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Spectroscopy of the variable K-dwarf UNSW-V-760: is it a pre-main-sequence pulsator?

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ABSTRACT

The star UNSW-V-760 is a known variable, showing both flares and two non-sinusoidal periodicities. Availability of high signal-to-noise spectra reported in this paper has enabled a revision of the spectral type of this star to K3 IV-Vk. The star is a very rapid rotator ($v \sin i \sim 140\,\mathrm{km\,s^{-1}}$), and the abundance of lithium appears to be enhanced. 48 radial velocity measurements were obtained over the course of three successive nights. These may show the same two frequencies detected photometrically, but there is some uncertainty in the interpretation. Application of pulsation theory suggests that photometric frequencies could be explained as low ℓ pulsation modes, but an excitation mechanism remains to be found.

Key words: stars: individual: UNSW-V-760 – stars: pre-main-sequence – stars: variables: T Tauri, Herbig Ae/Be.

1 INTRODUCTION

Variability in UNSW-V-760 (hereafter abbreviated as V760) was discovered by Christiansen et al. (2008), who reported a single 4.8 h periodicity. The authors noted that the position of the star on the sky was close to a *ROSAT* X-ray detection (2RXP J075145.0-681416). Further observations of the star were made by Koen (2011), who found that V760 was varying with two non-sinusoidal periodicities of 0.28 and 0.20 d (6.6 and 4.8 h). The spectroscopic type was established to be K1 Vke–K3 Vke. Yet more photometry by Koen (2012) showed that although both periodicities were persistently present, their amplitudes varied considerably from epoch to epoch. The latter conclusion was confirmed by an examination of ‘All Sky Automated Survey’ measurements of V760 obtained over the course of several years. Flares were also discovered.

The most plausible explanation for the presence of two frequencies appears to be pulsation. However, the actual periods are typical of RR Lyrae or δ Scuti stars (spectral types F or A), whereas pulsations appear not to have been detected in any K-dwarf star. This paper attempts to shed further light on the nature of V760 by reporting the results of a spectroscopic analysis.

2 OBSERVATIONS

The star was observed with the CCD spectrograph mounted on the South African Astronomical Observatory (SAAO) 1.9 m telescope during the three nights 2011 December 24–26. Measurements were made with grating 4, at 1 Å resolution over the range 4000–4870 Å. The seeing was generally very poor (in excess of 3 arcsec), necessitating the use of a rather wide slit. An exposure time of 900 s was used throughout. Each target observation was followed by an arc exposure. Reductions, which included wavelength and flux calibrations, used standard IRAF tasks.

V760 was also observed with the Robert Stobie Spectrograph (Burgh et al. 2003; Kobulnicky et al. 2003) on the Southern African Large Telescope (SALT; Buckley, Swart & Meiring 2006; O’Donoghue et al. 2006) on 2011 November 05 and December 19. The spectrograph configuration used for both observations was the PG2300 grating used at Littrow configuration with a grating angle of 48°.5 with a 0.6 arcsec long slit. This setup gave a spectral coverage of 6060–6885 Å with a central resolution of $R = 106\,00$. This provides a spectral resolution element of 0.64 Å and a dispersion of 0.268 Å pixel^{-1}.

The 2011 November 05 observations were taken under cloudy conditions, and the transparency showed significant variation between each exposure. Three exposures of 600 s were taken of the star during these observations. To wavelength calibrate the observations, spectra of a ThAr arc lamp were taken before and after the observations. On 2011 December 19 , four exposures were taken of V760 with spectra of an Ar lamp taken before, after the first two exposures, and after the final two exposures. The first three exposures had 500 s exposure time, but the last exposure only had 263 s due to aborting the observation early due to rising humidity. Conditions were clear, but with poor seeing (>4 arcsec).

A summary of all the spectroscopic observations is given in Table 1.

The SALT data were reduced using the PYSALT software package (Crawford et al. 2010). This encompassed basic CCD reductions including gain, overscan, crosstalk and cosmic ray cleaning.

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Table 1. A log of the spectroscopic observations. Resolutions of the SALT and 1.9 m spectra were 0.64 and 1 Å, respectively. The last SALT exposure was cut short at 263 s due to deteriorating weather conditions.

