KIC 10449976: discovery of an extreme helium subdwarf in the Kepler field

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ABSTRACT
Optical spectroscopy of the blue star KIC 10449976 shows that it is an extremely helium-rich subdwarf with effective temperature $T_{\text{eff}} = 40000 \pm 300$ K and surface gravity $\log g = 5.3 \pm 0.1$. Radial-velocity measurements over a 5 d time-scale show an upper variability limit of $\approx 50 \pm 20$ km s$^{-1}$. Kepler photometry of KIC 10449976 in both long and short cadence modes shows evidence for a periodic modulation on a time-scale of $\approx 3.9$ d. We have examined the possibility that this modulation is not astrophysical but conclude that it is most likely real. We discuss whether the modulation could be caused by a low-mass companion, by stellar pulsations or by spots. The identification of any one of these as cause has important consequences for understanding the origin of helium-rich subdwarfs.

Key words: stars: abundances – stars: chemically peculiar – stars: individual: KIC 10449976 – subdwarfs.

1 INTRODUCTION
Prior to the launch of NASA’s Kepler satellite, an extensive programme to identify bright dwarf G and K stars with minimal stellar activity was carried out, which resulted in the Kepler Input Catalog (KIC; Brown et al. 2011). Although a small number of photometric variability surveys were carried out pre-launch (Hartman et al. 2004; Pugliski et al. 2009; Feldmeier et al. 2011), they were either not especially deep, did not have a wide sky coverage or did not have a cadence shorter than a few minutes. To identify short-period variable sources which would be interesting to be observed using Kepler in short cadence (SC) mode, the RApid Temporal Survey-Kepler project commenced in the summer of 2011 (Brooks et al., in preparation). As part of a follow-up programme to determine the nature of sources which showed short-period variability and/or were blue, we obtained medium-resolution spectroscopy of a sample of objects using the Isaac Newton Telescope (INT) in La Palma. One of the targets, KIC 10449976 ($\alpha = 18^h47^m14.1^s, \delta = +47^\circ 41'46''.9$, J2000, $g = 14.49$), was observed because it was clearly blue ($g - r = -0.5$, KIC). The optical spectrum was notable because it showed a number of strong lines due to neutral helium and weak or absent hydrogen Balmer lines.

Early-type stars with absorption spectra dominated by neutral or ionized helium are extremely rare and fall into one of (roughly) two classes. Slightly better known are the extreme helium stars: low-gravity stars of spectral types B and A (Jeffery 2008). A few low-gravity helium stars of spectral type O are also known. These are almost certainly related to the cooler R Coronae Borealis variables, and are currently considered to be the product of the merger of a helium white dwarf with a carbon–oxygen white dwarf (Jeffery, Karakas & Saio 2011). Extremely helium-rich hot subdwarfs are found (naturally) at higher gravities with early-B- or late-O-type spectra (Naslim et al. 2010). Again, the merger of two helium white dwarfs is the strongest contender for their production (Zhang & Jeffery 2012).

Many of the extreme helium stars are small-amplitude flux variables, most probably caused by opacity-driven radial or non-radial pulsations (Saio & Jeffery 1988). However, probably due to extreme non-adiabaticity, the pulsations are relatively irregular and have proved difficult to study systematically with ground-based
The helium-rich subdwarfs may be subdivided into an extremely helium-rich class ($n_{\text{He}} > 80$ per cent) and an intermediate helium-rich class ($10 < n_{\text{He}} < 80$ per cent) (Naslim et al. 2012). None of the extremely helium-rich groups are known to pulsate or to be members of a binary system, with two exceptions. V652 Her (Jeffery, Woolf & Pollacco 2001) and BX Cir (Woolf et al. 2001) are somewhat cooler than the remainder and lie in the Z-bump instability strip, and pulsate with a period of 0.1 d (Landolt 1975; Kilkenny & Koen 1995). Amongst the intermediate group, there is at least one binary: CPD−20°1123 (Naslim et al. 2012) and one pulsator: LS IV−14°116 (Ahmad & Jeffery 2005). The latter shows an extraordinary surface chemistry, with 4 dex overabundances of zincium, strontium and yttrium and a 3 dex overabundance of germanium. This chemistry is probably produced by radiation-dominated diffusion (Naslim et al. 2011).

