Kepler observations of HD 181068: discovery of a hierarchical triple system with double eclipses

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Over two thirds of all stars reside in binary or multiple systems, and more than 90% of close binaries have at least one distant companion. These hierarchical triple (or higher) systems are key objects for testing star-formation theories and, having evolutionary pathways very different to those of the single stars, they are also important for studying the effects of nearby companions on stellar evolution. Here we announce the discovery of the first hierarchical triple star with two types of mutual eclipses. We obtained 218 days of *Kepler* photometry of KIC 5952403 (HD 181068, $V = 7.1$ mag), which has been supplemented with extensive ground-based observations to characterize the three components of the system. The primary component is a He-core-burning red giant star with light curve variations that are intimately linked to the orbital frequencies of the wide and the close pairs. We measured its angular diameter using the PAVO beam combiner at the CHARA array to be 0.398±0.008 milli-arcsecond. To our knowledge, this is the smallest stellar angular diameter with this kind of precision to have been measured using interferometry. The B and C components appear to be main-sequence dwarfs cooler and less massive than the Sun. In addition to the possibility of studying tidally driven oscillations in a red giant star, HD 181068 is a unique object in many other ways, most notably an ideal target for studies of dynamical evolution and testing tidal friction theories in hierarchical triple systems.

The *Kepler*[1] space mission is designed to observe continuously more than 10^5 stars, with the ultimate goal of detecting a sizeable sample of Earth-like planets around main-sequence stars using the transit method (*1*). Its unique capabilities mean *Kepler* is ideally placed to uncover new types of objects and phenomena, which so far include a multiple transiting planetary system (*2*), light modulation in close binary stars due to relativistic beaming ('Doppler boosting'; *3*),

[1] http://kepler.nasa.gov

an exotic system with a thermally bloated white dwarf companion (*4*), solar-like oscillations in almost 600 main-sequence and subgiant stars (*5*) and ∼800 red giants (*6, 7*), period doubling in RR Lyrae stars (*8*) and g-mode pulsation in an extreme horizontal-branch star (*9*).

Here we announce the discovery of the first hierarchical triple system with two types of eclipses. The star HD 181068 (KIC 5952403, and known as 'Trinity' within the authorship team) has magnitude $V = 7.1$ and a distance of about 250 pc. It has been identified as a single-lined spectroscopic binary (*10*) but there are no reports of eclipses. *Kepler* observations reveal two sets of eclipses with periods of ∼0.9 d and ∼45.5 d that arise from the wide and the close pairs of a hierarchical triple system. In addition to the eclipses, the light curve shows a host of other phenomena, such as oscillations with changing amplitudes, occasional flares that are somewhat correlated with the orbital phase of the close pair, and slow variability that may be related to ellipsoidal distortion of the giant component. All these features make HD 181068 an extremely complex system, which will be discussed in more detail in forthcoming papers. Here, we lay out the basic geometry and the fundamental properties of the three components, deduced by combining seven months of *Kepler* photometry with ground-based observations.

The photometric data were obtained by the *Kepler* space telescope (*11, 12, 13*) in long-cadence (LC) mode (one point every 29.4 minutes) over 218 days using Quarters 1, 2 and 3. These reveal a very distinctive light curve. It shows eclipses every ∼22.7 days and slow variations in the upper envelope (top panel in Fig. 1) that are presumably due to ellipsoidal distortion of the primary component. There are also very regular and much narrower eclipses, more clearly visible in the 28-d segment in the second panel of Fig. 1. These minima have alternating depths and we refer to this close pair as B and C, with an orbital period of ∼0.9 d. The 22.7-d eclipses all have similar depths, but there are subtle difference between consecutive minima and our radial velocity observations (see the Supporting Online Material) confirm that the true orbital period of the BC pair around the A component is twice this, i.e. 45.5 d. We also see that the narrow 0.9-d eclipses essentially disappear during both types of the deep min-

