Identifying Binary Central Stars of Planetary Nebulae
with Kepler K2 Campaign 11 Photometric Data

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Identifying Binary Central Stars of Planetary Nebulae with *Kepler* K2 Campaign 11 Photometric Data

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A large majority of planetary nebulae (PNe) are non-spherical, and many have complex structures; these are unlikely to be created trivially by a single central star. The *Binary Hypothesis* proposes that the complex morphologies of most non-spherical PNe are caused by interactions between their central stars and companions, with some unknown percentage in close binary systems. In this study, a software pipeline was developed to generate light curves for 140 PNe targets from the *Kepler* K2 campaign 11 field. Of these 140 targets, 29 appeared to show periodicity in their light curves, all of which had period under two weeks, for a close binary fraction of 21%; furthermore, 25 out of 29 (86%) detected periods were between two hours and five days. The size of this data set (140 PNe) is larger than any previous photometric search for close binary companions of PNe central stars, and the calculated short-period binary fraction is consistent with past photometric searches. These results support the Binary Hypothesis, which in turn helps explain the development of the varied and complex morphologies of PNe.

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I. INTRODUCTION

Planetary nebulae (PNe) are large, expanding clouds of ionized gas ejected from asymptotic giant branch (AGB) stars of between roughly 0.8 and 8.0 solar masses at the end of their stellar evolution cycle, as they transform into white dwarfs [Frankowski and Soker 2009]. These nebulae persist for only a few thousand to tens of thousands of years and in some cases can have very unusual, complex, and sometimes asymmetric structures [Frew and Parker 2010]. (Fig. 1)

There are two main theories regarding the development of the complex shapes of non-spherical PNe, dubbed by De Marco [2009] as the Single Star Paradigm and the Binary Hypothesis. The Single Star Paradigm suggests that the shapes of most non-spherical PNe are primarily influenced by magnetic fields; specifically, the magnetic field at the surface of a dying AGB star can be transported out by its wind, and because of stellar rotation, this magnetic field is dominated by a toroidal component with corresponding magnetic tension [Garcia-Segura 1997]. This magnetic tension is hypothesized by Garcia-Segura [1997], Rozyczka and Franco [1996] to induce various shapes on a developing planetary nebula. However, Soker [2006] argues that it is very unusual for single central stars to be able to sustain magnetic fields long enough to affect shaping of PNe.

De Marco [2009] argues that the complex shapes of non-spherical PNe are therefore unlikely to be created by a central star in its stellar evolution cycle without the influence of binary interactions or some other external force. The Binary Hypothesis suggests that the central stars of most non-spherical PNe are affected by binary interactions, which in turn shape the PNe through gravitational forces, with different morphological variations more or less likely to occur for varying binary separations [De Marco 2009]. Furthermore, some unknown percentage of PNe central stars should be in close binary systems with a cooler companion star or brown dwarf, or affected by binary interactions with a large planet [De Marco 2009].

Only 15 to 20% of PNe are spherical or nearly-spherical, (Fig. 2) and therefore explainable as likely created trivially by a single star [Jacoby et al. 2001, Parker et al. 2006]. This poses a significant question: of the remaining 80 to 85% of PNe, are their morphologies dictated primarily by binary interactions, magnetic forces, or some other cause? In this study, I sought to answer this question by searching for close binary interactions in a sample of 140 PNe central stars using data from the NASA Kepler space telescope. These objects represent all known PNe within the Kepler K2 campaign 11 observational field for which the Kepler space telescope was able to obtain data [Jacoby, Kronberger, Long, De Marco and Hillwig 2016].

There are currently four ways to identify the presence of binary interactions in PNe central
(a) Pre 3, imaged using an OIII filter

(b) Pre 13, imaged using an OIII filter. The clear bipolar PN structure displayed here is consistent with binary central star predictions.

FIG. 1: Two non-spherical PNe (not Kepler targets), which were previously unconfirmed and had no clear images published. Note that the central star in Pre 13 is clearly visible. Images were taken using the 40" Swope telescope at Las Campanas Observatory in the Atacama Region, Chile, by J. Hurowitz and G. Jacoby. (20-May-2017)

stars, only the last of which is considered in this study.

