Novel Photometry of Bright Stars using Contaminated *Kepler*/K2 Pixels

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Using *Kepler*/K2 Data, we describe a novel technique for doing photometric analysis of bright stars through the analysis of halo contamination of nearby postage stamps. We then follow by providing example results from the Scorpio constellation (π Sco, 4 Sco, δ Sco) and suggest further improvements to this technique and potential targets for further investigation. This technique is invaluable, as it allows useful photometry with very accurate telescopes such as *Kepler*, without the losses associated with storing and retrieving long-cadence data of bright stars.

1 Background

1.1 *Kepler* and K2

Kepler is a space telescope which was sent into space in 2009, and was at the time one of the most accurate photometric instruments ever sent in to space. The main benefit was continuous data, allowing for very high time resolution photometry. *Kepler* orbits the Sun, and made use of 4 reaction wheels to have very precise pointing control to keep it's intended field of view stationary on *Kepler*'s detectors (Van Cleve and Caldwell, 2009).

The *Kepler* mission has allowed for the discovery of many exoplanets, and has also allowed for unprecedented astroseismic investigation using high-precision photometry of many targets. Full technical details for the *Kepler* telescope can be found in Jenkins et al. (2010) and Koch et al. (2010).

However, by 2013 two of the reaction wheels had malfunctioned, rendering the intended field of view unobservable for continuous periods of time. A second mission was proposed, K2 (Howell et al., 2014). This mission would allow for *Kepler* to observe new fields despite operating with only two reaction wheels. However, the observed targets have an apparent motion on the detectors, as a regular compensation for the rotation of the telescope is done by using the telescope's thrusters (Shao et al., 2013, Section 3).

During K2, *Kepler* observes along the ecliptic plane, in order for the solar radiation pressure from the Sun to minimally affect the roll of the spacecraft (Howell et al., 2014). The ecliptic observing field can be seen in Figure 1.

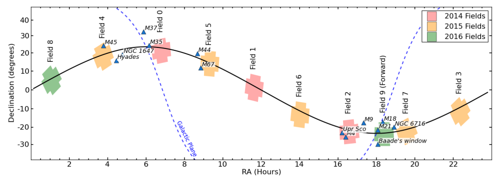

Figure 1: Sequence of observation fields chosen for *Kepler*/K2, all of which lie on the ecliptic plane.

Bandwidth

Due to *Kepler*'s distance from Earth (and also the immensely large field of view), the entire field observed cannot be downloaded at high time resolution. Instead *Kepler* produces “postage stamps”, which are selections of the *Kepler* CCD pixels to be downloaded. These pixels are chosen by NASA, based on proposals by the astronomical community (Barclay, 2014). An exposure of the entire *Kepler* field is taken every 30 minutes and the postage stamps are extracted and saved for download. Every 2 months a “full frame image” is also taken, containing all *Kepler* pixels. All astronomical objects inside or near the *Kepler*/K2 field of view are assigned a unique identifier known as an “EPIC target identifier”.

Very bright targets on a *Kepler* CCD cause an effect known as “bleeding”, where charge is spilled vertically on the detector, producing a long saturated streak in one or more columns within the light of the bright star.

Kolenberg et al. (2011) showed that it is possible to do photometry of bright targets (specifically, targets which are saturated), but it was generally believed that this is only possible if **all** of the flux from the star is used. One of the main goals of this project was to confirm whether this is indeed the case.

1.2 Asteroseismology

Asteroseismology is the study of stellar oscillations, probing inside stars to discover their internal structure. This allows for the measurement of stellar parameters with otherwise unattainable accuracy. While *Kepler* was primarily an exoplanet finding mission, the high accuracy of its CCD sensors result in it being the most accurate asteroseismic instrument currently in use.

Photometry

Photometry is a technique that can be used to do asteroseismology. It is, in essence, counting the amount of photons (flux) that are detected over time. This time series is then analysed using various techniques to study the oscillations of the star in question.

Since the star is not spatially resolved, we can only detect low-degree oscillations, due to the partial cancellation effect caused by multiple sections of the star increasing and decreasing in brightness. This can be seen in Figure 2, which quantifies the effect.