Telescope	Start date (HJD 245 0000+)	Run length (h)	Exposures	Exp. time (s)	Min. S/N	Mean S/N	Mean r.v. error ($km\,s^{-1}$)
SALT	5871.5600	0.8	3	600	46	78	
	5915.4815	0.6	4	500, 263	58	83	
1.9 m	5920.3968	4.2	15	900	12.2	16.4	7.1
	5921.3856	4.9	17	900	19.9	31.2	5.9
	5922.3753	4.7	16	900	14.3	19.3	6.7

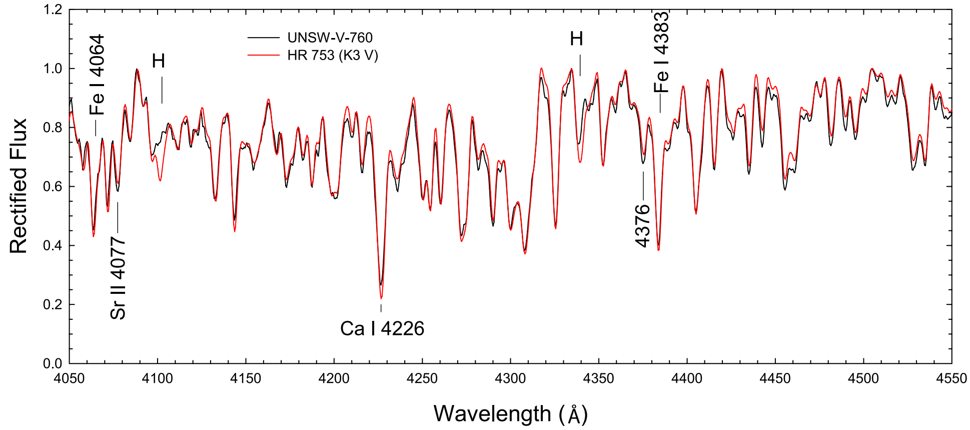

Figure 1. Comparison between the 1 Å resolution spectrum of V760 and the MK classification standard HR 753 (K3 V). The features marked were used in obtaining the spectral type (see the text).

Wavelength calibration and flux calibration were also performed using the PYSALT package. A spectrophotometric standard was only observed during the November observations, and the calibration curve was applied to observations from both dates. The variable nature of the SALT pupil along with the changing conditions during the observations prevents absolute calibration of the flux from the source.

3 SPECTROSCOPIC ANALYSIS

3.1 Improved spectral classification

Koen (2011) established that the spectral type of V760 is in the range K1 Vke–K3 Vke. The new SAAO 1.9 m telescope spectra enable a more precise classification. Spectral classification was carried out using the 1.8 Å resolution standards obtained at the Dark Sky Observatory (DSO) available on the Nearby Stars website.[1] Those standards were rotationally broadened by 140 $km\,s^{-1}$ to match the rotation of the program star (see below). Fig. 1 compares the 1 Å resolution spectrum of V760 with the MK DSO K3 V standard HR 753, rotationally broadened to $v \sin i = 140$ $km\,s^{-1}$. The two spectra are remarkably similar except for the features marked in that figure. It is evident that both Hδ and Hγ (and Hβ in 2 Å resolution spectra) are partially filled in with emission. Ca II K&H also show emission. Most other lines, including the *G* band, have strengths in good agreement with the MK standard, except the MK luminosity criteria involving Sr II 4077 (in ratio with nearby Fe I lines such as Fe I 4064) and the λ4376 blend (in ratio with the blend at λ4383, primarily due to Fe I). The Sr II 4077/Fe I 4064 ratio and the λ4376/λ4383 ratio both suggest a luminosity slightly above the main sequence. This is reinforced by the relative weakness of Ca I 4226 in V760; Ca I 4226 shows a marked negative luminosity sensitivity in K-type stars. We classify the star as K3 IV-Vk, where the 'k' indicates emission in Ca II K&H (Gray et al. 2003).

3.2 Modelling

Fig. 2 shows the SALT $R = 10\,600$ spectrum plotted with two synthetic spectra ($T_{\rm eff} = 4600$ K, $\log g = 4.0$ and 4.5, $\xi_t = 1.0$ $km\,s^{-1}$, [*M*/H] = 0.00) based on ATLAS12 models (Castelli 2005) and computed with the spectral synthesis program SPECTRUM (v. 2.76; Gray & Corbally 1994). The synthetic spectra were rotationally broadened to $v \sin i = 140$ $km\,s^{-1}$ to match the observed spectrum. The high rotational velocity of V760 obviously makes a traditional spectral analysis difficult. However, the gravity-sensitive lines in that spectral region (marked in the upper panel of the figure) are in much better agreement with the $\log g = 4.0$ model than with the $\log g = 4.5$ model. With that choice of gravity, the abundances of the alpha and iron-peak elements appear nearly solar. So, we adopt for the physical parameters of V760 the following values: $T_{\rm eff} = 4600 \pm 100$ K, $\log g = 4.00 \pm 0.25$, $\xi_t = 1.0$ $km\,s^{-1}$ (adopted) and [*M*/H] = 0.00 (adopted).