Ostensen et al. (2010) describe a systematic survey for compact pulsators and identify three He-sdOB stars in the Kepler field: (Galex) J19034+3841, (SDSS) J19352+4555 and J19380+4649. Surface properties have not been published. None pulsates, but J19352+4555 shows irregular low-frequency light variations (Ostensen et al. 2010). The maximum light variations in the other two He-sdOBs at low frequencies (100–500 \mu Hz) are 117 parts per million (J19034+3481) and 29 parts per million (J19380+4649). An intermediate helium-rich blue-horizontal-branch star in the Kepler field (KIC 1718290) has been identified as a non-radial g-mode pulsator (Ostensen et al. 2011).

No previously known extreme helium stars or helium-rich subdwarf lies in the Kepler field, so the discovery of new members of either group lying within the field offers an opportunity to explore the questions of duplicity (a close companion makes the white-dwarf merger model difficult to maintain) and pulsation stability.

In this paper we present an analysis of the spectrum of KIC 10449976 to measure its effective temperature, surface gravity and surface composition. We analyse six quarters of Kepler photometry, which appear to show some evidence of small-amplitude flux variability. We present a series of radial-velocity measurements obtained to establish whether it could be a binary. We discuss possible explanations for the variability.

## 2 OPTICAL SPECTROSCOPY

KIC 10449976 was initially observed using the Intermediate Dispersion Spectrograph (IDS) on the INT on the night of 2012 June 28 (see Table 1 for details). The spectra were reduced using standard procedures with the wavelength calibration being made using a CuNe+CuAr arc taken shortly after the object spectrum was taken. A flux standard was observed so that the spectra could be flux calibrated. The individual spectra were combined to give a mean spectrum which shows all the characteristics of a helium-rich star (Fig. 1), including all expected He I lines, He II 4686 Å and the He II Pickering series. With He II 4541 Å slightly weaker than He II 4649, a surface gravity of log $g \approx 5.3 \pm 0.3$ and a helium-to-hydrogen ratio of $n_{\text{He}}/n_{\text{H}} > 10$. This places KIC 10449976 firmly amongst the extremely helium-rich subdwarfs, rather than the extreme helium stars.

We obtained a further series of observations in 2012 August and September (Table 1) to search for radial-velocity variations. We took arc lamps for calibration before and after the target; this provides an estimate of the uncertainties in the wavelength calibration. Radial velocities were obtained by the method of cross-correlation. The four INT spectra from the nights of 2012 August 31, September 1 and 2 were co-added to form a template. All of the spectra, including the template, were rectified, continuum-subtracted and converted to log wavelength. The cross-correlation function (ccf) between each individual spectrum and the template was computed and converted to $\delta V_1$ and $\delta V_2$. The uncertainties in each individual radial-velocity measurement were determined from the cross-correlation analysis.

### Table 1. Summary of spectroscopic observations of KIC 10449976.

| Telescope | Date       | # spectra | Exp. time (s) | Grism | Slit width (arcsec) | FWHM (Å) | Velocity (km s$^{-1}$) | $\delta V_1$ | $\delta V_2$ |
|-----------|------------|-----------|---------------|-------|--------------------|----------|------------------------|----------------|----------------|
| INT       | 2012-06-28 | 2         | 180           | R400V | 1.0                | 4.0      | –2.9                   | 8.1            | 13.3           |
| WHT       | 2012-08-10 | 3*        | 900           | R600R | 1.2                | 16.1     | 10.5                   | 12.1           |                |
| INT       | 2012-08-28 | 1         | 600           | R300V | 0.5                | 5.4      | –46.3                  | 9.9            | 14.5           |
| INT       | 2012-08-29 | 2         | 600           | R300V | 0.5                | 3.9      | –24.0                  | 6.4            | 12.3           |
| INT       | 2012-08-31 | 2         | 600           | R632V | 0.5                | 2.6      | –13.6                  | 21.5           | 22.3           |
| INT       | 2012-09-01 | 1         | 600           | R632V | 0.5                | 1.7      | –37.0                  | 18.9           | 20.9           |
| INT       | 2012-09-02 | 1         | 600           | R632V | 0.5                | 1.7      | –49.9                  | 21.8           | 25.1           |

*Formal error in the cross-correlation measurement. Total error including wavelength calibration and template velocity.