The first technique is to take radial velocity measurements of the central star at multiple times to demonstrate the existence of periodic radial variations [Mendez 1989].

Another method is to search for excess red-color (V-I or V-J) in the central star [De Marco et al. 2013, Douchin et al. 2015]. Since the central stars of PNe should be very hot, and either white or blue, an excess of flux at "red" wavelengths can indicate the existence of a cooler companion. However, in some cases, this color discrepancy can be explained by interstellar dust or dust in the PN, making the conclusion of a binary interaction less certain.

Third, imaging PNe at very high spatial resolution can directly reveal the presence of a companion to the central star [Ciardullo et al. 1999]. Additionally, a bipolar PN structure often suggests that the central star is in a binary system [De Marco 2009].

Finally, photometric variations in the apparent magnitude or flux of a central star can indicate the presence of a companion [De Marco et al. 2015]. As a cooler companion revolves around the central star, one side of the companion is heated and will be observed brighter from our solar
FIG. 2: Two spherical PNe (not *Kepler* targets), which were previously unconfirmed and had no clear images published. Note that the central star in Pa 63 is clearly visible. Images were taken using the 40" Swope telescope at Las Campanas Observatory in the Atacama Region, Chile, by J. Hurowitz and G. Jacoby. (20-May-2017)

system. As this hotter side of the companion faces towards or away from us, the total amount of flux detected from the central star of the PN should increase and decrease accordingly. Furthermore, the central star of the PN may tidally distort the companion so that it appears oblate, and therefore larger and brighter, twice during its orbit, and smaller and fainter at two other times. Last, eclipses of the central star by the companion can reduce the amount of flux detected. These photometric data can be used to create a light curve and indicate the presence of said companion. Sinusoidal periodicity in the light curve is indicative of differential heating [De Marco et al. 2015], while the presence of two flux minima within one period suggests eclipsing binaries (e.g., McVean et al. [1997]).

The amplitude of the light curves of PNe central stars previously observed in the original *Kepler* mission ranged from about 0.5 to 140 mmag [De Marco et al. 2015]. Note that if the central star of a PN is affected by binary interactions with a brown dwarf or planet, the periodic variation in the flux of the star should hypothetically be smaller than if it were caused by a companion star [De Marco 2009]. To date, there are no known substellar companions to binary central stars in PNe [De Marco 2009].

This study only considers photometric data of PNe central stars. It is important to note that
detecting periodicity in the photometric data of PNe does not strictly imply that the central star displays binary interactions; instead, the central star could be a non-binary variable star. However, as noted in Sec. III A, a large majority of detected periods of the Kepler targets in this study are between two hours and five days. At these periods, it is far more likely that the central stars are binary rather than non-binary variable stars [Bond 1989]. Regardless, the shapes of the produced light curves can indicate whether the central star is variable [De Marco et al. 2015]. Further analytical support of these targets with data from one of the other three indicators of binary interactions, in particular radial velocity data, can conclusively prove that targets are not non-binary variable stars [De Marco 2009].

Previous binary central star searches for photometric variability have found that approximately 10 to 20% of PNe have binary signatures (see especially Bond [1989], Miszalski et al. [2009]). Due to its extremely high accuracy and precision in conducting photometric measurement, the NASA Kepler space telescope is an excellent candidate for a binary central star search for photometric variability, and can provide compelling statistical evidence that the majority of central stars of non-spherical PNe are in binary systems. In previous Kepler and K2 campaigns, 28 central stars of PNe have been observed, of which 6 (~21%) indicated binary signatures (4 from Kepler, 2 from K2) [De Marco et al. 2015, Jacoby, Long, Kronberger, De Marco and Hillwig 2016].

The Kepler K2 campaign 11 includes photometric observations of 140 confirmed or suspected PNe, the data for which were released on 30-Jun-2017 [Barentsen 2017]. These observations were made continuously over 76 days (with a three-day interruption in the middle, for a total duration of observations of 73 days), and the released data set contains flux measurements for each 30-minute period during this time, split into two smaller data sets of 30 and 43 days respectively [Barentsen 2018a, Sobeck 2016].