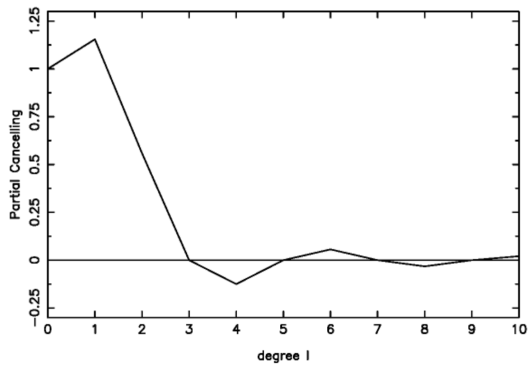

Figure 2: The partial cancellation factor for photometry for degree $l = 0, \ldots, 10$, showing that for degree $l \geq 3$ the cancellation effect renders meaningful photometry very difficult. Reproduced from Aerts et al. (2010, Figure 1.5)

Bright Stars

Bright star photometry is very hard, as described in section 1.1. Due to the bandwidth limitation, it is very impractical to download all of the pixels containing flux from a bright star.

However, bright stars are very important to asteroseismology as they can even be seen with a rudimentary telescope or the naked eye. As a result, they have been well studied for hundreds of years, and have accurate distance measurements (as they are generally closer to earth than other faint stars). Asteroseismic models are based on several parameters of a star which must be experimentally verified. By acquiring high-accuracy photometric data for these stars, it is possible to improve our asteroseismic models of how stars operate. In addition, further research can be done from the ground.

2 Method

The method used in this project was novel, given that standard photometric techniques of *Kepler*/K2 postage stamps were not applicable to our project. As such, a large amount of time spent on this project was used to devise and improve a novel photometric technique, as described below.

2.1 Halos

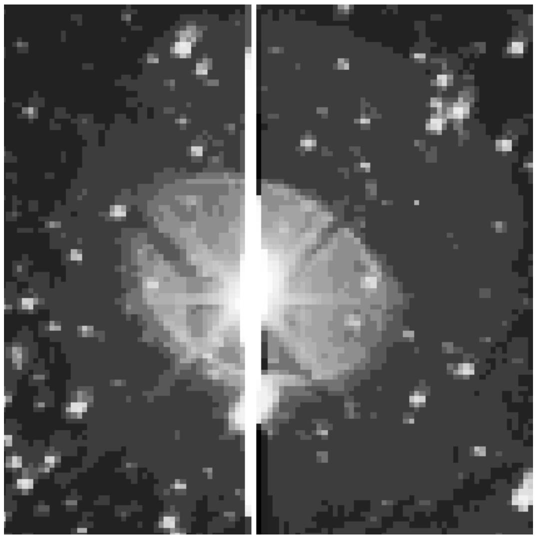

Figure 3: *Kepler*/K2: A bright star's halo and bleeding column.

Within the *Kepler* telescope, photons can be diffracted and internally reflected. This is an artefact of how most CCD-based telescope optics operate. This results in a ghosting effect (as well as diffraction spikes), culminating in a halo surrounding the star (Slater et al., 2009), as can be seen in Figure 3. The halo is much larger than the actual target, and we assume it contains a photon count proportional to the main target. This means that it should be possible (in principle) to do meaningful photometry of a target using only this halo (and, further, only a subset of the pixels in the halo).

This is a novel idea, and is an improvement to the result by Kolenberg et al. (2011) — that photometry is possible with bright stars using *Kepler* (even if they cause pixels to be become saturated and produce bleeding columns). Bright star photometry is a hard problem, as many pixels are saturated as a result of very bright sources, making it much more expensive in terms of pixels to do photometry of such targets.

Since pixel bandwidth is very limited, halo photometry could potentially allow for the study of bright stars without the large number of pixels required for such studies. However, there is currently no space photometry data for most bright targets due to the perceived pixel bandwidth requirements. As such, most of the research done was in trying to find serendipitous postage stamps which contained halo contamination from a nearby bright star. In that case, it would be possible to show that halo photometry is viable by masking contaminating halo pixels of interest.

2.2 Contamination

The proposal process of the *Kepler*/K2 mission is not perfect. Not all postage stamps are checked as thoroughly as possible, so proposals that contain a large amount of postage stamps may pick postage stamps which are near bright stars. If a postage stamp is close enough to a bright star, the halo from the star will contaminate the postage stamp.