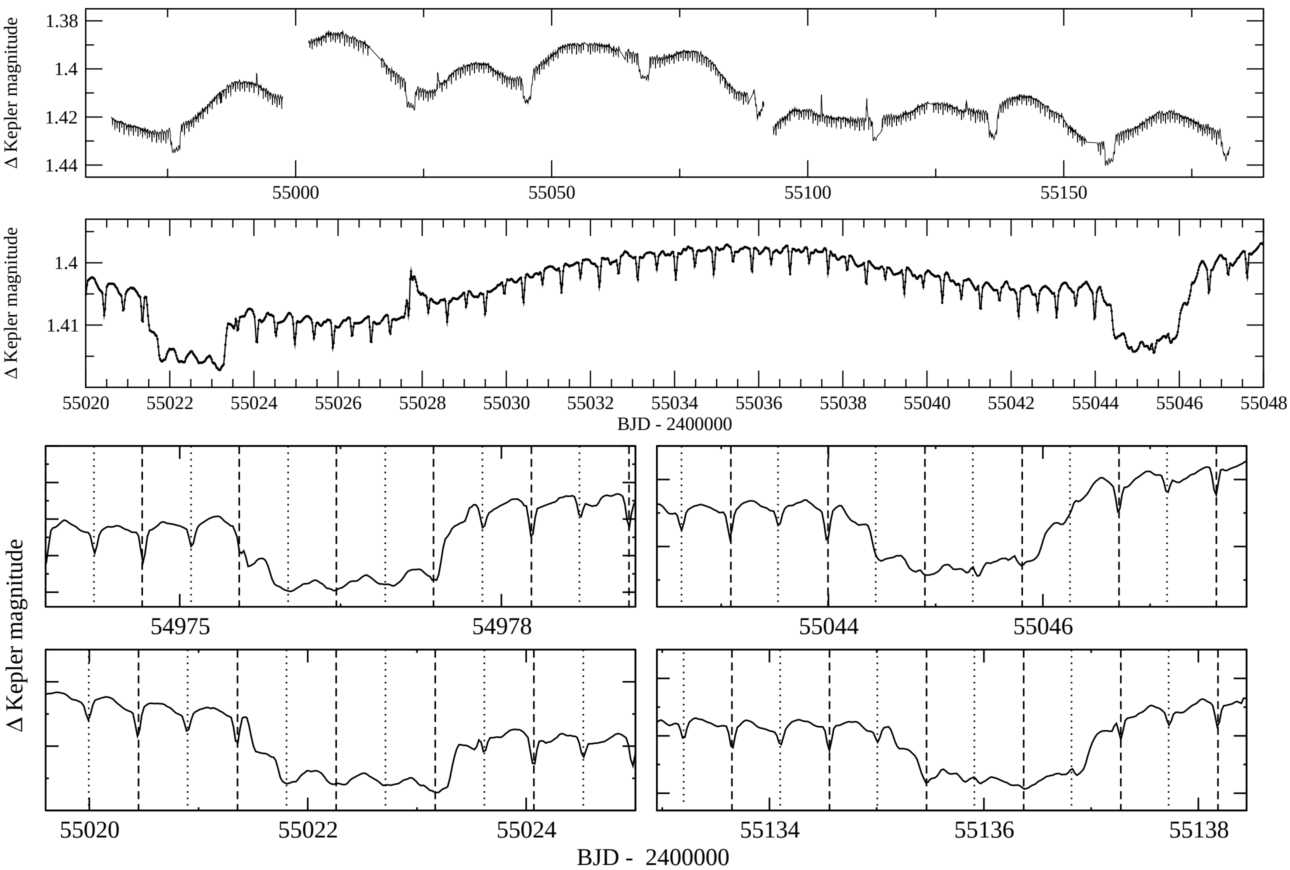

Figure 1: Light curve of HD 181068 from *Kepler* observations in long-cadence mode: (a) the full 218 days; (b) a 28-d segment showing two consecutive deep minima. (c–f) close-ups of two primary minima and two secondary minima of the 45.5 d eclipses. The dashed and dotted lines mark the primary and the secondary minima of the 0.9 d eclipses, respectively.

ima. This makes obvious sense for the secondary minima (BC get occulted behind star A), but requires some explanation for the primary ones (BC transiting in front of A). The implication is that the three stars have very similar surface brightnesses, so that when BC are in front of A, their mutual eclipses do not change the total amount of light coming from the system (also in good accordance with the nearly-equal depths of the two deep minima). To highlight some subtle differences between the primary and the secondary eclipses, we plot two examples for both, with dashed and dotted lines marking the two types of the BC minima (bottom four panels in Fig. 1). It is clearly seen that when BC is in front of A, the BC's secondary eclipses appear as tiny brightenings. This shows that the surface brightness of B is almost equal to A, while C is a bit fainter, so that its disappearance behind B allows the extra light from A to reach us.