However, closer examination of the vicinity of the Li I 6708 Å resonance line suggests that lithium may be overabundant. Fig. 3 shows a comparison of the SALT spectrum with three synthetic spectra computed with the abundance of lithium increased by 0.50, 1.00 and 1.50 dex above solar. These synthetic spectra were computed using oscillator strengths from the NIST compilation, and isotope shifts and hyperfine structure from Andersen, Gustafsson & Lambert (1984). Oscillator strengths for spectral lines in the vicinity

[1] http://stellar.phys.appstate.edu

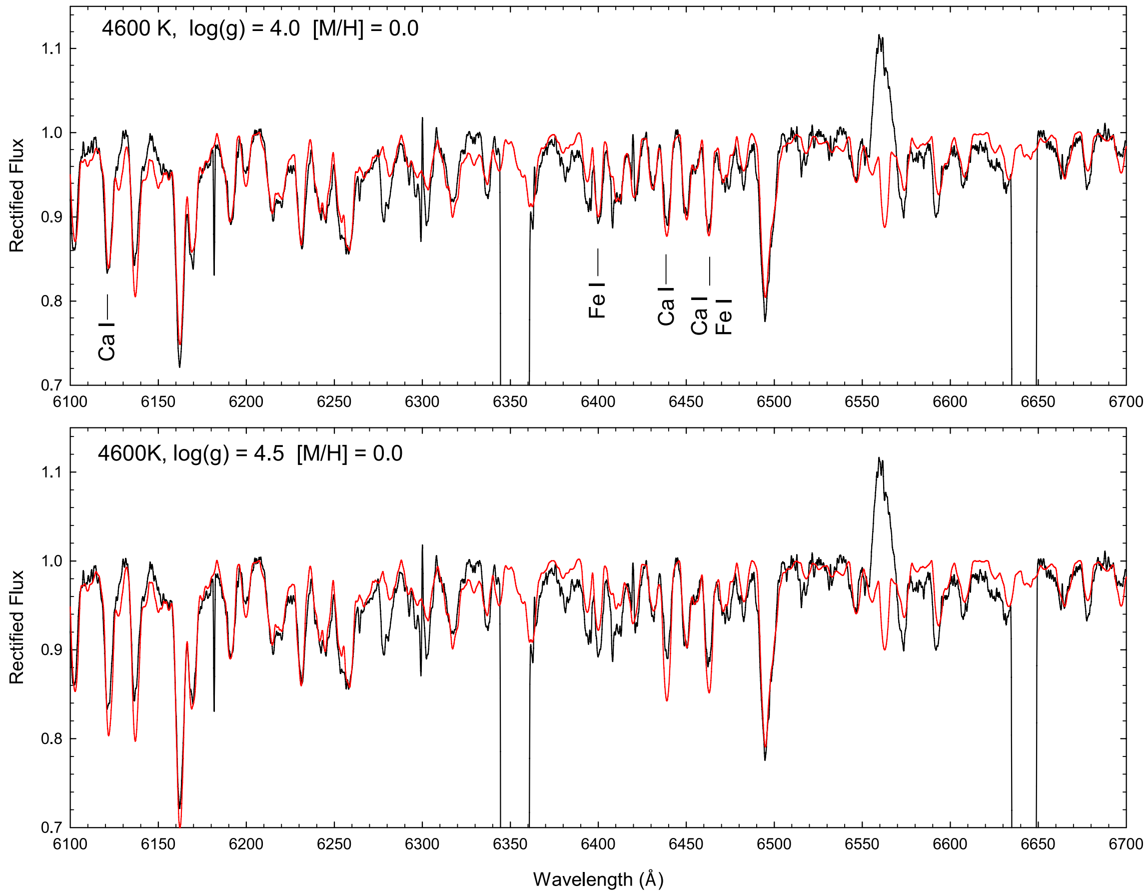

Figure 2. The SALT $R = 10\,600$ spectrum in comparison with two synthetic spectra with different gravities. Note that in the $\log(g) = 4.0$ spectrum (top), the gravity-sensitive spectral lines (marked) are in better agreement with the observed spectrum.