*All three spectra were combined for the velocity measurement.
to velocity units. The position of the peak of the ccf was measured by fitting a Gaussian. The radial velocity of the template was obtained by cross-correlation with the best-fitting theoretical spectrum at rest wavelength (see below). Heliocentric corrections were applied. The results are shown in Fig. 2 and Table 1. The measurements are consistent with there being no variation in the radial velocity; they are also consistent with a variation of up to 50 ± 20 km s⁻¹ over an interval of days.

Spectra were also obtained using the William Herschel Telescope (WHT) on 2012 August 10 (see Table 1 for details) using the Intermediate dispersion Spectrograph and Imaging System. Spectra were reduced in a similar manner to those obtained using the INT, and the radial velocity measured in the same way.

3 ATMOSPHERIC PARAMETERS

Best-fitting atmospheric parameters for KIC 10449976 were established by interpolation in a grid of synthetic spectra computed from a grid of line-blanketed model atmospheres computed in local thermodynamic, hydrostatic and radiative equilibrium. The grid covers a wide range in effective temperature $T_{\text{eff}}$, surface gravity $g$ and helium abundance $n_{\text{He}}$ for a number of distributions of elements heavier than helium, including solar, 1/10 solar and other custom-designed mixtures (Behara & Jeffery 2006). For the optical spectrum of KIC 10449976 we sought solutions in the range $32 000 < T_{\text{eff}} < 50 000$ K, $4.5 < \log g < 6.0$ and $0.90 < n_{\text{He}} < 0.999$ over the wavelength interval 3750–5100 Å (n is the fractional abundance by number). Solutions were obtained by $\chi^2$-minimization to the continuum-rectified and normalized spectrum using the optimization code SFIT (Jeffery et al. 2001). With no indicators for microturbulent velocity at the spectral resolutions used we assumed a value 5 km s⁻¹. The procedure was applied first to the June INT spectrum; this established KIC 10449976 to be, indeed, a helium-rich subdwarf. It was subsequently applied to the higher resolution higher signal WHT spectrum. A 1/10 solar mixture was chosen in preference to a solar mixture on the basis of the strengths of visible metal lines. Virtually identical results were obtained in both cases. The atmospheric parameters are shown in Table 2.

The fit to the WHT spectrum (Fig. 3) showed that a number of significant strong absorption lines could be resolved, in addition to those due to hydrogen and helium. Notably, these included N in lines around 4095 and 4640 Å, Ne II 4290 Å, and an absence of absorption around C III 4650 Å. In addition to optimizing by interpolation within a grid of precomputed spectra, SFIT has an option to optimize abundances of individual species with respect to an observed spectrum for a given model atmosphere. Taking a model with $T_{\text{eff}} = 40 000$ K, $\log g = 5.5$ and $n_{\text{He}} = 0.95$, abundances for carbon, nitrogen, silicon and neon were estimated (Table 2). If silicon can be taken as a proxy for metallicity, the star is relatively metal poor, as indicated by the optimization described above. No carbon lines are identified, providing an upper abundance limit. The surface is strongly CNO processed (low carbon, high nitrogen), with some evidence of $\alpha$-capture on to $^{13}$N to form an excess of $^{22}$Ne. Significant lines at $\lambda\lambda 3932, 4284$ and 4883 Å are not reproduced in the model fit. $\lambda 3932$ Å is likely to be due to Ca II and of interstellar origin. $\lambda 4284$ Å may be due to S III but the stronger S III 4254 Å is not seen. $\lambda 4883$ Å could be due to Fe III but, again, other Fe III lines are not positively identified. It is our practice not to accept line identifications without such confirmation.

4 Kepler PHOTOMETRY

The detector onboard Kepler is a shutterless photometer using 6 s integrations and a 0.5 s readout. There are two modes of observation: long cadence (LC), where 270 integrations are summed for an effective 28.4 min exposure, and short cadence (SC), where 9 integrations are summed for an effective 58.4 s exposure. Gaps in the Kepler data streams result from, for example, 90° spacecraft rolls every 3 months (called quarters) and monthly data downloads using the high-gain antenna.

