, color coded by adjusted isolation measure. In order to show a clear overview of trends, we set axis limits to exclude outliers in noise, S/N, and Kp. Note that the typical Kp ranges differ for each cluster. Note also that we do not plot the S/N ratio for nonvariable stars, as it is determined based on the highest-amplitude peak of variability, which becomes arbitrary in an amplitude spectrum dominated by noise.
We further compared the noise and S/N noise measurements for the EC-IRIS and TC-IRIS pipeline variants, as outlined in Section 2.4. In Figure 11, we show the measured noise and S/N ratios, with EC-IRIS on the x-axis and the ratio between TC-IRIS and EC-IRIS on the y-axis. Points are color coded by isolation measure, showing that noise and S/N per method have no dependence on target isolation. For both noise and S/N, points that lie above the one-to-one line indicate better performance by EC-IRIS. We found that EC-IRIS performed better for both metrics, producing lower noise levels for the majority of targets, and generally higher S/N ratios. The exceptions in S/N tend to be for lower-S/N (and therefore less-certain) signal detections, where one might expect to find more natural variance in method effectiveness. This leads us to suggest the use of an ensemble centroid measurement as favorable for future applications of image subtraction photometry; it has the additional advantage of saving significant computational time.

We also compared EC-IRIS to the output of a custom SAP pipeline, as described in Section 2.7. We show this in Figure 12, plotted with the same y-axis limits as the TC-IRIS/EC-IRIS ratio in Figure 11 for clear comparison. We found that SAP produced noisier light curves than EC-IRIS for fainter targets, though not as noisy as TC-IRIS, suggesting that further improvements can be made to the application of a target centroid measurement as part of the IRIS algorithm. EC-IRIS tends to be noisier than SAP for brighter targets. Encouragingly, however, we found that EC-IRIS recorded higher S/N ratios for the majority of detected variable targets, in particular low-S/N targets, regardless of their noise levels or isolation. This demonstrates that image subtraction performs as expected in emphasizing light-curve variability and, for the purposes of studying a large volume of stars in a crowded field, produces more favorable results than SAP.

### 3.4. Comparison to Kepler Data

We compared our data to Kepler long-cadence SAP data for 382 available stars, using the same light-curve processing methods to retrieve noise and S/N measures. We detected signal in 230 of these stars, creating a list of targets where S/N is a relevant measure; we then compared the S/N ratio from EC-IRIS data to the S/N ratio from Kepler SAP, as shown in Figure 13. The data points in this figure are color coded by how many more quarters of superstamp data are available than of Kepler long-cadence SAP data. For the majority of these stars, we were able to extract more quarters than the stars were targeted for during the Kepler mission. As would be expected, we find a weak correlation, showing that targets for which we have more quarters than Kepler SAP also have higher S/N ratios in EC-IRIS. However, this is not universally true; for the
majority of these stars we retrieve higher S/N ratios from Kepler SAP.

There are a number of potential contributing factors for the case where we have more quarters available than Kepler SAP but the measured S/N ratio from our data is lower. One simple explanation is the differences in photometry and light-curve processing methods between the two pipelines. Most of these stars are relatively isolated, i.e., there are no significant crowding issues in the TPFs; the Kepler SAP pipeline is optimized for these stars, whereas the EC-IRIS pipeline is optimized for faint stars. Additionally, our light-curve processing routine is designed to be broadly applicable, but not necessarily tailored, to individual stars, so some of these targets may be “bad luck” cases where the star is less suited to the processing. Finally, we note that our noise measurement is taken between 250 and 280 \( \mu \text{Hz} \), and if the EC-IRIS pipeline noise happened to be higher in that range for any given star, this could lead to a misleadingly low S/N measurement. Nevertheless, for the stars where we increase the number of quarters available compared to Kepler long-cadence SAP, the improvement in quality is significant. Figure 14 shows the time series of KIC 2570715, an oscillating red giant with only seven quarters of Kepler long-cadence data available. Though the EC-IRIS data (black) suffers from some discontinuity at quarter boundaries, the scatter within each quarter is comparable to the Kepler SAP (blue) scatter, and amplitude spectra show that the oscillations are much clearer in the EC-IRIS time series.