In this project, a software pipeline was created to rapidly process Kepler K2 photometric data to assist in the determination of whether the central stars of observed PNe displayed true periodicity, and thus binary signatures. The pipeline generates phased light curves for PNe for inspection by eye whether they display periodicity. This pipeline was created to process the large volume of PN targets from K2 campaign 11 but will be usable on targets of future (or previous) K2 campaigns.

Using the pipeline, I was able to identify periodicity in the photometric data for the central stars of 29 observed campaign 11 PNe. I was therefore able to identify photometric periodicity in 29 of 140 (21%) of observed targets, a large majority of which, if not all, likely result from binary

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1 Campaign 11 was planned to include observations on 186 confirmed or suspected PNe, but there were 46 (~25%) targets with no available photometric data due to Kepler satellite issues.

2 Between 10 and 20% of the Kepler targets are suspected, but unconfirmed PNe.
interactions (determined based on their periods; see Sec. III A and Bond [1989]). This percentage is consistent with previous, smaller-scale surveys of PNe. The proportion of these 140 PNe central stars which displayed short-period binary signatures can shed light on the mechanisms of formation for PNe, on the full life cycle of the low- to intermediate-mass stars that eventually produce these nebulae, and on the development of the unusual and often complex morphologies of PNe.

II. METHODS

A software pipeline was programmed in Python 2.7.13 to assist a search for photometric periodicity in the K2 campaign 11 photometric data for all PNe central stars. The pipeline outputs a photometric time series, a periodogram, and a phased, binned light curve for each target, regardless of if each actually displayed periodicity or not. After the pipeline generated the light curves, I inspected the light curves to see which ones showed true periodicity, implying binary interactions.

The pipeline consists of several steps, broken into subroutines, that it executes in series for each K2 target. Since the pipeline must download a large amount of data on the K2 targets, it requires Internet access to function properly; furthermore, Internet connection speed is the driving force behind program efficiency, with slower connections resulting in significantly longer pipeline run times. The pipeline takes as input a list of K2 ID numbers corresponding to each target.

In overview, the pipeline operates with the following steps for each K2 target:

1. Download Kepler photometric data on the target.
2. Plot a time series from the data.
3. Generate a Lomb-Scargle periodogram from the data.
4. Determine the frequency and period corresponding to the maximum power in the periodogram.
5. Create a phased light curve from the data, using the period found in step (4).
6. Create a phased and binned light curve from the data, which improves the signal-to-noise ratio of the detection of a binary signature.

The first task the pipeline executes is to download processed and reduced Kepler photometric data on each target from the Space Telescope Science Institute’s (STScI) on-line archive, the Mikulski Archive for Space Telescopes (MAST) [STScI 2018]. STScI performs some processing
and data reduction on the raw data output from *Kepler* to convert it to easily usable photometric data; specifically, the data used in this study were PDCSAP Flux measures \((e^-/s)\) and their corresponding dates and error measurements. PDCSAP Flux ("Pre-search Data Conditioning Simple Aperture Photometry Flux") was calculated by STScI by removing outliers, correcting for systematic artifacts, and detrending the raw flux measurements recorded by *Kepler* [Smith et al. 2012, Still 2013, Stumpe et al. 2012]. However, this resulting data set is still not without issue; crucially, there is a false period in the photometric data of many of the observed targets of approximately 0.244 days. This period is a well-known artifact in the data resulting from guiding errors in *Kepler* when running on two gyros [Barentsen 2018b]. Although STScI attempts to correct for this artifact, it fails to remove it completely from the data, leaving a residual signature that varies in magnitude across different targets. Fig. 3 shows this artifact, in addition to the software pipeline's response to observing the false period, in the light curve of K2 campaign 11 target NGC 6369 (K2 224716713).

(a) Periodogram for NGC 6369 displaying a false peak at 0.244 days, corresponding to the data artifact from *Kepler*.  
(b) "Phased" Light Curve for NGC 6369 output by the software pipeline with data phased to a period of 0.244. True periodicity is not detectable in the photometric data for this target.