Kepler data are available in the form of FITS files which are distributed by the Mikulski Archive for Space Telescope (MAST). For LC data each file contains one observing quarter worth of data whereas for SC data one file is created per month. After the raw data are corrected for bias, shutterless readout smear and sky background, time series are extracted using simple aperture photometry (SAP). The start and end times of each quarter of Kepler data used in this study are shown in Table 3. SC observations were made in Q3. (We note that when SC data are obtained, LC data are also produced.)

In any wide-angle photometric variability survey, variations in temperature and, in ground-based surveys, seeing and transparency can cause correlated variations in the resulting photometric data. The data from Kepler are no exception. We show in Table 3 the mean and standard deviation of the counts of KIC 10449976 for each quarter of LC data; the latter are shown both before and after removal of the long-term trend caused by differential velocity aberration. To

Table 2. Atmospheric parameters of KIC 10449976.

| Parameter  | Value          | Units   |
|------------|----------------|---------|
| $T_{\text{eff}}$ | 40.0          | ±0.3 Kk |
| $\log g$   | 5.33          | ±0.10 (cgs) |
| $v_{\text{turb}}$ | 5             | km s⁻¹ |
| $n_{\text{H}}$ | 0.06          | ±0.02   |
| $n_{\text{He}}$ | 0.94          | ±0.02   |
| $n_{\text{C}}$ | $<4.6 \times 10^{-6}$ |         |
| $n_{\text{N}}$ | $2.9 \times 10^{-4}$ | ±1.2 $\times 10^{-4}$ |
| $n_{\text{Si}}$ | $9.6 \times 10^{-6}$ | ±6.7 $\times 10^{-6}$ |
| $n_{\text{Ne}}$ | $9.6 \times 10^{-4}$ | ±5.7 $\times 10^{-4}$ |

Δ http://archive.stsci.edu/kepler
Figure 3. The normalized WHT optical spectrum of KIC 10449976 fitted with the model described in Section 3 optimized for abundances of C, N, Si and Ne, together with line identifications.

Table 3. The log of \textit{Kepler} observations of KIC 10449976. The start and end MJD and UT dates are the mid-point of the first and final cadence of the LC time series for each quarter, respectively. The next column shows the mean count rate of KIC 10449976, while the last two columns show the standard deviation of points determined from LC observations where the effects of long-term trends are (I) included and (II) removed.

| Quarter | Start MJD | Start UT  | End MJD  | End UT  | Mean \( \text{counts} \ s^{-1} \) | Std dev (I) \( \text{counts} \ s^{-1} \) | Std dev (II) \( \text{counts} \ s^{-1} \) |
|---------|-----------|-----------|----------|---------|--------------------------|--------------------------|--------------------------|
| Q3 (SC) | 550.92722 | 2009 Sept. 18 17:05 | 551.81996 | 2009 Dec. 17 00:09 | 12.963 | 111.9 | 7.1 |
| Q5 (LC) | 552.75991 | 2010 March 20 23:32 | 553.70660 | 2010 June 23 16:05 | 12.055 | 190.6 | 8.5 |
| Q6 (LC) | 553.71947 | 2010 June 24 22:29 | 554.61793 | 2010 Sept. 22 19:17 | 11.940 | 96.8 | 6.3 |
| Q7 (LC) | 554.62672 | 2010 Sept. 23 15:53 | 555.52049 | 2010 Dec. 22 01:25 | 13.379 | 107.8 | 6.8 |
| Q8 (LC) | 555.67864 | 2011 Jan. 06 20:30 | 556.34846 | 2011 March 14 20:32 | 11.078 | 12.5 | 6.3 |
| Q9 (LC) | 556.41016 | 2011 March 21 00:09 | 557.38423 | 2011 June 26 10:25 | 11.958 | 171.4 | 5.5 |

remove systematic trends in the data (Barclay et al. 2012, Kinemuchi et al. 2012) we used the \textit{Kepler} tool KEPCOTREND\(^2\) which utilizes the correlated global variability of sources in each quarter (this was done for both SC and LC data). We then filtered the data so that only points which were flagged \texttt{SAP\_QUALITY = 0} were kept (this removed data points which were potentially compromised by events such as solar flares). We then normalized the data so that the mean count rate in each quarter was unity.