While a detailed modelling of this complex behaviour is beyond the scope of this paper, the observed features confirm that the A and BC systems are physically associated and not a chance alignment. We measured the two periods to be $P_{\rm BC}$=0.90567(2) d and $P_{\rm A\text{-}BC} = 45.518(2)$ d. Given the shallow depths of the eclipses, star A must be far the most luminous object in the system. In addition to the eclipses, there are brightness fluctuations during the long period minima which imply that component A is also an intrinsic variable star with a mean cycle length close to the half the shorter orbital period, presumably indicating tidally-induced oscillations.

In addition, there were several flare-like events in the light curve that usually lasted about 6-8 hours. We checked the *Kepler* Data Release Notes[2] for documented instrumental effects in the vicinity of the 'flares', but found none. Moreover, almost all flares appear right after the shallower minimum of the BC pair, indicating that this activity is likely to be related to the close pair.

We have obtained ground-based imaging, spectroscopy and interferometry to determine system parameters (see Supporting Online Material). Firstly, lucky imaging data with a 1m telescope were checked for optically resolved companion(s), but none was found. Secondly, we

[2] Available at http://archive.stsci.edu/kepler/

Table 1: Orbital elements for the wider system derived from the A component's radial velocity curve.

Element	Value
$P_{\text{A-BC}}$	45.5178 d (fixed)
T_2	2455431.814 $\pm$ 0.095 (fixed)
K_2	37.195 $\pm$ 0.053 km s^{-1}
v_γ	6.993 $\pm$ 0.011 km s^{-1}
e_2	0.0 (fixed)
ω_2	$90\overset{\circ}{.}3 \pm 2\overset{\circ}{.}5$
$f(m)$	0.39 $M_\odot$

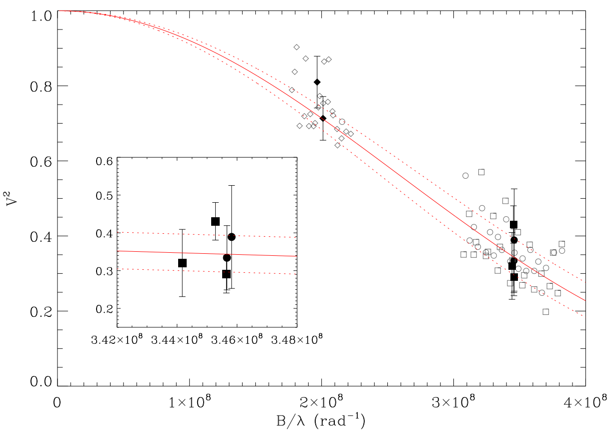

Figure 2: Squared visibility versus spatial frequency from PAVO on CHARA. Grey points show all collected measurements, and black symbols the average of each scan over all wavelength channels. Each symbol type corresponds to a different night of observations. The solid red line is the best fitting model, with 3-σ uncertainties indicated by red dotted lines. The left bottom inset shows a close-up of the observations at the longer baselines.

collected 41 high-resolution optical spectra at four observatiories to measure the orbital reflex motion of the A component. The orbital parameters for the wider system (Table 1) reveal that star A revolves on a circular orbit, which has an orbital period twice the separation of two consecutive flat-bottomed minima in the light curve (further details are presented in the Supporting Online Material). Thirdly, we carried out long-baseline interferometry using the PAVO beam combiner (Precision Astronomical Visible Observations, *14*) at the CHARA array (Center for High Angular Resolution Astronomy, *15*) to measure the angular diameter of the primary component. The interferometric results are shown in Fig. 2. We determined the angular diameter for HD 181068 A, corrected for limb darkening (*16*), to be $\theta_{LD} = 0.398 \pm 0.008$ milli-arcsecond, where the uncertainties were calculated using Monte Carlo simulations, as described in (*17*). To our knowledge, this is one of the smallest stellar angular diameter to have been measured using interferometry.