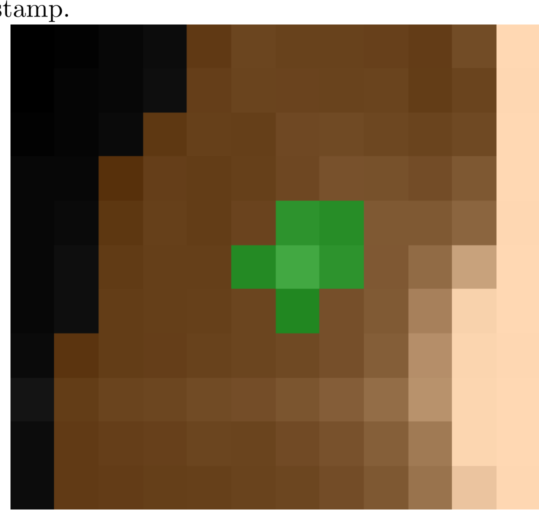

Figure 4: *Kepler*/K2: A contaminated postage stamp. Green pixels are the intended target pixels, orange pixels are halo contamination pixels from a nearby bright star.

As can clearly be seen in Figure 4, contamination of a bright star near a postage stamp can be quite significant. This is helped by the intended EPIC target being very faint in comparison to the halo contamination.

Note that while there may be significant halo contamination in a postage stamp, not all contamination pixels can be used. Due to the systematics outlined in subsection 2.3, some pixels will move out of the postage stamp rendering them unusable. In addition, the systematics also cause pixels near bleeding columns to produce an instrumental sawtooth variability.

2.3 Systematics

In order to achieve high precisions, it is important to account for the systematics of *Kepler*'s motion. Unlike standard *Kepler*/K2 photometry, we cannot create an aperture around all of the light we wish to capture and ignore the motion (as done by Vanderburg and Johnson (2014)).

Kepler's systematics are rotational in nature, so a rotational model is required to digitally track the apparent motion of the contamination in a postage stamp (Aigrain et al., 2015).

The centroid of each postage stamp on silicon is tracked (Lang et al., 2010, p 1784) and a rotational model was created. This produces an axis of rotation and angular velocity for each exposure in a campaign. Using this, it is possible predict the apparent motion of any set of pixels on silicon with sub-pixel high accuracy. This invaluable tracking data was provided by Benjamin Pope.

2.4 Pixel Masks

As the postage stamp contains a target that we are not interested in, the pixels whose flux is being integrated over must therefore be chosen based on whether the pixel is in frame for the campaign (or cadences of interest), the amount of contamination in a given pixel and that the pixel does not contain any other sources of variability where possible. Pixel masks were largely chosen by eye, using the above criteria.

Once a pixel mask has been chosen, a smoothed polygon (or "aperture") is constructed to contain the pixel mask with penumbra smoothing to ensure that there are minimal edge effects. The aperture is then followed with the apparent motion of the target, to ensure that the same subsection of the halo is used and that no brighter or darker regions intrude on the aperture, producing a systematic variability.

By following the aperture with the apparent motion (which has sub-pixel accuracy), in principle the same contaminated rays will be captured without introducing different sources of contamination throughout the analysis.

The amount of flux contained within the aperture is integrated over (fractional overlap between pixels and the aperture is counted as a weighted sum of the area of intersection between the pixel boundaries and the aperture), and taken as the amount of flux in a particular cadence.

3 Results

Using the above technique (as well as applications of standard *Kepler* photometric techniques), several targets were analysed using serendipitous postage stamp located within the halo of the target.

3.1 π Sco

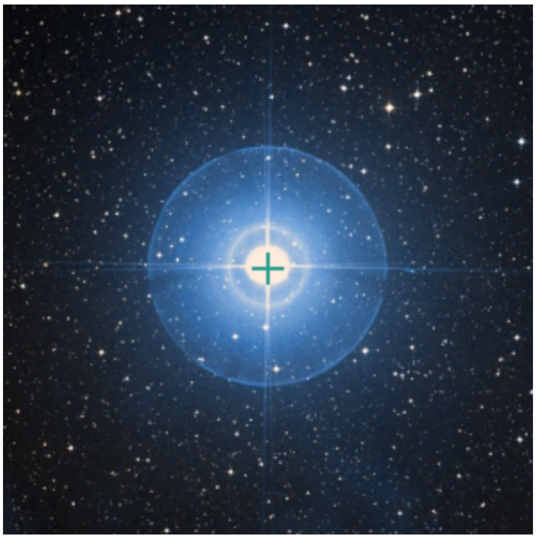

Figure 5: *AladinLite*: Ground-based image of π Sco.

