Kepler photometry and optical spectroscopy of the ZZ Lep central star of the planetary nebula NGC 6826: rotational and wind variability

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ABSTRACT
We present three years of long-cadence and over one year of short-cadence photometry of the central star of the planetary nebula NGC 6826 obtained with the Kepler spacecraft, and temporally coinciding optical spectroscopy. The light curves are dominated by incoherent variability on time-scales of several hours, but contain a lower amplitude periodicity of 1.237 99 d. The temporal amplitude and shape changes of this signal are best explicable with a rotational modulation, and are not consistent with a binary interpretation. We argue that we do not observe stellar pulsations within the limitations of our data, and show that a binary central star with an orbital period less than seven days could only have escaped our detection in the case of low orbital inclination. Combining the photometric and spectroscopic evidence, we reason that the hourly variations are due to a variable stellar wind, and are global in nature. The physical cause of the wind variability of NGC 6826 and other ZZ Leporis stars is likely related to the mechanism responsible for wind variations in massive hot stars.

Key words: stars: early-type – stars: mass-loss – stars: rotation – stars: winds, outflows – planetary nebulae: individual: NGC 6826.

1 INTRODUCTION
The ZZ Leporis stars (Handler 2003) are a group of 14 variable Central Stars of Planetary Nebulae (CSPN), named after their prototype, the central star of IC 418. The cause of their variability remains to be fully understood. Photometric variations are present on two time-scales, of the order of days and of the order of hours. The most plausible mechanisms for the variability are pulsation or variations in the stellar mass-loss rate – or both. Binary-induced light variations can in most cases be excluded due to the observed light-curve shapes, the lack of a dominant periodicity and the lack of corresponding radial velocity changes.

The reason why pulsations may be expected to be present in ZZ Lep stars is evident from their positions in the HR diagram. They are located at the intersection of the post-asymptotic giant branch evolutionary track with the instability strip of the β Cephei pulsators. Gautschy (1993) showed that stellar models reminiscent of those stars have pulsationally unstable eigenmodes. Zalewski (1993) confirmed these results and showed that non-linear models in the temperature range of the ZZ Lep stars undergo quite complicated light and radial velocity variability on time-scales of several hours.

Wind variability, on the other hand, was proposed as a mechanism by Méndez, Verga & Kriner (1983). Ultraviolet (UV) spectroscopic studies (e.g. Prinja et al. 2012a) support this idea, because all ZZ Lep stars examined indeed showed clear evidence for variable winds. It is believed that the temporal behaviour of the winds of those CSPN is similar to that of massive OB stars (e.g. Kaper et al. 1997), is related to the stellar rotational period and may be rooted close to or at the stellar surface (e.g. Fullerton et al. 1997). Further strong support for this interpretation was recently presented by Prinja, Massa & Cantiello (2012b), who also argued that the wind variations of the central star of NGC 6543 could be causally connected to subsurface convection. The radiation pressure driven winds of hot stars, whether on the main sequence, as supergiants, Wolf-Rayet (WR) stars or CSPN, generally appear to exhibit extensive variability.
Whatever the cause of variability of the ZZ Lep stars, it will have implications for our astrophysical knowledge of the evolution of CSPN. They cross the HR diagram on time-scales of a few thousand years under the influence of mass-loss. If ZZ Lep stars pulsate, then measurements of oscillation period changes could closely constrain their evolutionary speed. Model calculations (e.g. Blöcker 1995) imply that this speed is highly mass dependent and therefore CSPN masses could be accurately determined. If the complicated light variations of ZZ Lep stars were due to multimode pulsations, then they might even be accessible to asteroseismology. Constraints on CSPN mass-loss behaviour, on the other hand, are also an asset for understanding their evolution, spectral characteristics and even for the shaping of the surrounding nebulae (e.g. Huarte-Espinosa et al. 2012).

One of the reasons why the variability mechanism of the ZZ Lep stars is so hard to pinpoint may be their complicated behaviour in combination with a lack of supporting data. Ground-based observations suffer from gaps due to daylight interruptions (even in case of multisite campaigns), whereas time on rather large telescopes or UV spacecraft required for spectroscopic monitoring is very limited. In addition, ZZ Lep stars are rather faint and surrounded by bright nebulae that complicate measurements and their interpretation. On the other hand, their variations occur on shorter time-scales than those of massive OB stars, which are of the order of 1 d, which can be an observational advantage.

One ZZ Lep star is located within the field of view of the Kepler mission (Koch et al. 2010). HD 186924 = KIC 12071221 ($V = 10.4$) is the central star of NGC 6826. Its photometric variability was first reported by Bond & Ciardullo (1990) and confirmed by Handler (1998) and Michalska (2000). The light range of the variations was several hundreds of a magnitude and the time-scale several hours, with no clear evidence for a periodicity. UV spectroscopy (Pinjia et al. 2012a) revealed the presence of recurring discrete absorption components (DACs) in the absorption troughs of wind-sensitive lines, and clear evidence for variable wind structure.