FIG. 3: Software pipeline outputs for NGC 6369, a target without true periodicity. The pipeline calculates a false period for the photometric data equal to 0.244 days, which is an artifact in the data resulting from *Kepler* guiding errors.
Furthermore, because of the three-day interruption in the data collection by Kepler, the data are split into two data sets, one of length 30 days, and one of length 43 days. These data sets are not easily re-combinable, as the sets of photometric measures within each data set often have significantly different means, variances, and noise. These discrepancies are the result of STScI performing its data processing, and most importantly detrending methods, on the two data sets individually.

Therefore, no attempt was made to combine the two data sets. Instead, the pipeline considered each data set in isolation. A few targets appeared to display periodicity in the photometric data of only one of the two data sets, but a large majority of the time, the two data sets agreed with each other. Table I in Appendix A indicates which of the two data sets was used to generate the light curve for each target.

Finally, although data were collected in 30-minute intervals, a small percentage (~1%) of data points are missing from the photometric data altogether, presumably because of errors in data collection or because the points were significant outliers.

To demonstrate the following steps of the pipeline, I will examine its calculations on K2 campaign 11 target M 2-11 (K2 2235899761). G. Jacoby and I imaged M 2-11 with the 40" Swope telescope at Las Campanas Observatory to confirm that it is a planetary nebula. The images of the planetary nebula and the central star are shown in Fig. 4.

The second task the pipeline executes is to plot time series data from Kepler. Fig. 5 shows the times series of photometric data for M 2-11.
(a) M 2-11, imaged using an OIII filter. The clear bipolar PN structure displayed here is consistent with binary central star predictions.

FIG. 4: Planetary nebula M 2-11 and its central star. The resolution of a clear central star in the V filter and a clear nebula in OIII are evidence that M 2-11 is in fact a PN, as opposed to another astronomical object. (see Sec. III B) Images were taken using the 40” Swope telescope at Las Campanas Observatory in the Atacama Region, Chile, by J. Hurowitz and G. Jacoby.

(20-May-2017)
FIG. 5: Photometric time series (PDCSAP Flux vs. Time) for M 2-11 with data from *Kepler*. There are 2039 data points representing 30-minute intervals over 43 days. Time is given in BJD - 2454833, so that each increment of 1 represents a single Julian day (corrected to be the arrival times at the barycenter of the Solar System). Some periodicity is visible by eye, although it is unconvincing.

Third, the pipeline computes the Lomb-Scargle periodogram, shown for M 2-11 in Fig. 6. One can clearly identify a central peak in the power spectrum for M 2-11 at a period of approximately 0.575 days. The Lomb-Scargle method, also known as the Least-squares spectral analysis method, computes a periodogram of data using a least squares fit of sinusoids to data samples. Because the *Kepler* data are missing several individual data points, this method is preferred to a discrete Fourier transform of the data, which heavily relies on equally-spaced data points to calculate a periodogram. Fourth, the pipeline calculates the frequency and period corresponding to the maximum power in the periodogram for the given target. For central stars without any binary interaction, it is unlikely for there to be a single period for which the corresponding power is much
higher than any other period.

FIG. 6: Lomb-Scargle periodogram for M 2-11, with maximum power at period $\approx 0.575$ days, suggesting a binary orbital period of approximately $0.575$ days. Observe a small peak in the periodogram corresponding to the false period of $\approx 0.244$ days.

Fifth, using this period corresponding to the highest power in the periodogram, the pipeline phases the light curve data and plots it, such that the fluxes measured at each data point are plotted against the percentage of phase completed at the corresponding time. Fig. 7 shows the phased light curve for the data in Fig. 5 for M 2-11.

On occasion, the pipeline incorrectly picked an integer multiple or fraction of the correct period for a target because its power in the periodogram were higher. I was able to identify when this occurred and manually input the correct period. Additionally, the pipeline occasionally picked an incorrect period that was not an integer multiple or fraction of the correct period. In these cases,
I forced the periodogram to pick a lower peak to observe if the new phased light curve displayed periodicity. There were no targets for which the false period of 0.244 days had higher power than another clear peak in the periodogram, so this false period did not prevent the identification of true periodicity in any targets.