Combining the measured angular diameter with the Hipparcos parallax of 4.0 ± 0.4 mas (*18*), we find the linear radius of the primary component of HD 181068 to be $R = 10.7 \pm 1.1 R_\odot$. Using the spectroscopically determined $T_{\rm eff} = 5100 \pm 200$ K, this implies a luminosity of $L = 70 \pm 14 L_\odot$. This value is in a good agreement with that found from the Hipparcos parallax and the apparent magnitude. We also estimated the absolute magnitude of HD 181068 A based on the Wilson-Bappu effect (*20*), which correlates the width of the chromospheric Ca II K emission line at 3934 Å with the V-band absolute magnitude. Using the latest calibration (*21*), the measured width of the emission core W_0=72.8 km/s implies $M_V = -0.3$ mag, which agrees perfectly with the parallax and the interferometric results.

The mass of HD 181068 A was estimated by comparing the effective temperature and luminosity with evolutionary tracks from the BASTI database (*22*). We obtained $M_{\rm A} \sim 3.0\pm0.4 M_\odot$, corresponding to a core-helium-burning red giant in the so-called secondary clump (*23*). Finally, the full Spectral Energy Distribution, constructed using all published broad-band optical magnitudes and infrared flux values, does not show any excess in comparison to a 5200 K photospheric model.

We have constrained the parameters of the BC pair by modelling the short-period eclipses in the Kepler band using the JKTEBOP code (*24*, *25*). We found the ratio of the radii of the B and C components to be poorly constrained at present, partly due to the low sampling rate of the *Kepler* long-cadence data. The A component contributes 99.29% of the system light in the *Kepler* passband, and the BC pair contribute 0.44% and 0.27%, respectively. Taking the V-band absolute magnitude of HD 181068 A to be $M_V(\mathrm{A}) = -0.3$ and assuming that our results for the *Kepler* passband are representative of the V-band, we find $M_V(\mathrm{B}) = 5.6$ and $M_V(\mathrm{C}) = 6.1$. Such absolute magnitudes indicate spectral types of G8 V and K1 V for stars B and C, respectively (*26*).

One puzzling feature of the system is the short-period fluctuations that have the largest amplitudes whan the BC pair is behind star A, while remaining apparent with a slowly changing amplitude in all the other phases of the wide orbit. We have investigated this variability of HD 181068 A with a detailed frequency analysis and a comparison to other red clump giant stars that have similar properties (see the Supporting Online Material). Our findings are quite surprising: the frequency content of the light curve suggests an intimate link to tidal effects in the triple system, with the first four dominant peaks in the power spectrum identifiable as simple linear combinations of the two orbital frequencies. On the other hand, solar-like oscillations that are expected to produce an equidistant series of peaks in the power spectrum, are not visible, even though all stars with similar parameters in the Kepler database do show clear evidence of these oscillations. In other words, the convectively driven solar-like like oscillations that we would expect to see in a giant of this type seem to have been suppressed.

The physical characteristics presented in this paper mark HD 181068 as an extraordinary object, both from observational and astrophysical points of view. This is the first known triple system where both the inner (close), and the outer (wide) binary show mutual eclipses. This feature makes it possible to determine accurate geometrical and astrophysical parameters of the stars and their orbits from the eclipsing light-curves. According to the recent compilation of 724 triple stars (*27*), HD 181068 has the second-shortest wide period among the known systems (after λ Tau). Note that extremely compact hierarchical triple systems form a very small minority of hierarchical triplets, with only 7 of the catalogized 724 systems having outer periods shorter than 150 days. Furthermore, HD 181068 has the highest outer mass ratio among the known systems. In 97% of the known hierarchical triplets, the mass of the close binary exceeds that of the wider companion, and even the larger outer mass ratio remains under 1.5.