Jevtić et al. (2012) examined the first ~300 d of Kepler photometry of NGC 6826 by means of non-linear time-series analysis and phase-space reconstruction. They noted that the variability is coherent on time-scales of up to about 1.5 h, but becomes consistent with noise on time-scales exceeding 10 h. In this work, we analyse all presently available Kepler time-series photometry with more traditional techniques. Combining the photometric results with constraints from optical time-series spectroscopy, we discuss interpretations of the central star variability.

2 OBSERVATIONS

2.1 Photometry

Kepler photometry is provided in two modes, short cadence (SC) and long cadence (LC). In SC mode (Gilliland et al. 2010a), a data point is obtained every 58.8 s, whereas LC mode (Jenkins et al. 2010b) yields a data point every 29.4 min. The data are arranged in quarters of three months each, with the exception of the first two. Q0 consists of 10 days of commissioning data and Q1 of 1 month of science data. In between the quarters there are gaps of about 1 d for data download and spacecraft rotation.

1 In the remainder of this paper, we will use the name of the planetary nebula also as the designation of the central star.

NGC 6826 was and still is observed in LC mode from Q1 (starting on 2009 May 13) onwards. After examination of the first LC data, SC measurements were requested within the Kepler Asteroseismic Science Consortium (KASC; Gilliland et al. 2010b), which were obtained from Q7–Q11. Kepler photometry is available as ‘corrected’ and ‘uncorrected’ data. In this sense, ‘uncorrected’ means that the data have undergone standard reductions such as bias correction, flat-fielding and correction for the smear induced by the readout, whereas it has been tried to remove instrumental systematics in the ‘corrected’ data. We started from the ‘uncorrected’ data because a comparison showed that these will result in a lower noise level. Both the LC and SC light curves were first converted to magnitudes, visually inspected, and in case of the presence of simultaneous LC and SC data compared. Long-term drifts were assumed to be instrumental (for instance, arising from differential velocity aberration) and were filtered out with polynomials up to third order in one-month data chunks to account for the instrumental drifts properly whilst avoiding to ‘overfit’ the data. Hence, our analysis will not be sensitive to periodocities longer than about a week. Some very few outliers and bad sections of data, e.g. after pointing losses of the spacecraft whose times are documented were removed by hand. The final data set on which this paper is based comprises the Q1–Q12 LC data, which span 1051 d with a duty cycle of 93.3 per cent, and the SC data containing 468 d of observation with a 92.3 per cent duty cycle. We estimate a precision per data point of 0.17 mmag for the SC data; the apparent precision of the LC data however only is 0.43 mmag per point, implying that most of the ‘noise’ in these measurements is actually signal.

One difficulty with CSPN photometry is the presence of the nebula (that is not expected to vary on the time-scales investigated here). Its influence can be suppressed by choosing filters at low nebular continuum flux, and avoiding strong nebular emission lines. Another method is to mathematically subtract the nebular contribution or image subtraction. All these are not suitable for the Kepler data. We use the normal simple aperture photometry (SAP; Jenkins et al. 2010a) data. Those contain some nebular flux but are more robust than single-pixel data against artificial amplitude changes coming from, e.g. (quarterly) pointing changes of the spacecraft. As a consequence, the amplitudes of the light variations reported here are smaller than they intrinsically are. A comparison between SAP and pixel data implies an amplitude reduction to less than one quarter of the intrinsic value. A subset of the SC data is displayed in Fig. 1.

2.2 Spectroscopy

We obtained high-resolution spectroscopy cotemporal with a section of the Kepler photometry. The first data set stems from the 3.6 m Canada–France–Hawaii Telescope (CFHT) and the ESPaDOnS spectrograph (Donati 2003). Observations were taken on three consecutive nights from 2010 May 30/31 to June 1/2 (UT), totalling 14 spectra with individual exposure times of 1800 s, a wavelength coverage of 3700 to 10480 Å and a spectral resolution of 68 000 in ‘star + sky’ mode. On the 2.6 m Nordic Optical Telescope (NOT), the FIES (Frandsen & Lindberg 1999) spectrograph was used on the nights of 2010 June 6/7 to 7/8 (UT). 13 spectra were gathered with individual exposure times of 1800 s, in a wavelength range of 3640 to 7360 Å with $R = 46 000$.