4. Discussion and Conclusions

In this work, we produced light curves for stars in and around the Kepler open clusters NGC 6791 and 6819, using the Kepler superstamps, which are 200 \( \times \) 200 pixel images with long-cadence time-series coverage of \( \sim 14'' \) square regions around the two clusters. Of the 9150 light curves included in this data release, 8427 are new light curves for objects which were not targeted for individual photometry during the Kepler mission. Using a novel implementation of the image subtraction photometry method, the Kepler IRIS light curves exhibit low noise levels for faint targets, which comprise the majority of the catalog, and prioritize variable signal. The catalog is available as a HLSP from MAST, and expands the completeness of the Kepler long-cadence data set, as well as providing new light curves for the further study of two old open clusters.

This study has shown that image subtraction photometry is a highly suitable method for producing light curves for faint targets, and also for performing crowded-field photometry. Using a novel algorithm, we show that increased-resolution image subtraction (IRIS) is particularly well suited to working with space-based data. With this initial study of the data set, we have already made some new finds, including the excess of variable targets in NGC 6819 and a new and undocumented Kepler systematic (Section 3.2). We have identified key targets for further study such as KIC 2438249, the \( \gamma \) Doradus EB analyzed by Li et al. (2020).
Figure 13. Comparing the retrieved S/N of 230 stars with signal in the sample between EC-IRIS photometry and Kepler SAP photometry, using the same data preparation methods. Points are colored according to how many more quarters of data are available in the IRIS catalog. The y-axis is inverted as in Figure 11 and 12 to indicate that points above the line represent a better result from the EC-IRIS pipeline. Note that the x-axis is shown in log scale to display outliers with very high S/N measurements.

Figure 14. Time series (top) and amplitude spectrum (bottom) for KIC 2570715, an oscillating red giant with only seven available quarters of Kepler SAP data. EC-IRIS data are shown in black, and Kepler SAP in blue. Both light curves in the top panel were produced using the same processing methods. Dashed red lines indicate quarter boundaries.
There are inevitably drawbacks associated with a data set of this size. We issue two caveats for users of the Kepler IRIS data. First, the light curves were processed and corrected using a one-size-fits-all method, aimed at maximizing the variability yield without needing to perform custom corrections on individual targets. We corrected using a 100 day Gaussian filter, which necessarily means that longer-period signals will be lost, and suggests that we may have slightly underestimated the overall variability fraction across both cluster fields. We strongly recommend that users searching for long-period targets work with the raw light curves. These provide their own challenges, such as differing point scatter between quarters, as outlined in Section 3.1. The second caveat for users is that, due to the crowding of these fields, the emphasis on variability provided by image subtraction photometry, signal blending is inevitable in the light curves of targets adjacent to variable stars which are particularly subject to crowding. We suggest that variability should be compared with targets nearby in R.A. and decl. in order to confirm the source of the signal.

In future work, we aim to adapt IRIS for TESS data. The TESS FFIs cover almost the whole sky, including a wealth of open clusters in the field, providing many opportunities for crowded-field photometry. The fields around open clusters would also provide a useful way to test the brightness and isolation limits of the efficacy of this method for TESS data. For future use, we can improve on the TC-IRIS method, which appears to be underperforming here, given that a comparable SAP procedure produces better results. Improved TC-IRIS will be useful for TESS data, as it quickly becomes unfeasible to produce ensemble centroid measurements for data of that scope. We can also explore alternative methods, such as performing cross-correlation across the superstamp time series. Another potential use for the IRIS pipeline is with regular long- or short-cadence Kepler TPFs, aiming to improve S/N ratios for faint and/or crowded targets, or to extract light curves for serendipitous background stars in larger TPFs.

Finally, we note that there is a wealth of science that can be done using this data release, such as testing new light-curve correction methods to search for long-period variability, studying and modeling the large range of variable stars across both cluster fields, and searching for exoplanets. It is our hope that these data will be of broad use to the community as both an expansion of the Kepler long-cadence data set and a new avenue for studying the open clusters NGC 6791 and NGC 6819.

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