π Sco is an ellipsoidal binary, meaning that there are two stars orbiting one another. Both stars are elliptical in shape due to tidal forces, so as they orbit, different surface areas of the star become visible. In addition, the two stars' transit is on-axis with the Earth so the two stars move in front of one another over time. This means that the flux from the binary is variable over time. This binary system has been previously studied, making it a good test to see if the data obtained from our technique is valid.

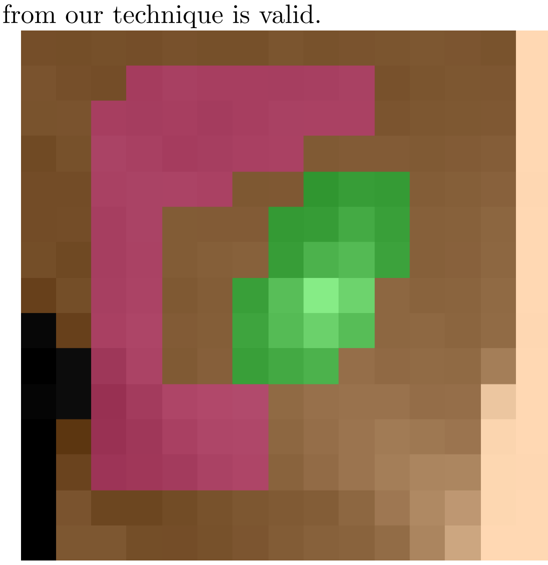

Figure 6: *Kepler*/K2: `EPIC 203442993`'s postage

stamp with all contamination pixels coloured purple, the aperture pixels are coloured purple. Green pixels are the intended EPIC target.

`EPIC 203442993` was the chosen postage stamp, and it is clear from Figure 6 that there is plenty of halo contamination present. A contamination mask with $n = 48$ pixels was chosen to contain all halo pixels which do not move out of the postage stamp in the time series and also do not intersect with the bleeding column.

The bleeding column is a completely saturated spike of pixels, however due to *Kepler*'s rotational systematics, the bleeding column pixels cause an apparent sawtooth variability. To avoid this, all pixels near the bleeding column were not included in the halo pixel mask. The chosen mask is overplotted in Figure 6.

An aperture was constructed using the mask, the aperture was offset to follow the apparent motion of the contamination for each frame and the flux contained in the aperture was integrated. The produced light curve then had a high-pass filter applied with a width of $5 days$ using a 6th order polynomial. The Fourier transform of the resulting time series is shown in Figure 7.

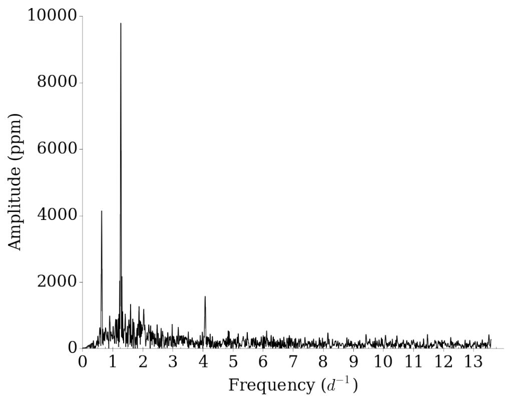

Figure 7: Fourier transform of contamination time series. The two peaks near 1 d^{-1} are from π Sco, and the single peak at 4 d^{-1} is due to the motion correction done by Kepler and is entirely instrumental variability.

We would like to show that the detected variability is not an artefact of our technique, and is the real variability of π Sco. Shobbrook (2005) conducted a photometric study of π Sco which used ground-based telescopes to yield an ellipsoidal period of $1.570103d$, and provides a phase folded plot of the flux from the star. This is overplotted in Figure 8.