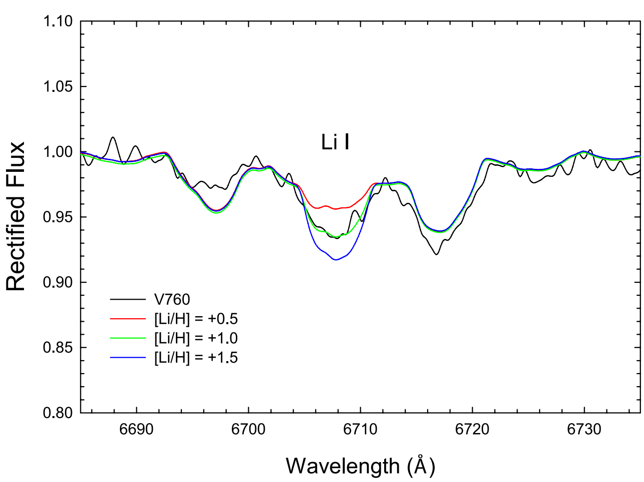

Figure 3. The region near the Li I λ6708 resonance line. The superimposed synthetic spectra are computed with [Li/H] = 0.5, 1.0 and 1.5 dex.

of the Li I feature, if not available from the NIST compilation, were determined from synthetic spectrum fits with the solar spectrum. From this comparison, we conclude that $[\mathrm{Li/H}] = 1.0 \pm 0.2$.

The rapid rotation, the relatively low gravity (for a dwarf), the emission in the Balmer lines and Ca II K&H, and the high lithium abundance all suggest that V760 is a pre-main-sequence K-type star.

3.3 Radial velocities

Radial velocities were measured from the 1 Å dispersion 1.9 m spectra, using the IRAF FXCOR cross-correlation procedure. Template spectra were 360 s exposures of the K2 V radial velocity standard LTT 1804. The 48 velocity measurements are plotted in Fig. 4. The mean velocity on HJD 245 5921 is markedly different from that on the other two nights; there are no overt calibration problems, so the origin of this feature is currently unknown.

An amplitude spectrum of the velocities is presented in the top panel of Fig. 5. The frequency corresponding to maximum amplitude is $f_0 = 0.49 \pm 0.05\,\mathrm{d}^{-1}$; a least-squares fit gives the refined amplitude of $10.6 \pm 5.6\,\mathrm{km\,s}^{-1}$. This ~2 d periodicity is evidently due to the substantial difference in the mean nightly radial velocities referred to above.

If f_0 is pre-whitened from the radial velocities (i.e. the fitted sinusoid is subtracted), the amplitude spectrum in the second panel of Fig. 5 results. The maximum is at $f_1 = 4.07 \pm 0.03\,\mathrm{d}^{-1}$ and the least-squares amplitude is $10.6 \pm 1.3\,\mathrm{km\,s}^{-1}$. If both f_0 and f_1 are pre-whitened, the residual radial velocity amplitude spectrum in the third panel of Fig. 5 is obtained: the maximal amplitude is $4.1\,\mathrm{km\,s}^{-1}$, at $f_2 = 4.55 \pm 0.06\,\mathrm{d}^{-1}$. Pre-whitening by all three frequencies leaves the featureless spectrum in the bottom panel, with a maximum amplitude below $3\,\mathrm{km\,s}^{-1}$.

At first glance there is little connection between the two frequencies f_1 and f_2 extracted from the radial velocities and the two most prominent frequencies in the photometry of the star, namely $F_1 = 5.053$ and $F_2 = 3.628\,\mathrm{d}^{-1}$ (Koen 2011, 2012). However,

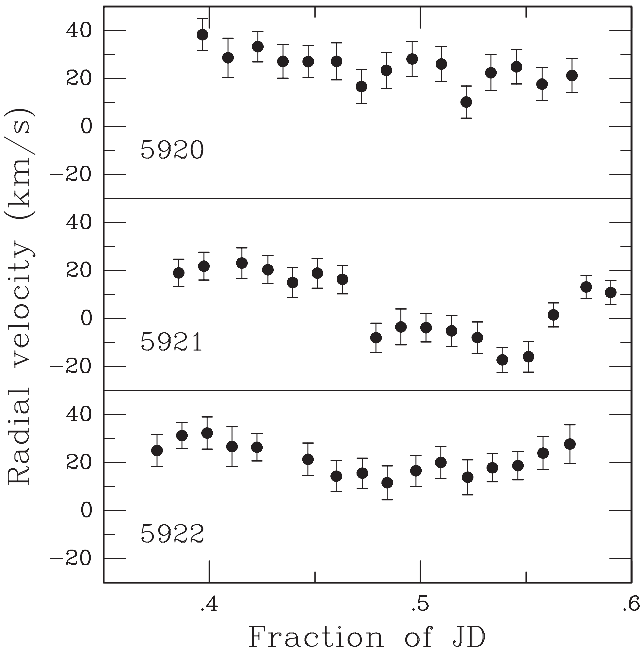

Figure 4. Radial velocity measurements of V760. Each panel is labelled with the last four digits of the Julian Day of observation.

