Periodic photometric variability of the brown dwarf Kelu-1

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Abstract

We have detected a strong periodicity of $1.80 \pm 0.05$ h in photometric observations of the brown dwarf Kelu-1. The peak-to-peak amplitude of the variation is $\sim 1.1$ per cent ($11.9 \pm 0.8$ mmag) in a 41-nm wide filter centred on 857 nm and including the dust/temperature-sensitive TiO and CrH bands. We have identified two plausible causes of variability: surface features rotating in and out of view and so modulating the light curve at the rotation period; or ellipsoidal variability caused by an orbiting companion. In the first scenario, we combine the observed $v \sin i$ of Kelu-1 and standard model radius to determine that the axis of rotation is inclined at $65^\circ \pm 12^\circ$ to the line of sight.

Key words: techniques: photometric – stars: atmospheres – binaries: close – stars: low-mass, brown dwarfs – stars: oscillations – stars: rotation.

1 INTRODUCTION

The study of rotation and variability in main-sequence stars has led to a great improvement in our understanding of their physics (e.g. Stauffer & Hartmann 1986). Recently, several groups have shown that variability can also be detected in substellar brown dwarfs (Tinney & Tolley 1999; Bailer-Jones & Mundt 1999, 2001; Martín, Zapatero Osorio & Lehto 2001).

In this paper we present differential photometry of the brown dwarf Kelu-1, in a search for rotational variability. Kelu-1 is a field brown dwarf, discovered by Ruiz, Leggett & Allard (1997) via its brown dwarf, Kelu-1, in a search for rotational variability. Kelu-1 is a field brown dwarf, discovered by Ruiz, Leggett & Allard (1997) via its brown dwarf, Kelu-1, in a search for rotational variability. Kelu-1 is a field brown dwarf, discovered by Ruiz, Leggett & Allard (1997) via its brown dwarf, Kelu-1, in a search for rotational variability. Kelu-1 is a field brown dwarf, discovered by Ruiz, Leggett & Allard (1997) via its brown dwarf, Kelu-1, in a search for rotational variability. Kelu-1 is a field brown dwarf, discovered by Ruiz, Leggett & Allard (1997) via its brown dwarf, Kelu-1, in a search for rotational variability. Kelu-1 is a field brown dwarf, discovered by Ruiz, Leggett & Allard (1997) via its brown dwarf, Kelu-1, in a search for rotational variability. Kelu-1 is a field brown dwarf, discovered by Ruiz, Leggett & Allard (1997) via its brown dwarf, Kelu-1, in a search for rotational variability. Kelu-1 is a field brown dwarf, discovered by Ruiz, Leggett & Allard (1997) via its brown dwarf, Kelu-1, in a search for rotational variability.

In Section 2 we describe the data acquisition and reduction. Time-series analysis of the resulting differential photometry is presented in Section 3. In Section 4 we discuss our observations in terms of surface features on the brown dwarf, or the nature of an orbiting companion.

2 DATA

2.1 Observations

Kelu-1 was observed on 2000 March 24–25 using the Taurus-2 instrument on the 3.9-m Anglo-Australian Telescope with a charge-coupled device (CCD) detector denoted MITLL3. MITLL3 is a 2048×4096 pixel device with 15 $\mu$m pixels, giving an image scale of 0.373 arcsec pixel$^{-1}$. Observations were performed through an intermediate bandpass blocking filter for the Taurus Tunable Filter. This filter (denoted R6) is 41 nm wide and is centred at 858 nm. The bandpass of the filter is shown overlaid on a spectrum of Kelu-1 (taken from Martín et al. 1999) in Fig. 1. Also plotted in Fig. 1 is the spectrum of the slightly hotter L0 dwarf DENIS-P J0909−0658 (Martín et al. 1999), indicating the temperature sensitivity of the TiO and CrH molecular bandheads selected by our filter.

A specially constructed slot mask was installed in the focal plane wheel of Taurus-2 (the same mask as used by Tinney & Tolley 1999). Multiple exposures of a sky field can then be made through this slot, between which charge is shuffled and stored on the unilluminated surface of the CCD. When used to observe Kelu-1, the entire Taurus-2 instrument was rotated at an angle of 140°, so that several suitable photometric reference stars could be observed (see Fig. 2). This observing technique results in a series of 30 exposures, following which the CCD is read out only once, providing very low readout overheads and precise timing. Table 1 gives a log of the observations.