The optical spectrum of NGC 6826 is characterized by variable lines including He II 4542 and 5411 Å in absorption. N v 4604 Å exhibits a weak P Cygni profile, and He II 4686 Å as well as C IV 5801 Å and 5812 Å are in strong (stellar) emission. Further visible are the Balmer absorption wings (the line cores are contaminated...
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3 ANALYSIS

3.1 Photometric frequencies

The light variations of NGC 6826 are quite complicated, predominantly occur on time-scales of a few hours and show no obvious periodicity (Fig. 1). We analysed the whole SC data set using the PERIOD04 software (Lenz & Breger 2005). This package applies single-frequency power spectrum analysis and simultaneous multi-frequency sine wave fitting. It also includes advanced options such as the calculation of optimal light-curve fits for multiperiodic signals including harmonic, combination and equally spaced frequencies.

The amplitude spectrum of the SC data is shown in Fig. 3. It is dominated by a single frequency, surrounded by apparent noise dropping continuously in amplitude towards higher frequencies. No coherent signal is present between 20 $\mu$Hz up to the Nyquist frequency of 8500 $\mu$Hz. However, the predominant light variations of NGC 6826 seem to occur on this time-scale (Fig. 1). Therefore, we computed time-Fourier spectra of all the SC data. One example of those is shown in Fig. 4, where we chose a 5 d sliding window and a time step of 0.5 d. Again, there is no evidence for coherent or recurrent signals. If there is power in the time-Fourier spectrum, it is short lived, as experiments with different temporal window sizes prove. In Fig. 4 it is also visible that the amplitudes and frequencies of the short-term variations are not stable in time, but are variable as well. As there is no more astrophysical information to be extracted from the time-Fourier analysis, we decided to continue our investigations with the simplest possible methods.

As an additional test, we divided the data set into two halves and computed their amplitude spectra. Their appearance is consistent with that expected from noise: their background levels are similar, but compared to the full data set by a factor of about $\sqrt{2}$ higher. This result is fully consistent with the earlier study by Jevtić et al. (2012), who showed that the variations are coherent over short time-scales only.

Turning to the apparently coherent signal, we can make use of the LC data and their longer time base. The amplitude spectrum of these measurements is examined in Fig. 5 (upper panel). As in Fig. 3, there is a dominant signal, but its amplitude is only about 60 per cent of that in the SC data. Pre-whitening this signal (lower panel of Fig. 5) does not remove all the power around this frequency; several peaks in a narrow interval ($\sim$0.06 $\mu$Hz) remain. In addition, a subharmonic of this signal is detected. Investigating the subharmonic with the same methodology shows a similar picture: it is not reproducible with a single coherent frequency, and residual peaks in an $\sim$0.09 $\mu$Hz interval remain after pre-whitening.

To assess the significance of the detection of the two signals, we adopted the widely used and reliable criterion by Breger et al. (1993). According to this criterion, any peak that exceeds a signal-to-noise (S/N) ratio of 4 in the amplitude spectrum is statistically significant. To compute the noise level in the presence of red noise and time-variable signals, we integrated over the amplitude spectrum between 0–8 and 20–28 $\mu$Hz and interpolated the results to the frequencies of interest. The dominant peak has S/N of 22.5, and its subharmonic is of 4.4. The next tallest peak in Fig. 5 has S/N = 3.6 and is therefore not significant.

These findings were traced to a change of the light-curve amplitude and shape over monthly time-scales. Phase diagrams of two month stretches of data, folded among the subharmonic frequency are displayed in Fig. 6. Averaging over such time intervals was found most suitable to suppress the incoherent short-term variations whilst sampling the temporal change of the periodic component of the light curve well and not affecting any scientific conclusions drawn. The light curve evolved from a double-wave shape to a single-wave variation, then almost dropped to zero amplitude and reached almost a 0.01 mag light range before dropping to an asymmetric double-wave variation again. The phases of light maximum and minimum varied only slightly over the three years of Kepler observations.

We adopted the subharmonic frequency 9.3491 $\pm$ 0.0001 $\mu$Hz, corresponding to a period of 1.23799 $\pm$ 0.00001 d, as the fundamental time-scale of the regular variability of NGC 6826. The reason for this choice is that in almost all variable stars in whose amplitude spectra a subharmonic is detected, it is the subharmonic by nebular emission), and N IV 6381 Å is a rare, but very weak, photospheric line. Fig. 2 shows examples of the hourly variability present in He II 4686 and 5411 Å in the CFHT and NOT spectra (see Section 3.2).
frequency that is related to the physical cause of the variability. Prominent examples are eclipsing binaries or ellipsoidal and rotational variables. The only exception from this rule is the period doubling phenomenon, a rare and complex resonance effect in some pulsating stars (e.g. see Szabó et al. 2010). Aside from that, adopting the tallest peak in the amplitude spectrum as the physical variability time-scale would leave the subharmonic unexplained.

3.2 Spectroscopic constraints

The 1.237 99 d Kepler photometric period is not detected in our spectroscopic data set. However, we caution that the temporal sampling of the spectra is not well suited to study a modulation on this time-scale. Nevertheless, phasing the optical spectra on 1.237 99 d does not provide a convincing result.