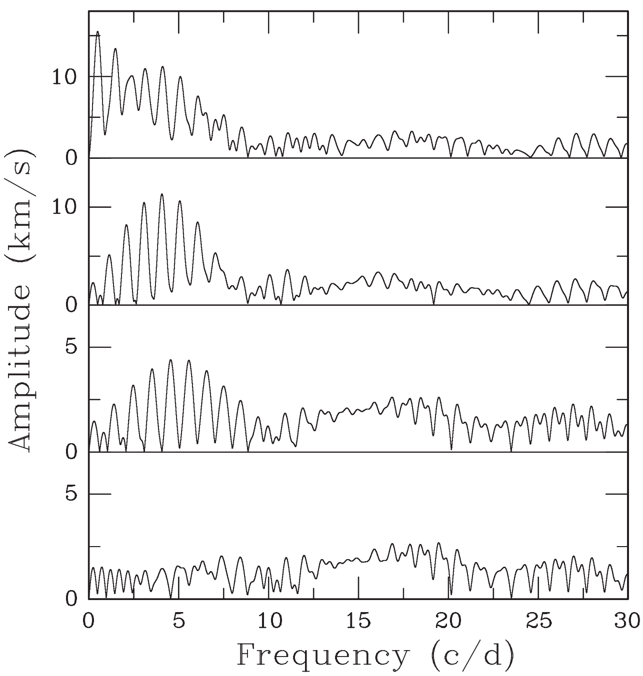

Figure 5. The top panel shows an amplitude spectrum of the radial velocities. The middle panel is the residual spectrum, after subtracting a sinusoid with frequency determined by position of the highest peak in the top panel. The remaining two panels show residual spectra after pre-whitening by a further one and two frequencies, respectively.

examination of Fig. 5 shows complexes of 1 d^{-1} alias peaks, meaning that a frequency f which is present in the data gives rise to several peaks at frequencies separated by about 1 d^{-1}. Furthermore, due to the presence of measurement errors, the true frequency will not necessarily correspond to the highest peak. The fact that $f_1 \approx F_1 - 1$ (difference about 1σ) and $f_2 \approx F_2 + 1$ (difference about 1.4σ) suggests that the photometric frequencies are also present in the radial velocities.

Table 2. Photometric data for V760. Optical and NIR photometry is from Koen (2011) and Skrutskie et al. (2006), respectively.

Band	B	V	R_C	I_C	J_s	H_s	K_s
Magnitude	13.33	12.27	11.65	11.07	10.208	9.652	9.491

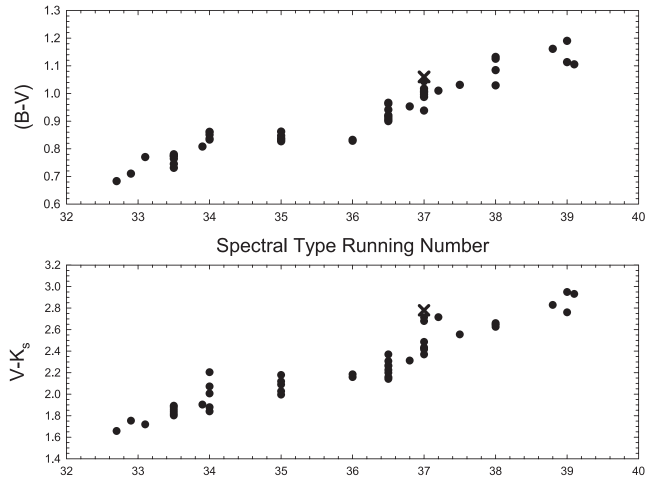

Figure 6. Photometric colour indices $B - V$ and $V - K_s$ plotted against spectral-type running number for normal dwarfs (filled circles). V760 is indicated as an 'X' in both diagrams. The position in both plots suggests that V760 is slightly reddened.

4 THE STELLAR ENERGY DISTRIBUTION AND THE EFFECTIVE TEMPERATURE

Table 2 lists the photometric data for V760.