We initially searched for periods shorter than 0.5 d using SC data obtained in quarter 3 using the Lomb–Scargle periodogram in the package VARTOOLS (Hartman et al. 2008). There were three peaks in the power spectra which were detected at a significance greater than 3\(\sigma\) – 220.7, 196.2 and 252.2 s. All of these periods are almost certainly due to spurious signals (\textit{Kepler} Data Characteristics handbook). There is therefore no evidence for a light modulation of KIC 10449976 with a period of less than 12 h.

We then searched for periodic signals in the range 0.5–10 d using the same procedure as before. We show the resulting power spectra in Fig. 4 for each individual quarter and also the power spectrum from the combined data from quarters 3–9. We list the period and false alarm probability of peaks which are significant at a level greater than 3\(\sigma\) in Table 4. We detect significant peaks in the power spectra at periods between 3 and 4 d, the most significant being at 3.9 d. We folded the data from the different quarters on the most prominent peaks. We show the folded light curves from quarters 3 and 8 in Fig. 5. The quarter 3 data folded on the 3.9 d period result in a peak-to-peak modulation of less than 0.02 per cent; for quarter 8 this becomes 0.04 per cent (we note that the specific CCD on which KIC 10449976 was recorded was different in quarters 3 and 8). These amplitudes are similar to that found in the sdB star BD +42\,3250 which has a period of 1.09 d (Østensen et al. 2010).

The \textit{Kepler} CCDs have a pixel scale of 3.98 arcsec \(\times\) 3.98 arcsec. We therefore analysed the data on the pixel level and find that the variability originates from a star which is on the same pixel as the flux centre of KIC 10449976. Using our images taken using the Wide Field Camera on the INT, we find that the nearest star (\(g = 19.7\)) to KIC 10449976 is 25.8 arcsec distant. We therefore do not believe that the variability which we detect is due to blending.

To investigate further the possibility of an instrumental origin, we obtained data from the \textit{Kepler} archive of 16 stars which are within 10 arcmin and 0.5 mag and observed in the same quarters as KIC 10449976. Four of these stars (KIC 1044981, 10450110,...

\(^2\)http://keplergo.arc.nasa.gov/PyKE.shtml
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10515199 and 10580086) showed a clear modulation on a dominant period of 6–10 d in their Kepler light curve. None showed a modulation on a period close to 3.9 d. Several more stars showed evidence for less significant periods close to 8 d. The remaining stars showed no evidence for a period seen in every quarter or at a period of 3.9 d. Although we cannot rule out the possibility that the periods noted in Table 4 are due to an instrumental effect, there are good grounds to conclude that they are astrophysical in origin.

5 DISCUSSION

With \( n_{He} > 0.90 \) and its position on the \( g\sim T_{eff} \) diagram (Fig. 6), KIC 10449976 is well established as an extreme helium-rich subdwarf (EHe-sd), and amongst the hottest of its class. Zhang & Jeffery (2012) argue that the hottest EHe-sds are also the most
massive, having $M > 0.70 \, M_\odot$, although they also point out that, unlike KIC 10449976, these are also predominantly carbon rich.

A number of questions are posed by the *Kepler* photometry. Foremost is whether the variation is genuine and intrinsic to the star. We have examined whether the variation could be due to an instrumental effect and, while we cannot rule out this possibility, we believe it more likely to be astrophysical in origin and proceed on this basis. The second question concerns the cause of the variability. The folded light curve points to a sinusoidal variation which could originate either in pulsation, in reflection from a companion or from the rotation of a non-spherical star (ellipsoidal variation). All three present difficulties.

Many hot subdwarfs do pulsate (Kilkenny et al. 1997; Green et al. 2003; Jeffery 2005). For a star with the dimensions of KIC 10449976, the fundamental radial mode would have a period of the order of 200 s. Even high-order gravity modes are unlikely to have periods in excess of a few hours. The pulsating helium-rich subdwarf LS IV-14 116 shows up to six g-mode oscillations with periods between 1953 and 5084 s (Ahmad & Jeffery 2005; Green et al. 2011; Jeffery 2011). Pulsation periods more than 20 times this value would only be expected in stars where the radius is some 10 times larger, or the gravity was 1 dex lower, a possibility that is ruled out by the spectroscopy.