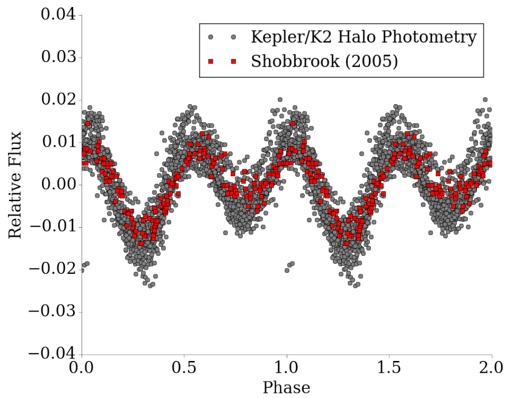

Figure 8: π Sco phase folded light curve, comparing halo photometry and Shobbrook (2005).

It is clear that the variability in both lightcurves are identical. This is proof that the detected variability in using our technique really is from π Sco, and that halo photometry is a viable photometric technique. In addition, *Kepler*/K2 data is far more continuous than ground-based data.

Ephemeris

In addition to providing a period, Shobbrook (2005) provided the time of a minima in the signal at some point in the past. This ephemeris can be used to predict the time of minima in the *Kepler*/K2 data set. This prediction was used to compute the phase offset in Figure 8, which is definite proof that the detected variability is really from π Sco.

3.2 4 Sco

It is important to ensure that halo photometry does not introduce systematic variability, and so a bright non-variable star was tested to verify that our technique is valid.

To this end, the target 4 Sco was chosen. It is a non-variable star, and has one nearby postage stamp, `EPIC 203407633` as can be seen in Figure 9.

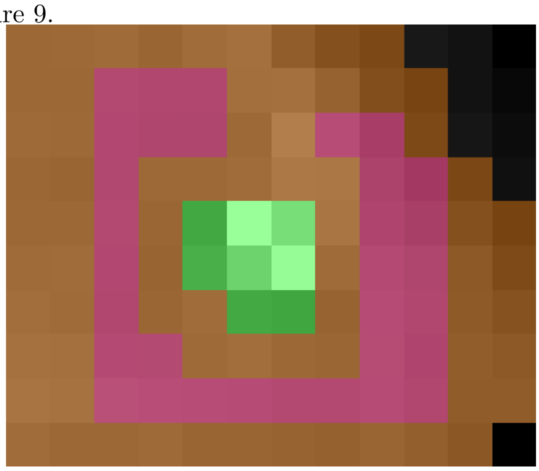

Figure 9: *Kepler*/K2: `EPIC 203407633` – There is plenty of contamination in the frame. The purple pixels are the selected mask, green are the intended EPIC target and orange are all halo contamination pixels.

It is clear there is significant contamination in the frame. Very similar steps were taken as with π Sco to extract a time series. A Fourier transform is shown in Figure 10, the lack of any distinguishable peak above 3σ indicates that there is only noise in the contamination. Therefore, our technique does not add variability which does not exist in the target star, which is a confirmation of the validity of halo photometry.

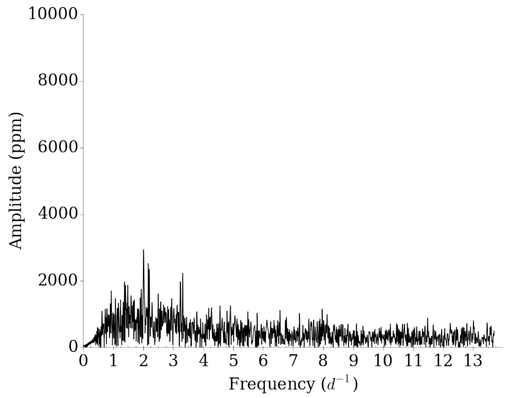

Figure 10: Fourier transform of contamination time series. There is no clear peak, indicating that the contamination only contains instrumental noise.

3.3 δ Sco

δ Sco is a binary with a highly eccentric, 11 year orbit (Bedding, 1993), and shows line-profile variability of degree $l = 5 \pm 1$ (Telting and Schrijvers, 1998). Photometric confirmation of line-profile variability above $l = 2$ is very difficult due to the cancellation of high degree spherical oscillations, as mentioned in section 1.2.

It is possible for δ Sco to show previously unknown variability, and our technique could be used to uncover such variability. We found 7 postage stamps near δ Sco which contain halo contamination. None of these postage stamps have enough useful contaminated pixels. The closest two postage stamps contain secondary sources of contamination, as in Figure 11.