If we assume that the colours of V760 are similar to those of K3 main-sequence stars, we can estimate the reddening. Fig. 6 shows the relationship between the spectral type (from Gray et al. 2003 and using their spectral type running number), and $B - V$ and $V - K_s$ for normal late G- and early K-type stars. Both comparisons suggest that V760 is slightly reddened; we deduce $E(B - V) \sim 0.06$ from the $B - V$ data and $E(B - V) \sim 0.11$ from the $V - K_s$ data. We take $E(B - V) \sim 0.08$ as our best estimate. This yields the following dereddened magnitudes: $B_0 = 13.00$, $V_0 = 12.02$, $R_0 = 11.45$, $I_0 = 10.96$, $J_0 = 10.14$, $H_0 = 9.61$ and $K_0 = 9.46$. Fig. 7 shows the stellar energy distribution (SED) based on those dereddened magnitudes along with two flux models ($T_{\rm eff} = 4500$ K and 4600 K, $\log g = 4.0$, $\xi_t = 1.0\,{\rm km\,s^{-1}}$ and $[M/H] = 0.00$; Castelli 2005) normalized to the flux in the Johnson V band. The 4600 K model is clearly the better match to the dereddened SED; varying $\log g$ by ± 0.5 dex makes little difference to the fit. We estimate the effective temperature to be 4600 ± 100 K. This is consistent with $\bar{T}_{\rm eff} = 4750 \pm 115$ K for K3 dwarfs (Gray et al. 2003).

5 THE AGE OF V760

V760 has the attributes of a weak-lined T Tauri star (WTTS; e.g. Stahler & Palla 2004): X-ray emission, flares, moderate Calcium emission and strong lithium absorption (Koen 2011, 2012, and above). Inspection of Fig. 2 shows that Hα emission can be added to this list. It is noteworthy that there are no overt signs of

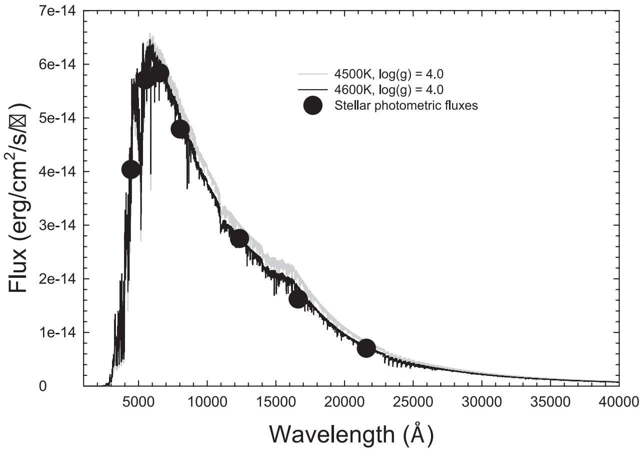

Figure 7. Photometric fluxes for V760 (filled circles) plotted against two models, one with $T_{\rm eff}$ = 4500 K and the other with $T_{\rm eff}$ = 4600 K. Both models are computed with $\log(g) = 4.0$ and are normalized to the stellar flux in the Johnson *V* band.

accretion-related variability, in the form of apparently random brightness changes as seen in classical T Tauri stars. Magnetic activity is most likely of chromospheric origin, rather than associated with any interaction between the star and circumstellar material (Aarnio, Stassun & Matt 2010). Unfortunately, V760 is not part of any known young cluster or association; hence, no direct age estimate is available.

As seen above, the optical and near-infrared (NIR) colours of the star are consistent with a spectral type of K3. Recently, mid-infrared (MIR) photometry of the star, obtained by the *WISE* mission (Wright et al. 2010) has become available, which can be examined for further clues as to the age of the object. In order to place the photometry of V760 in context, in Fig. 8 its colour indices are compared to those of 198 main-sequence stars of similar spectral types. The optical photometry of the stars was taken from Koen et al. (2010); since these stars are of particular interest, having large parallaxes, accurate spectral types are available for them. The MIR wavelengths are 3.4, 4.6, 12 and 22 µm, for filters $W1$–$W4$.

Examination of the colour–colour plots shows that the $(W1 - W2)$ colour is similar to the bulk of K0–K3 stars; the $(W1 - W3)$ colour is amongst the reddest and the $(W1 - W4)$ index redder by about half a magnitude than the mean for stars of similar spectral type (though the error bar is rather large). The suggestion is of a small infrared excess, which increases with wavelength over the range covered by *WISE*. The implication is that any remaining circumstellar material is cold, and hence, is at some distance from the star – consistent with its other attributes marking it as a WTTS. In fact, V760 resembles the WTTS V819 Tau, in which the infrared (IR) excess redwards of about 12 µm is ascribed to an outer annular disc at some distance from the young (age $\sim$ 2 Myr) K7 star (Furlan et al. 2009).