These properties make HD 181068 an ideal target for dynamical evolutionary studies, and for testing tidal friction theories. Due to the compactness of the system and the massive primary, we can expect short-term orbital element variations on two different time-scales of 46 days (i.e. with period of $P_{\text{A-BC}}$), and approximately 6 years ($P^2_{\text{A-BC}}/P_{\text{BC}}$), the time-scale of the classical apsidal motion and nodal regression (*28*), which for the doubly eclipsing nature, could be observed relatively easily. We can therefore hope that *Kepler* will be able to follow the full dynamical evolution of the system. From these data, the relative orientation of the orbits (the mutual inclination, and the positions of the apsidal lines relative to each other) could be determined (*29, 30*).

We conclude that HD 181068 promises to be an exciting astrophysical laboratory to study red giant oscillations influenced by nearby companions, evolution in hierarchical triple stars and the fine details of celestial mechanics that would be impossible to capture in any of the currently known similar systems.

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Sections to the Supporting Online Material

A Observations and methods

A.1 Lucky Imaging

We checked HD 181068 for resolved optical companions with lucky imaging on the 1m RCC telescope of the Konkoly Observatory. For this, we took over 100,000 short-exposure frames on 2010 June 28/29 and June 29/30, using an Andor IXon^{EM}+888 EMCCD, with exposure times of 30–61 ms in $UBV(RI)_\mathrm{C}$ filters. The median seeing was about 1.6″. In each filter we obtained 10,000–30,000 frames, from which the best 0.3% was selected and combined. The resulting images show clean single-star profiles with typical FWHM of 0.9″ in U, 0.64″ in V and 0.45″ in I_C.

A.2 Spectroscopy

To measure the orbital motion of HD 181068 A, we acquired optical spectra at four different observatories. We obtained 41 spectra in total, as follows: 6 spectra with the FIES spectrograph at the Nordic Optical Telescope (NOT; resolution 47 000, wavelength range 3623–7270 Å); 14 spectra at the Dominion Astrophysical Observatory (DAO; resolution 10 000 and wavelength range 4300–4556 Å); 16 spectra with the 2-m telescope at the Thüringer Landessternwarte (TLS) in Tautenburg (resolution 66 000, wavelength range 4700–7400 Å); and 5 spectra at the McDonald Observatory (McD) using the 2.7m telescope and the Robert G. Tull coudé spectrograph (resolution 60 000 and wavelength range 3700–10000 Å).

From the light curve, we know that HD 181068 A contributes almost all the light of the triple system. We fitted theoretical template spectra from the library of (*S1*) to a NOT spectrum and determined the following parameters: $T_\mathrm{eff} = 5100 \pm 200\,\mathrm{K}$, $\log g = 2.8 \pm 0.3$, $[M/H] = -0.6 \pm 0.3$ and $v\ \sin i = 14\,\mathrm{km\ s^{-1}}$. These values are all in good agreement with those of (*S2*). As a check, we can also use Strömgren photometry from (*S3*): $V = 7.091$, $b - y = 0.586$,

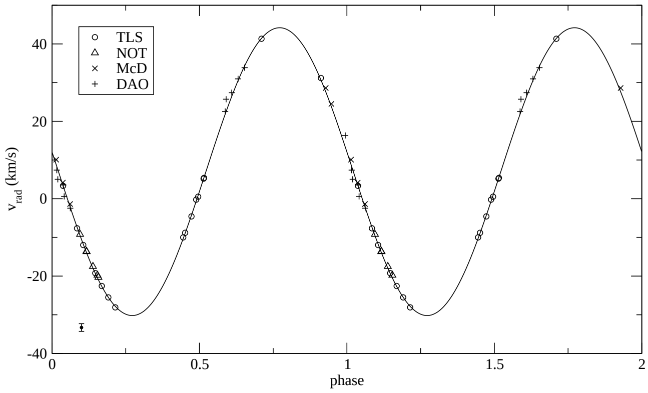

Figure 3: Measured RVs versus the orbital phase (45.5 d) for the TLS (circles), NOT (triangles), McDonald (McD, crosses), and DAO (pluses) observations. The vertical bar in the lower left corner shows the size of the representative ± 1 km s^{-1} uncertainty.