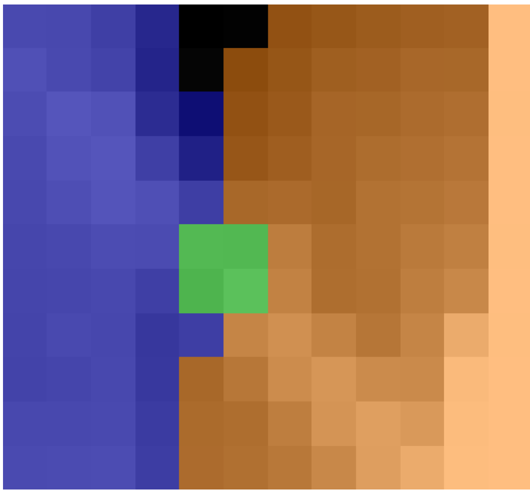

Figure 11: *Kepler*/K2: `EPIC 204367097` – A secondary source of contamination (blue) is present on the left. Green pixels are the intended EPIC target and orange pixels are the primary source of contamination from δ Sco

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As such, many of these postage stamps were rendered unusable. A potential technique would be to combine the pixels from multiple postage stamps and doing a weighted sum to use more pixels and perhaps find a signal. However, this analysis was beyond the scope of this project and could perhaps be followed up in future research.

4 Future Research

The bulk of this project was spent devising and improving the contamination photometry technique. As a result, there was limited scope for application of this technique to a large number of stars. However, as this technique has been shown to be effective, further research can be done into improving halo photometry and studying bright stars with unprecedented precision.

4.1 Targets

Several targets in the Scorpio constellation were studied. Future analysis could be done on the following targets, all of which have serendipitous postage stamps within their halo:

- ω_1 Sco
- i Sco
- ν Sco
- ρ Oph

In addition, campaigns in *Kepler*/K2 other than campaign 2 (specifically campaign 4 which contains the Pleiades cluster) also contain bright stars which could be surveyed using this technique.

As mentioned in subsection 3.3, further research into combining postage stamps near δ Sco could lead to the discovery of previously unknown variability using this technique.

4.2 *Kepler*/K2 Proposals

Postage stamps for the *Kepler*/K2 campaigns are chosen based on community proposals which are approved by NASA. Following on from this research, it would be plausible to have proposals of postage stamps which contain a subset of the halo pixels of a bright star to be accepted by the *Kepler*/K2 committee.

This would allow high-precision photometry of all of the pixels in a postage stamp for halo photometry, without the need to mask out pixels which are rendered useless due an unrelated EPIC target being in the postage stamp.

5 Conclusion

We have shown that halo photometry is a viable technique for the study of bright stars which could not have been studied previously, without downloading large amounts of pixels. Several stars were studied, and some other stars were proposed for future studies. The research undertaken as part of this project has resulted in an entirely new method of doing photometry with *Kepler*/K2 data, with potential applications to other space photometry data.

6 Acknowledgements

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References

C. Aerts, J. Christensen-Dalsgaard, and D. W. Kurtz. *Asteroseismology.* Springer Netherlands, January 2010. ISBN 978-1-4020-5178-4. doi: 10.1007/978-1-4020-5803-5.

S. Aigrain, S. T. Hodgkin, M. J. Irwin, J. R. Lewis, and S. J. Roberts. Precise time series photometry for the Kepler-2.0 mission. *Monthly Notices of the Royal Astronomical Society*, 447:2880–2893, March 2015.

T. Barclay. How to Propose Targets for K2, May 2014. URL `http://keplerscience.arc.nasa.gov/K2/ProposeTargets.shtml`.

T. R. Bedding. The orbit of the binary star Delta Scorpii. *The Astronomical Journal*, 106:768–772, August 1993. doi: 10.1086/116684.

S. B. Howell, C. Sobeck, M. Haas, M. Still, T. Barclay, F. Mullally, J. Troeltzsch, S. Aigrain, S. T. Bryson, D. Caldwell, W. J. Chaplin, W. D. Cochran, D. Huber, G. W. Marcy, A. Miglio, J. R. Najita, M. Smith, J. D. Twicken, and J. J. Fortney. The K2 Mission: Characterization and Early Results. *Publications of the Astronomical Society of the Pacific*, 126:398–408, April 2014. doi: 10.1086/676406.