The lack of an NIR excess implies that V760 no longer has a relatively hot inner disc, and hence, is probably older than 1–3 Myr (e.g. Williams & Cieza 2011). It has been observed that once the inner disc has disappeared from around a young star, the rest of the primordial disc soon follows suit. Even debris discs older than 10 Myr are rare. The pattern of the MIR excess suggests that V760 may have a 'transition' disc (Williams & Cieza 2011). The IR photometric evidence therefore suggests an age in the range 1–10 Myr. Measurement of its far-infrared (FIR) brightness would be interesting: on the basis of the MIR excess, a relatively large FIR excess may be expected.

6 PULSATION THEORY

Models of pre-main-sequence evolution that pass through the spectroscopic error box have masses that are somewhat higher than solar and ages of a few million years (for solar metallicity). Models with masses between about 1.15 and 1.52 solar masses pass (mostly) vertically through the error box during the last stages of Hyashi contraction. The radii of these models range from 2.3 to 0.62 solar radii.

Within that range, we examined stellar models for radial and low-degree non-radial modes to see if any had frequencies corresponding to the photometric frequencies F_1 and F_2 (corresponding to periods of 0.276 and 0.198 d). The radial fundamental mode period is about 0.241 d for models with $\log g = 3.75$, 0.156 d for models with $\log g = 4.00$ and 0.089 d for $\log g = 4.25$. Non-radial p modes generally have periods shorter than the radial fundamental, while g modes show periods that are longer.

On the low-gravity side of the box, the presence of non-radial g modes can be eliminated as those modes had frequencies significantly lower than those observed in V760. The low frequencies make sense on two fronts. First, these lower gravity models have mostly convective interiors, with at most a small radiative core. Thus, any g modes (which are evanescent in convection zones) are concentrated in the deep core and have periods that are much longer than the radial fundamental. At and below $\log g = 4.00$, we found that only $\ell = 1$ and 2 p modes with $n = 0$ could match the observed periods and, significantly, no models could match both F_1 and F_2 together. The g-mode spectrum for models with $\log g \approx 4.0$ had periods in excess of 0.4 d for $l \leq 2$.

Models on the high-gravity side have larger radiative cores and higher densities, leading to the g-mode spectrum shifting to higher frequencies that reach the range of the observed values of F_1 and F_2. If the true gravity is slightly above our current estimate, then the non-radial mode spectrum in the models is rich enough to accommodate both F_1 and F_2 with low-degree g modes. For example, a 1.2 $M_\odot$ model with $\log g = 4.176$, $T_{\rm eff} = 4575$ (and an age of 6.1×10^6 yr) has an $\ell = 1$, $n = 1$ g mode with a period of 0.272 d and an $\ell = 2$, $n = 1$ g mode with a period of 0.203 d. This is not intended to be a precise fit, but is tantalizingly close to the observed periodicities (both in value and in the ratio F_1/F_2); note also the correspondence of the age with the age of V760 deduced in Section 5.

Regardless of whether these are p modes or g modes, we note that there is no clear mechanism that can destabilize these models to non-radial pulsation. Their masses are significantly higher than the masses considered by Palla & Baraffe (2005), who looked at models destabilized by deuterium burning on the pre-main sequence, while Baran et al. (2011) and Rodríguez-López, MacDonald & Moya (2012) found that ^{3}He burning could destabilize somewhat more massive models (but with $M < 0.5\,M_\odot$). All of these studies attributed the instability to the ϵ mechanism as the destabilizing source. If the above mode identification is correct, then models of these stars should be subject to non-adiabatic non-radial analysis to see whether higher mass pre-main-sequence stars may be pulsationally unstable, with driving perhaps by nuclear burning.