$m_1 = 0.296$ and $c_1 = 0.399$. From these quantities and the calibration of (*S4*), we find: $T_{\rm eff} = 5200\,$K, $E(b-y) = 0.087$ and $(b-y)_0 = 0.499$. These numbers are consistent with the spectroscpic results and confirm that HD 181068 A is a G-type giant star.

Radial velocities were determined using the IRAF task FXCOR. The template for all but the TLS spectra was selected from (*S1*), with closely matching parameters, which ensured that no systematic errors were introduced by spectral template mismatch. The 16 TLS RVs have been determined in a first step from cross-correlation with the mean spectrum that was iteratively built from the single spectra by shift-and-add according to the measured RVs. This mean spectrum was then analysed using the program LLMODELS (*S5*) to compute a grid of stellar atmosphere models and the program SYNTHV (*S6*) to compute the synthetic spectra. We found $T_{\rm eff} = 5300 \pm 100K$, $\log g = 2.8 \pm 0.2$ dex, $[M/H] = -0.2 \pm 0.1$, and $v\ \sin i = 14 \pm 1$ km s^{-1}. Finally, we used the best-fit synthetic spectrum as a template for cross-correlation to determine the RVs of the TLS spectra on an absolute scale. Depending on the instrument and the spectra, the velocities are accurate to $\pm$0.5–2 km s^{-1}.

The orbital solution (see Fig. 3) was calculated by the method of differential corrections. We omitted the DAO RVs because they show a much larger scatter around the calculated orbital curve, despite being observed during the same epoch as the other instruments. The eccentricity from the fit was $e = 0.022 \pm 0.023$, which is consistent with zero, and in the final solution we set $e = 0$ because its inclusion as a free parameter did not improve the solution. We also fixed the orbital period to that obtained from the light-curve fitting (a free search gives a slightly different value but does not improve the quality of the solution). Table 1 lists the derived orbital elements. In the corresponding solution, we corrected the NOT RVs by -0.35 km s^{-1} and the McDonald RVs by -0.70 km s^{-1} with respect to the TLS RVs. This correction minimized the rms to 214 m s^{-1}, and its influence on the derived elements was only marginal.

A.3 Interferometry

Inteferometric observations were performed on three nights in 2010 July, using two different baselines (156.3 m and 248.1 m) of the CHARA array. We obtained 7 calibrated scans. All the observations were performed outside the long-period eclipses, meaning that some flux from the BC pair was present during all observations. With an eclipse depth of only 1%, however, the companions are much fainter than the primary and are negligible in our analysis. The raw data were reduced using the PAVO data analysis pipeline. Six stars were observed to calibrate the visibilities (single stars within 5° on the sky) and with predicted diameters at least a factor of two smaller than HD 181068 A.

A.4 HD 181068 B and C

We have constrained the parameters of the BC pair by modelling the short-period eclipses in the Kepler band. First, we removed the long-term variations of the uneclipsed brightness in the light curve by fitting spline function polynomials and removing data obtained during the long-period eclipses. In this way, the light from star A was assigned to be the ‘third light’ component. A preliminary fit was performed, allowing a few outlying data points to be identified and removed. A detailed fit was then made, using numerical integration to account for the 30-minute long duration of individual observations. Uncertainties were calculated using 1000 Monte Carlo

Table 2: Photometric parameters obtained for the short-period eclipses, denoted using standard symbols in the study of eclipsing binary systems.

Parameter	Best fit	Uncertainty
$P_{\rm BC}$ (d)	0.9056770	0.0000026
$T_{\rm MinI}$ (BJD)	2455051.23625	0.00020
i_1 (degrees)	87.7	1.6
$(R_{\rm B}+R_{\rm C})/a_{\rm BC}$	0.3288	0.0044
$R_{\rm C}/R_{\rm B}$	1.01	0.13
$R_{\rm B}/a_{\rm BC}$	0.164	0.011
$R_{\rm C}/a_{\rm BC}$	0.165	0.011
$L_{\rm A}$	0.9929	0.0006
$L_{\rm B}$	0.0044	0.0007
$L_{\rm C}$	0.0027	0.0004

simulations (*S7*). The resulting photometric parameters are given in Table 2.