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point spread function (PSF) photometry of these data is required. A master flat-field exposure was then constructed modified so as to include the correct timing and positional information. A PSF was determined for each individual exposure as bad. These bad pixels were interpolated over during the PSF fitting stage, but completely ignored during the actual photometry. PSF photometry also has the advantage of being relatively immune to cosmic ray events, which would affect aperture photometry. In order to verify our PSF photometry, we also performed aperture photometry in the same fashion as Martín et al. (2001). The aperture photometry was found to give the same, but noisier, results as the PSF photometry.

To obtain high-precision differential photometry of Kelu-1, we compared its apparent brightness with that of surrounding reference stars, cancelling the effects of apparent brightness changes due to variable extinction, seeing, instrument performance or exposure time. There are four available reference stars in our field of view (the brightest star in the field was often saturated). We define the brightest of these four stars to be our comparison star, which sets the magnitude zero-point for each exposure. The three remaining stars can then be used as check stars, allowing us to detect intrinsic variability in our comparison star. One of the check stars was found to be variable and therefore discarded. The remaining check stars were averaged to define a mean check magnitude. These stars are identified in Fig. 2.

The differential light curves obtained are shown in Fig. 3. The top panel shows differential photometry for Kelu-1 minus comparison as described in Section 2.2) over two nights. The bottom panel shows comparison minus check to the same scale, clearly indicating that the variability detected is from Kelu-1, not the comparison. The uncertainties plotted are based on the photon counting errors as produced by DAOPHOT and propagated to the differential results for Kelu-1, comparison and check stars. This plot shows raw differential photometry, before the correlation of Fig. 4 is removed.

2.2 Reduction and photometry

Each CCD frame contains 30 separate exposures, so the data processing is slightly more complicated than for standard CCD imaging. Each frame was bias-subtracted and then sliced into 30 individual exposures. The header file for each exposure was modified so as to include the correct timing and positional information. A master flat-field exposure was then constructed from dome flats observed in the same manner as the data. The data were then divided by this flat, providing correction to the cent level.

Owing to the proximity of a nearby star to our primary target, point spread function (PSF) photometry of these data is required. Photometry was performed using DAOPHOT within the IRAF environment. A PSF was determined for each individual exposure by fitting a profile to several of the brightest (non-saturated) stars in the field. This profile was then scaled to all the stars in the field to determine their brightness. No faint neighbours were found after the PSF had been subtracted from the target stars. Pixels that varied by more than 5 per cent from the mean in the flat field were flagged as bad. These bad pixels were interpolated over during the PSF fitting stage, but completely ignored during the actual photometry. PSF photometry also has the advantage of being relatively immune to cosmic ray events, which would affect aperture photometry. In order to verify our PSF photometry, we also performed aperture photometry in the same fashion as Martín et al. (2001). The aperture photometry was found to give the same, but noisier, results as the PSF photometry.

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The differential light curves obtained are shown in Fig. 3. The top panel shows differential photometry for Kelu-1 minus comparison, and the lower panel shows comparison minus check. It is clear from these plots that Kelu-1 minus comparison photometry is more variable than comparison minus check photometry – indicating that the variability detected is due to changes in the apparent brightness of Kelu-1 itself (an increase in Δm represents a dimming of Kelu-1). Variability in the comparison star would manifest itself as equal, but opposite, changes in each light curve. This effect can be seen on the first group of data points – the Kelu-1 minus comparison data are above the mean, and the comparison minus check photometry is below the mean, indicating that the comparison star has dimmed. We neglect this group of (60) data points in further analysis.

As the photometry presented in Fig. 3 is differential, most sources of systematic error that might produce a ‘spurious’ signal in Kelu-1 are cancelled out. The remaining possible sources of error are differential effects due to the differences in colour of Kelu-1 and the reference stars, or their different locations on the CCD. Differential position effects have been minimized by keeping all objects within 30 pixels of a nominal position on the detector for all observations. However, differential photometry for Kelu-1 versus detector position shows a residual correlation between Δx and y position on the CCD (Fig. 4). We have fitted this correlation with a straight line and subtracted it. The cause of this effect remains

![Figure 3](https://academic.oup.com/mnras/article-abstract/332/2/361/992042/362_F_J_Clarke_C_G_Tinney_and_K_R_Covey)

**Figure 3.** The top panel shows differential photometry for Kelu-1 (in the sense Kelu-1 minus comparison as described in Section 2.2) over two nights. The bottom panel shows comparison minus check to the same scale, clearly indicating that the variability detected is from Kelu-1, not the comparison. The uncertainties plotted are based on the photon counting errors as produced by DAOPHOT and propagated to the differential results for Kelu-1, comparison and check stars. This plot shows raw differential photometry, before the correlation of Fig. 4 is removed.