FIG. 7: Phased Light Curve for M 2-11 with 2039 data points representing 30-minute intervals over 43 days, and with error bars indicated. The mean error of each data point is $3.4 \times 10^{-4}$, or approximately $6.0 \ e^{-/s}$.

Finally, the data in the phased light curve are binned into 50 points, which simplifies the light curve and greatly decreases the relative errors. To generate each point in the binned, phased light curve, each of the original 2000 data points is weighted by the inverse of the error squared, before being used to calculate a weighted average. Fig. 8 shows the final light curve that the pipeline generates for M 2-11. The small variations in the light curve represent noise introduced by the 0.244-day period artifact in the data.
**FIG. 8:** Binned and Phased Light Curve for M 2-11, and with error bars indicated. Data were binned to 50 points (with 40 or 41 data points per bin). The mean error of each binned data point is $5.4 \times 10^{-5}$, or approximately $0.94 \, e^-/s$.

Finally, I inspected the output light curves from the pipeline to determine if the targets displayed true photometric periodicity (i.e., the phased light curves appeared consistent with light curves of known binary systems).

**III. RESULTS**

**A. Kepler K2 Data**

The pipeline generated light curves for all 140 observed K2 campaign 11 targets. Of these 140 targets, I determined by inspection that 29 central stars of PNe displayed periodicity. Therefore, the total fraction of the K2 campaign 11 targets with detected binary signatures from the photometric data is about 21%, which is consistent with previous, smaller-scale surveys of PNe. Seventeen
out of 29 (~59%) detected orbital periods were between two hours and one day, and 25 out of 29 (~86%) detected periods were between two hours and five days. No detected orbital periods were longer than two weeks. The median detected period was 0.491 days, and the mean detected period was 2.68 days. The short periods detected indicate that the targets are likely in close binary systems. These fractions are consistent with previous surveys for photometric variability of PNe central stars, which themselves led De Marco et al. [2008] and Miszalski et al. [2009], to conclude that it is very unlikely from a physical perspective for binaries with period longer than about three days to develop in such a way to affect PNe morphologies significantly in a manner consistent with photometric variability searches. Furthermore, the maximum possible period detectable in this method was proposed by De Marco et al. [2008] to be about two weeks, since detecting photometric variation resulting from differential heating of the companion star in systems of correspondingly large separation is unlikely.

There is some observational bias—since the data sets used to generate the light curves only span 30 and 43 days respectively, longer periods are more difficult to detect within the data. Future work with this data should include a careful methodology to combine the two data sets to search for longer periodicity in the observed targets. In fact, it is not certain that the four targets with calculated periods longer than five days display true periodicity or are binary systems. These systems, and especially PHR J1752-2527, K 5-31, and K 6-25, which rely on the shorter of the two data sets, should be considered binary with additional skepticism.

I have included some notable light curves for brief discussion in this section. A full list of targets displaying photometric variability, along with images of their phased and binned light curves and corresponding periodograms, can be found in Appendix A and B, respectively.
Fig. 9: Binned and Phased Light Curve for MPA1717-2356 (K2 251248526), with error bars indicated. Data were binned to 50 points (with 40 or 41 data points per bin). The post-binning mean error of each data point is $5.2 \times 10^{-4}$, or approximately 0.63 e$^-$/$s$. The sinusoidal shape of the light curve is likely caused by differential heating of a companion star.

Fig. 9 shows a phased and binned light curve for MPA1717-2356. The sinusoidal shape of the light curve, like that of M 2-11 in Fig. 8, suggests that differential heating of a companion star is the primary cause of the observed flux variations, as opposed to eclipses.
FIG. 10: Binned and Phased Light Curve for Terz N 19 (K2 251248550), with error bars indicated. Data were binned to 50 points (with 40 or 41 data points per bin). The post-binning mean error of each data point is $4.1 \times 10^{-4}$, or approximately $0.69\, e^{-}/s$. The central star of Terz N 19 and its companion may be W UMa eclipsing binaries.