We found the ratio of the radii of the B and C components to be poorly constrained at present, partly due to the low sampling rate of the *Kepler* long-cadence data. The A component contributes 99.29% of the system light in the *Kepler* passband, and the BC pair contribute 0.44% and 0.27%, respectively. Taking the V-band absolute magnitude of HD 181068 A to be $M_V(\mathrm{A}) = -0.3$ and assuming that our results for the *Kepler* passband are representative of the V-band, we find $M_V(\mathrm{B}) = 5.6$ and $M_V(\mathrm{C}) = 6.1$. Such absolute magnitudes indicate spectral types of G8 V and K1 V for stars B and C, respectively.

B The variability of HD 181068 A

The light curve (see Fig. 1) shows slow variations with the same timescale as the long-period eclipses, which presumably arise from ellipsoidal distortion of the primary. We also see faster oscillations with the same timescale as the orbital period of the BC pair. These are visible both outside and during the eclipses and are less obvious to interpret.

To investigate this further, Fig. 4*a* shows the amplitude spectrum of the light curve after first removing observations made during both the long- and short-period eclipses. This procedure left a light curve with a duty cycle slightly above 60%, and it introduced alias peaks in the amplitude spectrum at the multiples of the orbital frequencies. The strongest peak in the spectrum occurs at $25\ \mu$Hz, corresponding to half the orbital period of the BC binary. As mentioned, this periodicity is clearly visible in the light curve.

To search for other frequencies we used iterative sine-wave fitting (prewhitening) with Period04 (*S8*). In five steps, we measured and identified the following frequencies:

- $f_1 = 24.54\,\mu\mathrm{Hz} = 2(f_{\mathrm{short}} - 2f_{\mathrm{long}})$
- $f_2 = 25.05\,\mu\mathrm{Hz} = 2(f_{\mathrm{short}} - f_{\mathrm{long}})$
- $f_3 = 25.56\,\mu\mathrm{Hz} = 2f_{\mathrm{short}}$
- $f_4 = 51.12\,\mu\mathrm{Hz} = 4f_{\mathrm{short}}$
- $f_5 = 12.83\,\mu\mathrm{Hz} = f_{\mathrm{short}} + 1/T_{\mathrm{obs}}$

Here, $f_{\mathrm{short}} = 1/P_{\mathrm{BC}}$, $f_{\mathrm{long}} = 1/P_{\text{A-BC}}$, and T_{obs} is the time span of observations. Fig. 4*b* shows the amplitude spectrum after the slow variations and these five strongest peaks have been subtracted from the time series.

Could the observed signal in HD 181068 arise from solar-like oscillations? According to the parameters derived from the interferometry and spectroscopy, HD 181068 A is a He-core burning red giant star located in the secondary clump. Studies of similar red giants with *Kepler* (*S9*, *S10*) show that essentially all stars in this region of the H-R diagram exhibit solar-like oscillations that appear as a broad power excess centred at a characteristic frequency ν_{max} and composed of a regularly spaced series of peaks. Using the scaling relation of S11 with the derived values of mass, radius and effective temperature, we estimate $\nu_{\mathrm{max}} = 85 \pm 21\ \mu$Hz for HD 181068 A. .

For comparison, Fig. 4*c* shows the amplitude spectrum of a typical red giant with $\nu_{\mathrm{max}} \sim 80\ \mu$Hz (KIC 12507577). To make the comparison exact, we calculated this amplitude spectrum using exactly the same portions of the light curve that were used for HD 181068 in Fig. 4*a*. In

KIC 12507577 we see the regular peaks that characterize solar-like oscillations, whereas in HD 181068 A we see just a few peaks whose removal (Fig. 4*b*) leaves only a slowly rising power distribution. The observed signal in HD 181068 A is clearly not compatible with solar-like oscillations. Indeed, the solar-like oscillations that we would expect to see in a giant of this type seem to have been suppressed.