![Figure 2](https://academic.oup.com/mnras/article-abstract/332/2/361/992042/362_F_J_Clarke_C_G_Tinney_and_K_R_Covey)

**Figure 2.** ‘Slot’ mask image of Kelu-1 and the comparison and check stars used in our differential photometric analysis. The vertical bars in the image are bad columns on the MITLL3 detector. The orientation of the sky through the mask when Taurus-2 is rotated to PA = 140° is indicated.

![](https://academic.oup.com/mnras/article-abstract/332/2/361/992042/362_F_J_Clarke_C_G_Tinney_and_K_R_Covey)

**Table 1.** Log of Kelu-1 observations in 2000 March 24–25.

| Date | Start UT | End UT | No. of images | Exposure time (s) |
|------|----------|--------|---------------|-------------------|
| 24   | 11:20    | 11:53  | 60            | 60                |
| 24   | 13:15    | 14:00  | 90            | 30                |
| 24   | 15:04    | 19:05  | 480           | 30                |
| 25   | 10:10    | 12:56  | 270           | 30                |
| 25   | 13:39    | 19:00  | 300           | 60                |

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We have calculated the least-squares weighted power spectrum of the differential light curve to look for periodicities. The power spectrum is calculated in the manner described by Frandsen et al. (1995), which we briefly describe here. The data are represented by the function \( A_i \sin(2\pi ft + \phi_i) \) for a range of frequencies \( f \), where \( A_i \), \( \phi_i \) and \( t \) are the amplitude, phase and time respectively. The power at each frequency is then \( P_i = A_i^2 \alpha^2 + \beta^2 \), where \( \alpha \) and \( \beta \) are given by
\[
\alpha = (sx_2 - cx)(sx_2 - c^2 - x^2),
\beta = (sx_2 - sx)(sx_2 - c^2 - x^2),
\]
with
\[
c = \sum w_j x_j \cos(\Omega_i t_j),
\]
\[
s = \sum w_j A_j \sin(\Omega_i t_j),
\]
\[
c_2 = \sum w_j \cos^2(\Omega_i t_j),
\]
\[
s_2 = \sum w_j \sin^2(\Omega_i t_j),
\]
\[
x = \sum w_j \sin(\Omega_i t_j) \cos(\Omega_i t_j),
\]
where \((t_j, x_j, w_j)\) are the data points and associated weights, and \( \Omega_i = 2\pi f_i \). Each data point is assigned a weight of \( w_j = 1/\sigma_j^2 \), where \( \sigma_j \) is the error associated with point \( j \). This system gives higher weights to data points with smaller errors.

The discrete sampling of observations means that the observed power spectrum is the convolution of the ‘true’ power spectrum with the ‘spectral window function’. We have calculated the spectral window as prescribed by Roberts, Lehar & Dreher (1987):
\[
W(f) = \frac{1}{N} \sum e^{-2\pi N f},
\]
(1)
The power spectrum and spectral window of our data are shown in Fig. 6. The upper panel shows the power spectrum over the complete range of frequencies available to us; 1 d\(^{-1}\) up to the Nyquist frequency of 0.5 min\(^{-1}\) (1 < \( f \) < 720 d\(^{-1}\); 24 > \( P > 0.033 \) h). There is only one main peak in the power spectrum. The lower panel shows a close-up of the region of interest (1 < \( f \) < 30 d\(^{-1}\)). The power spectrum of the Kelu-1 differential photometry (solid line) shows a strong peak at a frequency of 13.34 ± 0.38 d\(^{-1}\), corresponding to a period of 1.80 ± 0.05 h. The peaks at higher and lower frequencies are produced by the first sidelobes of the spectral window, as shown in the middle panel of Fig. 6. The maximum power of the main peak is 3.5 × 10\(^{-5}\) mag\(^2\), corresponding to a peak-to-peak amplitude in the light curve of 11.9 mmag. Monte Carlo simulations of the data give a 1σ error in the amplitude of 11.9 ± 0.8 mmag. Cleaned power spectra (Roberts et al. 1987) do not reveal any other periodicities hiding in the sidelobes of the main frequency.