Fig. 10 shows a phased and binned light curve for Terz N 19. The calculated period of 0.095 days ($\sim 2.3$ hours) is the smallest of all 30 targets with observed periodicity. The "flat" flux minimum centered around the 0.50 phase value is strongly suggestive of an eclipse of the primary star by the companion passing in front of it (relative to Kepler's frame of reference). The other "flat" flux minimum (centered around the 0.00 phase value) likely represents an eclipse of the companion star by the primary. The "M" shape of the light curve and the short period of the system indicate the primary and companion may be W UMa variable stars (low mass contact binaries), a type of eclipsing binary system; however, the two flux minima are not of equal magnitude, which is common in the light curves of W UMa binaries [Muller and Kempf 1903].
Fig. 11 shows a phased and binned light curve for Th 3-15. As with Terz N 19 (Fig. 10), the shape and short period of the light curve suggest the central star of Th 3-15 to be in a W UMa binary system. Note that the deeper flux minimum in the light curve of Th 3-15 shows the "flatness" characteristic of binary star eclipses.
Fig. 12 shows a phased and binned light curve for PTB 26. Again, the shape and short period of the light curve suggest a W UMa binary system. Note that the deeper flux minimum in the light curve of PTB 26 shows the “flatness” characteristic of binary star eclipses.

B. Ground Observations

G. Jacoby was allotted time on the 40" Swope telescope at Las Campanas Observatory (LCO) in the Atacama Region, Chile to image *Kepler* K2 campaign 11 targets to confirm that they are planetary nebulae. These observations were scheduled for six nights in May 2017. Unfortunately, the weather at LCO was cloudy, snowy, and windy for most of the run. As such, we were only able
to open for one and a half nights. On 20-May-2017, we imaged nine K2 campaign 11 targets. On 21-May-2017, we imaged 6 targets. Targets were imaged with H-alpha, OIII, V, and R filters.

To these targets as PNe, we imaged them to answer the following questions:

1. Does the target look like a PN, as opposed to some other astronomical object, noting that there are similar morphological themes across all PNe? The relative brightness of the target in emission lines, specifically H-alpha and OIII, can indicate the object as a PN.

2. Can we resolve the central star separately from the PN? For Kepler to measure photometric variability, the central star must be both bright enough to be observed, as well as bright enough so that the nebula emission does not mask any variability. The V and R filters allow resolution of the central star.

If the target appears the same in both the H-alpha and V filters, it is unlikely to be a true PN. Once imaged in H-alpha, the target must also be imaged in the OIII filter; this is because there are objects that emit in the H-alpha wavelength but are not PNe, such as HII regions, emission-line stars, supernovae remnants, and novae; however, these other objects are almost always faint in the OIII filter, while PNe usually appear brighter in OIII [Bowen 1927, Knisely 2013, O’Dell 2001]. Finally, the central star should be resolvable in the V or R filter to confirm the target as a PN.

To confirm targets as PNe, it is important to image at both the H-alpha and OIII wavelengths. Although PNe usually appear brighter in OIII than their surroundings, there are some PNe, such as YM16 (not a Kepler target), which emit strongly in H-alpha but faintly in OIII, and vice versa [Goldman 2010]. Additionally, most PNe are originally identified using survey images that were taken in a bandpass that includes H-alpha. Therefore, imaging the target in H-alpha, and determining whether it looks like a PN in this filter, is an important step to confirming objects at PNe. PNe identified using these survey images are often regarded as unconfirmed because of very poor image quality from the surveys.

The only target we imaged at LCO that displayed periodicity in its light curve generated from the Kepler data was M 2-11. (Fig. 4) Note that these images clearly show that M 2-11 is a PN. Fig. 13 shows images for target Th 3-1 and its central star. These images clearly show that Th 3-1 is a PN.
(a) Th 3-1, imaged using an H-alpha filter. This image (b) The central star of Th 3-1, imaged using an R filter, clearly shows an extended, fuzzy PN.