J. M. Jenkins, D. A. Caldwell, H. Chandrasekaran, J. D. Twicken, S. T. Bryson, E. V. Quintana, B. D. Clarke, J. Li, C. Allen, P. Tenenbaum, H. Wu, T. C. Klaus, C. K. Middour, M. T. Cote, S. McCauliff, F. R. Girouard, J. P. Gunter, B. Wohler, J. Sommers, J. R. Hall, A. K. Uddin, M. S. Wu, P. A. Bhavsar, J. Van Cleve, D. L. Pletcher, J. A. Dotson, M. R. Haas, R. L. Gilliland, D. G. Koch, and W. J. Borucki. Overview of the Kepler Science Processing Pipeline. *The Astrophysical Journal Letters*, 713:L87–L91, April 2010. doi: 10.1088/2041-8205/713/2/L87.

D. G. Koch, W. J. Borucki, G. Basri, N. M. Batalha, T. M. Brown, D. Caldwell, J. Christensen-Dalsgaard, W. D. Cochran, E. DeVore, E. W. Dunham, T. N. Gautier, III, J. C. Geary, R. L. Gilliland, A. Gould, J. Jenkins, Y. Kondo, D. W. Latham, J. J. Lissauer, G. Marcy, D. Monet, D. Sasselov, A. Boss, D. Brownlee, J. Caldwell, A. K. Dupree, S. B. Howell, H. Kjeldsen, S. Meibom, D. Morrison, T. Owen, H. Reitsema, J. Tarter, S. T. Bryson, J. L. Dotson, P. Gazis, M. R. Haas, J. Kolodziejczak, J. F. Rowe, J. E. Van Cleve, C. Allen, H. Chandrasekaran, B. D. Clarke, J. Li, E. V. Quintana, P. Tenenbaum, J. D. Twicken, and H. Wu. Kepler Mission Design, Realized Photometric Performance, and Early Science. *The Astrophysical Journal Letters*, 713:L79, April 2010. doi: 10.1088/2041-8205/713/2/L79.

K. Kolenberg, S. Bryson, R. Szabó, D. W. Kurtz, R. Smolec, J. M. Nemec, E. Guggenberger, P. Moskalik, J. M. Benkő, M. Chadid, Y.-B. Jeon, L. L. Kiss, G. Kopacki, J. Nuspl, M. Still, J. Christensen-Dalsgaard, H. Kjeldsen, W. J. Borucki, D. A. Caldwell, J. M. Jenkins, and D. Koch. Kepler photometry of the prototypical Blazhko star RR Lyr: an old friend seen in a new light. *Monthly Notices of the Royal Astronomical Society*, 411:878–890, February 2011. doi: 10.1111/j.1365-2966.2010.17728.x.

D. Lang, D. W. Hogg, K. Mierle, M. Blanton, and S. Roweis. Astrometry.net: Blind Astrometric Calibration of Arbitrary Astronomical Images. *The Astronomical Journal*, 139:1782–1800, May 2010.

M. Shao, B. Nemati, C. Zhai, S. Carey, and A. Leger. White paper, Jet Propulsion Laboratory, California Institute of Technology, September 2013. URL `http://keplerscience.arc.nasa.gov/K2/docs/WhitePapers/Shao_etal_Kepler_2Wheel.pdf`.

R. R. Shobbrook. Photometry of 20 eclipsing and ellipsoidal binary systems. *Journal of Astronomical Data*, 11:7, December 2005.

C. T. Slater, P. Harding, and J. C. Mihos. Removing Internal Reflections from Deep Imaging Data Sets. *The Publications of the Astronomical Society of the Pacific*, 121:1267–1278, November 2009. doi: 10.1086/648457.

J. Telting and C. Schrijvers. Line Profile Variability in the Rotating Beta Cephei Stars Epsilon Cen, Omega-1 Sco, and beta SCO. In P. A. Bradley and J. A. Guzik, editors, *A Half Century of Stellar Pulsation Interpretation*, volume 135 of *Astronomical Society of the Pacific Conference Series*, page 149, 1998.

J. Van Cleve and D. Caldwell. Kepler Instrument Handbook, July 2009. URL `https://archive.stsci.edu/kepler/manuals/KSCI-19033-001.pdf`.

A. Vanderburg and J. A. Johnson. A Technique for Extracting Highly Precise Photometry for the Two-

Wheeled Kepler Mission. *Publications of the Astronomical Society of the Pacific*, 126:948–958, November 2014. doi: 10.1086/678764.