Also shown in the lower panel of Fig. 6 is the power spectrum of the comparison minus check photometry (dashed line). There is no peak at the frequency detected in the Kelu-1 photometry, and the maximum power in this spectrum is an order of magnitude lower. This confirms that the periodic variability we detect in the Kelu-1 minus comparison photometry is due to intrinsic variability of Kelu-1 rather than the comparison star.

To investigate further the periodicity detected, we have treated each night’s data separately. The periodograms are shown in Fig. 7. The same ~1.8 h periodicity is detected in both data sets, indicating that the source of the variability is stable over at least ~48 h (~25 rotations).

3 TIME-SERIES ANALYSIS

We have calculated the least-squares weighted power spectrum of unknown. The maximum pixel-to-pixel sensitivity variation in the flat field is 2.5 per cent in the region of interest, and does not display any gradient. All data discussed hence have had this correlation removed. No correlation was found with x position.

Differential colour effects will be produced when the effective wavelength of a star through a filter is different from that of the reference objects. The target will then suffer a different amount of atmospheric extinction as the target rises and sets. If such an effect is present, we would expect that spurious periodicities would be produced at aliases of 24 h (i.e. 6, 12 or 24 h). We would also expect to observe a correlation between differential photometry and airmass if this effect is present. Fig. 5 shows a plot of the differential photometry for Kelu-1 (upper panel) and comparison stars (lower panel) versus airmass. There is no evidence (from Spearman rank correlation tests) for a correlation in either of these plots. In addition, Fig. 1 shows that Kelu-1 does not have a strong colour gradient over our filter bandpass.

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Differential photometry plotted against Y pixel position on the CCD. There is a clear correlation at the level of 0.003 mag pixel\(^{-1}\), which we remove by subtracting a straight-line fit.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Differential photometry plotted against airmass for Kelu-1 minus comparison (top panel) and comparison minus check (bottom panel). A Spearman rank correlation test shows no significant correlation between airmass and differential magnitude.
Close examination of the data reveals a slow linear change in the brightness of Kelu-1 at a level of 0.003 mag d$^{-1}$ over the duration of the observations (this is not caused by the previously discussed correlation between $d_m$ and $y$ position on the CCD (Fig. 4). We have not removed this effect for the time-series analysis. Fig. 8 shows the Kelu-1 photometry folded on a period of 1.80 h (with the slow, linear trend this time removed), and combined into 5 min bins. We derive the following ephemeris for the time of minimum light, $t_{\text{min}}$:

$$t_{\text{min}} = \text{JD } 2451628.037 + 0.075 \times \epsilon$$

where $\epsilon$ is the number of rotations since JD = 2451628.037.

4 DISCUSSION

Kelu-1 clearly displays periodic variability, but what is the cause of this variability? We have developed four possible explanations, which we discuss in this section:

(i) surface inhomogeneity moderated by meteorology and variable dust formation;
(ii) surface inhomogeneity moderated by magnetic star-spots;
(iii) light-curve variability due to gravitational (i.e. tidal) distortion of Kelu-1’s envelope by a close companion; and
(iv) light-curve variability due to an eclipsing binary.

4.1 Dust cloud meteorology

At the cool temperature of the photosphere of Kelu-1, dust
formation will play an important role. Theoretical spectra indicate that Kelu-1 is better matched by models with dust suspended in the photosphere than by models in which condensates are ‘rained out’ (Baraffe et al. 1998). However, we cannot expect the atmospheres of brown dwarfs to be placid, homogeneous places – especially if rotating at \( v \sin i = 60 \text{ km s}^{-1} \). They are no doubt dynamic and evolving, much like the atmospheres seen on planets in our own Solar system. This leads us to investigate the possibility that we are observing dust cloud morphology in Kelu-1’s atmosphere.

Gelino et al. (2002) suggest that there is a possible correlation between \( J - \) colour and variability in L dwarfs – variable objects tend to have bluer \( J - \) colours, which they claim is evidence that holes in dust clouds are causing variability. Kelu-1 has a \( J - K_s \sim 1.6 \) (Kirkpatrick et al. 1999). This is not significantly different from the mean colour for an L2 dwarf \( (J - K_s \sim 1.5) \), so the strong variability of Kelu-1 sheds no light on this suggestion.