FIG. 13: Planetary nebula Th 3-1 and its central star. The resolution of a clear central star in the R filter and a clear nebula in H-alpha are evidence that Th 3-1 is in fact a PN, as opposed to another astronomical object. Images were taken using the 40" Swope telescope at LCO by J. Hurowitz and G. Jacoby. (20-May-2017)
(a) M 3-38, imaged using an H-alpha filter. This image clearly shows an extended PN. 
(b) The central star of M 3-38, imaged using an R filter. The central star is only marginally visible.

FIG. 14: Planetary nebula M 3-38 and its central star. The resolution of a central star in the R filter and a clear nebula in H-alpha are evidence that M 3-38 is in fact a PN, as opposed to another astronomical object. Images were taken using the 40" Swope telescope at LCO by J. Hurowitz and G. Jacoby. (20-May-2017)

Fig. 14 shows images for planetary nebula M 3-38 and its central star. Although the central star of M 3-38 is only marginally visible, M 3-38 is most likely a PN.
FIG. 15: Images of K2 campaign 11 target PM 1-130. It is not clear that there is a planetary nebula emitting stronger in the H-alpha wavelength than in R. Furthermore, there is no clear central star for the target. It is unclear whether PM 1-130 is a planetary nebula. Images were taken using the 40" Swope telescope at LCO by J. Hurowitz and G. Jacoby. (20-May-2017)

It is unclear whether target PM 1-130 (shown in Fig. 15) is a planetary nebula. The target is only slightly brighter in H-alpha than in R. Furthermore, the central star is not resolved over PM 1-130.

We determined that K2 campaign 11 target PHR J1658-2515 is probably not a planetary nebula, since it is not seen as an emission line source in the H-alpha filter. That is, the target appears the same in the H-alpha and V filters.

IV. CONCLUSIONS

In this study, through inspection of the light curves of a sample of 140 PNe from the Kepler K2 campaign 11 field, I determined that 29 of the targets (21%) displayed photometric variability, all of which had periods under two weeks. Additionally, 25 out of 29 (86%) detected periods were between two hours and five days. Given the periods of these targets, it is likely that most, if not all, of the 29 targets with periodicity are affected by binary interactions. The short-period binary fraction (i.e. fraction of PNe with detected periodicity under two weeks) computed in this study
is consistent with past photometric searches for close binary PNe central stars. Due to the slightly subjective nature of determining periodicity in generated light curves, and the fact that the data on the targets only span at most 43 days, it is possible that the short-period binary fraction of this sample is higher than calculated here. Furthermore, there are likely targets in the sample with detectable binary interactions using one of the three other methods given in Sec 1. Further work should include analysis of the radial velocity measurements of these 140 targets to determine if any short-period binary central stars were missed in this study’s photometric search. Finally, there are likely longer-period binary central stars (i.e. with period greater than two weeks) in the sample which I was unable to detect given the data collection length of at most 43 days.

De Marco [2009] predicts that under the Binary Hypothesis, the short-period binary fraction should be about 20%. The results in this study are consistent with this prediction, and therefore bolster the hypothesis. The implications of the hypothesis are clear even in our own solar system. Our sun is in the mass range likely to form a planetary nebula, and we know that it is non-binary. The results of this study lead us to predict that the Sun will produce a spherical PNe when it begins to die in several billion years.

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Appendix A: Targets with Detected Periodicity

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<tr>
<th>K2 ID</th>
<th>Object Name</th>
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<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>Period (days)</th>
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</table>

**TABLE I:** Calculated period (days) for all *Kepler* K2 campaign 11 targets with detected periodicity. Data set 1 refers to the campaign 11 data set of 30 days; data set 2 refers to the campaign 11 data set of 43 days. Targets are sorted by increasing period.
Appendix B: Light Curves and Periodograms

The light curves for all targets with detected periodicity, 50 points per bin, and with error bars indicated, are included here. Note that the error bars are usually smaller than the circles. They are accompanied by their corresponding periodograms. The targets are sorted in order of increasing period, as in Table I.