The frequency content of the light curve suggests an intimate link to the orbital frequencies in the triple system. We are led to suggest that we are seeing tidally-induced oscillations that are driven by the orbital motion of the BC pair. Tidally-induced oscillations have previously been reported in a few binary systems (*S12, S13, S14*), but here the situation is different because the period of the oscillations does not correspond to the orbit of the A component, but rather to that of the BC pair. A fuller discussion of this possibility is postponed to a future publication.

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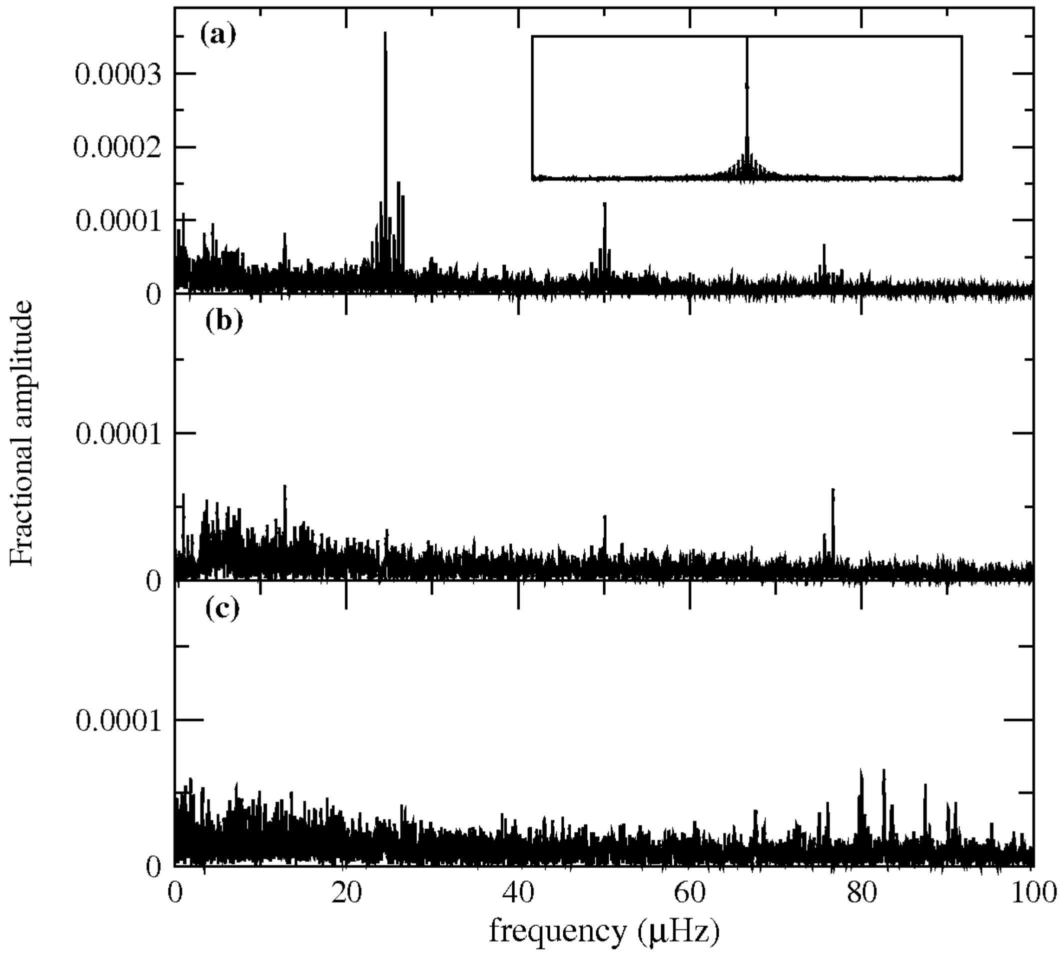

Figure 4: The amplitude spectrum of HD 181068 A and the change after five prewhitening steps (panels a and b). The inset shows the spectral window function. Panel c: the spectrum of a typical red clump star (KIC 12507577), for which $\nu_{\mathrm{max}} \sim 80\ \mu$Hz. The vertical scale in panels b and c is increased by a factor of two.

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