Could the variability be due to a large feature on one side of the brown dwarf? The surfaces of all the Solar system giant planets are dominated by surface banding, which is driven by an interior in which Coriolis forces dominate over buoyant convection, to produce long, thin quasi-cylindrical cells oriented with their axes parallel to the axis of rotation (Schubert & Zhang 2000). In brown dwarfs, however – even brown dwarfs with a 1.8 h rotation period – buoyancy forces should dominate to produce chaotic three-dimensional convection. So banding structures, like those seen on Jupiter, are probably not to be expected. If cloud formation is inhomogeneous, rotation and convection should combine to produce less ordered structures. So convective upwelling or large cloud inhomogeneities may be possible.

4.2 Magnetic star-spots

Another possibility is that the inhomogeneities that we detect are caused by magnetically induced star-spots, analogous to those observed on the Sun and other cool stars. However, Gelino et al. (2002) have shown that the atmospheres of brown dwarfs are unable to sustain star-spots, as low Reynolds numbers imply that the atmosphere is not bound to magnetic field lines. In addition, several groups have shown that there is no strong evidence for the link between variability and activity (as measured by \( H \alpha \) equivalent width), which would be expected if magnetic forces drove variability. We note, however, that this conclusion is weakened by the small number statistics currently involved.

4.3 Binarity

One intriguing possibility is that we are seeing variability induced by a companion orbiting Kelu-1. A companion could modify Kelu-1’s brightness in two ways: either by partial or total eclipsing, or via the gravitational perturbation of Kelu-1’s photosphere, causing ellipsoidal variability (see Hilditch 2001). We have not been able to derive any orbital configuration that could reproduce the observed light-curve amplitude and shape, and we therefore reject an eclipsing companion. In the case of ellipsoidal variability, we would observe two maxima per rotation, and hence the orbital period would be 3.6 h. It is reasonable to assume the orbits will be circular due to tidal effects, and we can therefore directly calculate the orbital separation as

\[
a = 0.48 R_\odot \left( \frac{M_1}{0.065 M_\odot} \right)^{1/3} \left( \frac{P}{3.6 \text{ h}} \right)^{2/3},
\]

where \( M_1 \) is the primary (Kelu-1) mass, and \( P \) is the orbital period.

Unfortunately, when fitting for ellipsoidal variability, there is a degeneracy between the mass of the secondary object and the orbital inclination of the system. If, however, we assume the secondary companion is also a brown dwarf (lack of X-ray flux rejects the possibility of a massive dark companion such as a neutron star or black hole), we can place limits on its mass. Fig. 9 shows the possible secondary mass as a function of primary mass. Companions are excluded from the hatched region for two different reasons: (1) if \( M_1 \approx 45 M_{\text{Jup}} \), the minimum mass is determined by the need to produce 1.1 per cent ellipsoidal variations with \( i \approx 65^\circ \); and (2) for \( M_1 \approx 45 M_{\text{Jup}} \), brown dwarfs cannot exist in the hatched region, as they would overflow their Roche lobes, transferring matter to the primary. It is not clear what the final outcome of such an interaction would be, but the lack of activity indicates that this cannot currently be happening. An object more compact than a brown dwarf or gas giant planet could survive in this region. We note that these limits are based on simplistic models and are very sensitive to the exact amplitude of Kelu-1’s variability. They do, however, indicate that any companion to Kelu-1 would be a brown dwarf rather than a massive planet (i.e. \( M_2 > 13 M_{\text{Jup}} \)).

Pure ellipsoidal variability produces a sinusoidal light curve, which is statistically consistent with Kelu-1’s folded light curve. If a secondary companion is responsible for the variability, future observations will return the same amplitude and ephemeris. We note that a binary system would have an orbital velocity of \( \sim 130 \text{ km s}^{-1} \), and would be capable of mimicking the observed 60 km s\(^{-1}\) line broadening over a 1-h integration.

4.4 Surface structures

Doppler imaging codes have been used extremely successfully to mapping and understanding the surface features of solar-type low-mass stars. However, the process requires very high-quality photometry and spectroscopy, combined with a full understanding of photospheric physics, all of which seem a long way off for brown dwarfs.

Although mapping the surface of a brown dwarf is a distant goal, we can make some headway. By synthesizing photometry from theoretical spectra (Allard et al. 2001) of two limiting cases – (1)
dust is suspended in the atmosphere (DUSTY), and (2) dust forms but immediately settles below the photosphere (COND) – we can investigate what degree of surface structure is required to reproduce the observed variability.