Hot subdwarfs in HW Vir-type close binary systems show light variations due to reflection from an M-dwarf companion (e.g. Lee et al. 2009). Reflection-effect light variations should be strictly periodic over the time interval covered by the *Kepler* observations. Supposing that observational errors account for the quarterly variation in an apparent period, a simple test calculation involving only assumed masses for the helium star and its companion (e.g. $M_1 = 0.7 \, M_\odot$ and $M_2 = 0.38 \, M_\odot$), the albedo of the companion (e.g. $A = 0.9$), the inclination (e.g. $i = 45^\circ$) and the measured period (3.9 d) can be used to estimate the amplitude of the orbital variation in both total light (0.016 per cent) and projected helium-star radial velocity ($50 \, \text{km s}^{-1}$). In order to simulate a system in which the projected velocity amplitude is less than $50 \, \text{km s}^{-1}$ and the light amplitude is greater than 0.02 per cent, we require a high albedo ($A > 0.8$), a low inclination ($i < 50^\circ$) and, with $M_1 \geq 0.7 \, M_\odot$ for example, $0.20 \leq M_2 / M_\odot \leq 0.33$. These are not unreasonable values; the principal remaining argument against a reflection-effect origin is the lack of stability in the apparent period.

Following a similar argument and making reasonable assumptions about masses and radii, the maximum contribution of any ellipsoidal contribution to the total light can be computed (Morris 1985) and is found to be negligible ($<10^{-4}$ per cent) in this case.

A further and quite realistic possibility is the existence of spots on the stellar photosphere, as found in certain helium-rich B stars on the main sequence; e.g. $\sigma$ Ori E (Greenstein & Wallerstein 1958). Such spots are usually associated with the poles of strong magnetic fields and surface chemical inhomogeneity; surface brightness variations are tied to the rotation of the star’s magnetic axis (Townsend, Owocki & Groote 2005). Moreover, spots are relatively short lived and have been observed to give a *Kepler* signature similar to that reported here (Balona, in preparation). In this case, the constraint of constant period and amplitude would be less strong, but is still not negligible, since the spots are locked in position by the magnetic field.

Finally, intrinsic variability in an unresolved and fainter close companion cannot be ruled out, although any mechanism