It is instructive to also consider the possibility that the two frequencies are rotationally split components of a single mode. The frequency difference $F_1 - F_2 = 1.425\,{\rm d}^{-1}$ corresponds to a period of 0.70 d, and with $v \sin i \approx 140\,{\rm km\,s^{-1}}$, $P_{\rm rot} \approx 0.36 R \sin i$ d, where the stellar radius R is in solar units. The gravity determination $\log g = 4$ implies $R = 1.66\sqrt{M}$ (with the mass of V760 in solar units); hence, $P_{\rm rot} \approx 0.60\sqrt{M} \sin i$ d. If the gravity were lower by

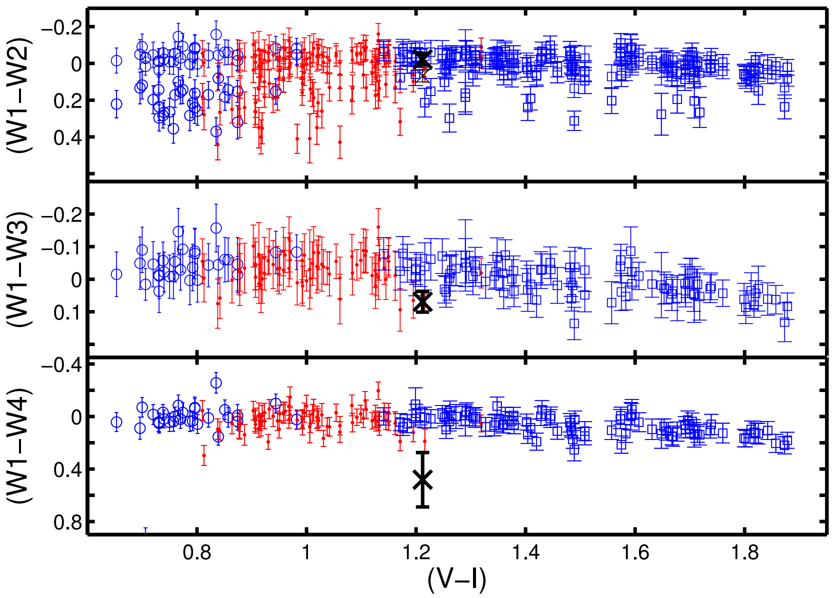

Figure 8. Optical–MIR colour–colour diagrams of 197 G–K stars, with the position of V760 marked by the cross. Formal errors in $(V - I)$ are not available, but values were obtained by precision photometry and errors will generally be well below 0.05 mag. The circles, dots and squares, respectively, indicate spectral types G5–G9, K0–K3 and K4–K7.

0.2 dex, then $P_{\rm rot} \approx 0.75\sqrt{M}\,\sin i$ d. A limit can be placed on $\sin i$ by the requirement $P_{\rm rot} > 0.12\sqrt{R^3/M} = P_{\rm breakup}$: this leads to $\sin i > 0.32\sqrt{R/M}$, giving $\sin i > 0.41M^{-1/4}$ ($\log g = 4$) or $\sin i > 0.46M^{-1/4}$ ($\log g = 3.8$). It follows that $0.25M^{1/4} < P_{\rm rot} < 0.60M^{1/2}$ ($\log g = 4.0$) or $0.35M^{1/4} < P_{\rm rot} < 0.75M^{1/2}$ ($\log g = 3.8$).

It may be concluded that F_1 and F_2 are probably not a frequency doublet, unless the gravity is somewhat lower than $\log g = 4.0$. Note though that (i) if azimuthal mode numbers differed by 2, rather than unity, then $P_{\rm rot} = 0.35$ d would be required, which could be accommodated at low inclinations and higher gravity and (ii) given the very rapid rotation, the usual linear theory of mode splitting most likely does not apply, and hence, frequency separations may depend on higher orders of $P_{\rm rot}$ (e.g. Dupree 2009).

7 CONCLUSIONS

The projected rotational velocity of V760 is quite similar to the $v \sin i = 132\,{\rm km\,s^{-1}}$ of the very active young K3 star BO Mic (‘Speedy Mic’; Barnes 2005), which is generally considered – as its nickname suggests – an ultrafast rotator. Aside from the rapid rotation, the enhanced lithium abundance and low gravity also point to youthfulness, and in fact they suggest that V760 may be a pre-main-sequence star.

Given the fact that V760 may be classified as a WTTS, it is reasonable to consider whether at least the longer of the two principal periods may be due to the presence of starspots. By implication, the rotation period of the star would then be $P = 0.28$ d. This eventuality was investigated in Koen (2011), where it was shown to be physically plausible. However, material in Koen (2012) demonstrated that the amplitudes of the two periodicities have evolved over time and that the changes are of similar nature for both periodicities. Although this could conceivably be explained by a physical model, it seems more plausible that the two periodicities are due to the same mechanism.

The radial velocity measurements are unfortunately not very accurate, but if these are taken at face value, it is difficult to escape the conclusion that V760 is oscillating. If confirmed, this would, as indicated in Section 6, pose a challenge for the theory of pulsational excitation in such cool stars.

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