The spectrum of Kelu-1 is best matched by a DUSTY atmospheric model (Baraffe et al. 1998), so we assume a model in which variability is caused by clear (COND) ‘holes’ in a photosphere dominated by DUSTY ‘clouds’. The COND spectrum is 0.55 mag brighter than the DUSTY spectrum through our filter. The amplitude of 0.012 mag that we observe in Kelu-1 corresponds to COND ‘holes’ covering \( \sim 1.7 \) per cent of an otherwise DUSTY photosphere. This value is a lower limit, as less perfect clear patches would have a smaller effect on the variability, requiring them to cover larger fractions of the surface.

Note that the covering fractions above actually represent the difference in covering fraction between maximum and minimum light. They are therefore only representative of surface features on \( \sim 180^\circ \) scale. It may be that the surface has a far more significant small-scale structure, which simply averages out over large regions.

4.5 The radius of Kelu-1

Interpreting the 1.8-h variability as the rotation period allows us to make one of the first firm tests of brown dwarf evolutionary theory. Evolutionary models (e.g. Chabrier et al. 2000) predict that, after \( \sim 100 \) Myr, brown dwarfs (independent of mass) reach a stable radius of \( \sim 0.1 R_\odot \). We can combine the rotation period and the rotational velocity to produce an observational lower limit (due to the unknown inclination) on Kelu-1’s radius. For the observed values of 1.80 \( \pm 0.04 \) h and 60 \( \pm 5 \) km s\(^{-1} \) (Basri et al. 2000), Kelu-1 must have \( R \geq 0.09 \pm 0.01 R_\odot \). The evolutionary models are therefore in agreement with our observations of Kelu-1. This is not the case for the observations of BRI0021 - 0214 made by Martin et al. (2001). They require a radius of at least 0.14 \( R_\odot \) to fit their observations with metastable photospheric surface features. We note that this argument would require the features responsible for photometric variability to have the same rotation period as the photosphere.

Alternatively, we can invert this argument and, assuming a model radius of 0.1 \( \pm 0.05 R_\odot \) (to include a range of possible ages and masses), determine the inclination of Kelu-1 to the line of sight as \( 53^\circ \leq i \leq 77^\circ \). This means that between 80 and 97 per cent of the surface can cause variability. The remaining fraction (polar regions) is either permanently in view, or never visible.

5 CONCLUSIONS

It is now clear that variability from brown dwarfs can be detected, but that photometry of better than 1 per cent is required to do so. In the near future, further studies of variability and rotation in brown dwarfs should greatly increase our understanding of their physics. We have detected a strong periodicity of 1.80 \( \pm 0.05 \) h in differential photometry of the L2 brown dwarf Kelu-1. We have investigated four possible mechanisms to explain this variability:

(i) surface inhomogeneity moderated by meteorology and variable dust formation;
(ii) surface inhomogeneity moderated by magnetic star-spots;
(iii) light-curve variability due to gravitational distortion of Kelu-1’s envelope by a close companion; and
(iv) light-curve variability due to an eclipsing binary.

Mechanisms (ii) and (iv) seem unlikely explanations, but we are unable to differentiate conclusively between mechanisms (i) and (iii). Ellipsoidal variability, mechanism (iii), would produce a twin-peaked light curve, giving a period of 3.6 \( \pm 0.1 \) h. This mechanism will give stable and repeatable photometric variability in future epochs. Alternatively, mechanism (i) associates the 1.80 \( \pm 0.05 \) h period with the rotation period, which is consistent with the rotational velocity of 60 km s\(^{-1} \) and theoretical radius of \( \sim 0.1 R_\odot \), indicating an inclination in the range \( 53^\circ \leq i \leq 77^\circ \).

Over the duration of our observations, the general shape and period of the light curve are unchanged (at least to within the measurement noise), implying that the process causing the modulations is also stable on this time-scale. This is in contrast to previous variability observations, where no periodicity, or a period that changes on the order of the observation length, has been measured.

The two explanations we have presented lead to different predictions for future observations of Kelu-1. Variability induced by a secondary companion will be completely repeatable at future epochs, whereas long-term evolution of surface features will result in secular changes in the light curve. Further observations of Kelu-1 will be a powerful discriminant between the two hypotheses we have presented.

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