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**Figure 6.** The surface gravity–effective temperature diagram for hot subdwarfs showing the positions of normal sdB and sdO stars (open symbols), intermediate helium-rich subdwarfs (filled circles), extreme helium-rich subdwarfs (filled diamonds) and KIC 10449976 (filled square). Approximate positions of the zero-age hydrogen main sequence (ZAMS), the helium main sequence (HeMS) and the zero-age extended horizontal branch (ZAHB) are also indicated. Data for individual stars are taken from Naslim et al. (2010, 2011), Stroeer et al. (2007), Ahmad & Jeffery (2003) and Edelmann et al. (2003).
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Barclay T., Still M., Jenkins J. M., Howell S. B., Roettenbacher R. M., 2012, MNRAS, 422, 1219
Behara N. T., Jeffery C. S., 2006, A&A, 451, 643
Brown T. M., Latham D. W., Everett M. E., Esquerdo G. A., 2011, AJ, 142, 112
Drilling J. S., Hill P. W., 1986, in Hunger K., Schönborner D., Kameswara Rao N., eds, Astrophysics and Space Science Library, Vol. 128, Proc. IAU Colloq. 87, Hydrogen Deficient Stars and Related Objects. Reidel, Dordrecht, p. 499
Drilling J. S., Jeffery C. S., Moehler S., Heber U., Napiwotzki R., 2013, A&A, in press
Edelmann H., Heber U., Hagen H.-J., Lemeke M., Dreizler S., Napiwotzki R., Engels D., 2003, A&A, 400, 939
Feldmeier J. J. et al., 2011, AJ, 142, 2
Greenstein J. L., Wallerstein G., 1958, ApJ, 127, 237
Green E. M. et al., 2003, ApJ, 583, L31
Green E. M. et al., 2011, ApJ, 734, 59
Grevesse N., Sauval A. J., 1998, Space Sci. Rev., 85, 161
Hartman J. D., Bakos G., Stanek K. Z., Noyes R. W., 2004, AJ, 128, 1761
Hartman J. D., Gaudi B. S., Holman M. J., McLeod B. A., Stanek K. Z., Barranco J. A., Pinsonneault M. H., Kalirai J. S., 2008, ApJ, 675, 1254
Jeffery C. S., 2005, JA&A, 26, 261
Jeffery C. S., 2008, in Werner A., Rauch T., eds, ASP Conf. Ser. Vol. 391, Hydrogen-Deficient Stars. Astron. Soc. Pac., San Francisco, p. 3
Jeffery C. S., 2011, Inf. Bull. Var. Stars, 5964, 1
Jeffery C. S., Woolf V. M., Pollacco D. L., 2001, A&A, 376, 497
Jeffery C. S., Karakas A. I., Saio H., 2012, MNRAS, 414, 3599
Kilkenny D., Koen C., 1995, MNRAS, 275, 327
Kilkenny D., Koen C., O’Donoghue D., Stobie R. S., 1997, MNRAS, 285, 640
Kilkenny D., Lawson W. A., Marang F., Roberts G., van Wyk F., 1999, MNRAS, 305, 103
Kincemichi K., Barclay T., Fanelli M., Pepper J., Still M., Howell S. B., 2012, PASP, 124, 963
Landolt A. U., 1975, ApJ, 196, 789
Lee J. W., Kim S.-L., Kim C.-H., Koch R. H., Lee C.-U., Kim H.-I., Park J.-H., 2009, AJ, 137, 3181
Morris S. L., 1985, ApJ, 295, 143
Naslim N., Jeffery C. S., Ahmad A., Behara N. T., Şahin T., 2010, MNRAS, 409, 582
Naslim N., Jeffery C. S., Behara N. T., Hibbert A., 2011, MNRAS, 412, 363
Naslim N., Geier S., Jeffery C. S., Behara N. T., Woolf V. M., Classen L., 2012, MNRAS, 423, 3031
Østensen R. H. et al., 2010, MNRAS, 409, 1470
Østensen R. H. et al., 2012, ApJ, 753, L17
Pigulski A., Pojmanski G., Pilecki B., Szczygiel D. M., 2009, Acta Astron., 59, 33
Saio H., Jeffery C. S., 1988, ApJ, 328, 714
Stroer A., Heber U., Lisker T., Napiwotzki R., Dreizler S., Christlieb N., Reiners D., 2007, A&A, 462, 269
Townsend R. H. D., Owocci S. P., Groote D., 2005, ApJ, 610, L81
Woolf V. M., Aznar Cuadrado R., Pandey G., Jeffery C. S., 2001, A&A, 371, 638
Zhang X., Jeffery C. S., 2012, MNRAS, 419, 452

REFERENCES

Ahmad A., Jeffery C. S., 2003, A&A, 402, 335
Ahmad A., Jeffery C. S., 2005, A&A, 437, L51

responsible would be subject to a similar commentary to that outlined above. There is no evidence for such a companion in the spectrum, but either an M dwarf or a white dwarf would not be detected spectroscopically.

It is emphasized that all of the above interpretations for the apparent light modulation in KIC 10449976 are, at this stage, conjecture. The discovery of an extremely helium-rich subdwarf in a close binary would have profound consequences for a proposed white-dwarf merger origin (Zhang & Jeffery 2012). Further observations are necessary to investigate the long-term stability of the period and to increase the precision of the radial-velocity measurements.

6 CONCLUSION

KIC 10449976 is a blue star in the KIC which shows small-amplitude light variations with a period of approximately 3.9 d. Our spectroscopic classification identified it as a helium-rich subdwarf, a conclusion which is confirmed by higher resolution spectroscopy. The latter shows the helium abundance to be greater than 90 per cent by numbers, and that the star is silicon poor, nitrogen rich and neon rich. Carbon was not detected. On the basis of effective temperature and surface gravity, KIC 10449976 should have $M > 0.7\,M_\odot$, but the high nitrogen/carbon ratio implies $M < 0.7\,M_\odot$, suggesting a mass close to this boundary. An upper limit of $50 \pm 20\,\text{km s}^{-1}$ in radial-velocity amplitude places constraints on any putative binary companion. The absence of long-term stability in the light variation is also a challenge for a binary interpretation, although the amplitudes could be consistent with a reflection-effect solution. The period is far too long to be due to pulsation. Starspots remain a plausible interpretation. Further high-quality radial-velocity and photometric studies will be required to establish the authenticity and cause of the light variations.

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