The stellar wind changes are extensive over short time-scales (cf. Fig. 2). The He ii 4686 emission equivalent width changes by $\sim$30 per cent over 24 h and by $\sim$10 per cent in just 30 min. Even in the latter rapid fluctuation the outflow is simultaneously altered over almost 300 km s$^{-1}$ blueward and redward of line centre, i.e. $\sim$0.25 of the wind terminal velocity in NGC 6826. We suggest that the stochastic nature of the dynamic spectra in Fig. 2 and the unstable frequencies evident in Fig. 4 point to the onset of clumping in the fast wind of the central star.

However, Fourier analysis of the optical spectroscopy suggests at least one potentially interesting modulation time-scale, as demonstrated in Fig. 7. We determined the central velocities of the C IV 5801 and 5812 Å emission lines by least-squares Gaussian fits. The internal error bars on the velocities are $<1$ km s$^{-1}$, and are ‘normalized’ to the central velocity measurements of the H$\beta$ nebular emission. The amplitude spectrum shows the strongest peak ($f_{\text{spec}}$)
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Figure 5. Amplitude spectra of the ~3 year LC Kepler photometry in the low-frequency domain. The dominant signal $f_1$ does not cleanly pre-whiten. In the lower panel, the subharmonic of $f_1$ also stands out.

at 7.821 d$^{-1}$, or $P_{\text{spec}} \sim 3.1$ h, with $S/N \approx 3.9$, just below our significance limit.

A phase diagram relative to this period (middle panel of Fig. 7) folds nicely as to be expected. In the uppermost panel of Fig. 7, the dynamic spectra of the He\textsc{ii} 5411 Å absorption feature have been folded on the 3.1 h period. The phase coverage is reasonable, and the image suggests some evidence for organized behaviour, such as the red-to-blue enhancement of the flux with respect to the mean. Unfortunately, this 3.1 h spectral line modulation has no convincing counterpart in the Kepler photometry, even when only analysing the parts of the light curve coinciding with the spectroscopic observations (Fig. 8). Although we cannot rule out a binary system based solely on the optical spectroscopy, we nevertheless do not detect a consistent periodicity in the radial velocities of different emission and absorption lines in NGC 6826. The spectroscopic time series does not fold well with a 0.619 or 1.238 d period, which is at least partly due to the sampling of the data. For the same reason a 3.1 h signal cannot be seen in Fig. 2.

3.3 Summary of observational results

The variability of NGC 6826 is characterized by the following.

(i) A basic 1.237 99 ± 0.000 01 d photometric modulation with a (mostly) double-wave variable light-curve shape and total light range not exceeding 0.01 mag.$^2$

(ii) Irregular variability with a light range of about 0.05 mag$^2$ and a time-scale of a few hours.

(iii) Optical stellar absorption and emission lines variable on time-scales of a few hours, a possible periodicity of 3.1 h, with evidence for organized behaviour.

(iv) DACs in wind-sensitive UV spectral lines, with at least two episodes occurring over ~8.5 h (Prinja et al. 2012a).

$^2$ As estimated in Section 2.1, the intrinsic light amplitude would be a factor of 4 or more higher due to the presence of the nebula.
There is no evidence for a spectroscopic counterpart of the photometric 1.237 99 d modulation, and no photometric evidence for the DAC re-occurrence time. Also, there is no correspondence between the optical radial velocity changes and the simultaneous Kepler photometry.

4 DISCUSSION

The lack of radial velocity variations with the same period as the only coherent signal in our data, its double-wave shape, and the temporal changes of this shape strongly argue against a pulsational or binary origin. The observed temporal behaviour of this signal is rather consistent with rotational modulation, i.e. we see areas of different surface brightness moving in and out of the line of sight. Prinja et al. (2012a) measured $v \sin i = 50 \pm 10$ km s$^{-1}$ for NGC 6826. With the temperature ($T_{\text{eff}} = 46 000$ K) and surface gravity ($\log g = 3.8$) of the central star spectroscopically determined by Kudritzki, Urbaneda & Puls (2006), these authors obtained $R = 1.8 R_\odot$. This gives a maximum rotation period of about 1.8 d. The period of 1.237 99 d inferred above is consistent with this value, and implies an inclination angle of the rotational axis of the order of 45°. This leaves sufficient horizon for brightness inhomogeneities to appear and disappear. The shape of this photometric modulation and its slow changes may be interpreted as two ‘spots’ whose size or surface brightness contrast somewhat vary with time.

Concerning the hourly photometric variability, the time-scales themselves immediately rule out a binary or rotational origin; a potential secondary component would be located within the primary CSPN, or the CSPN would need to rotate faster than breakup speed, respectively. The absence of any short-term periodicity in the whole data set and the irregularity of these variations argue that we do not see a photospheric phenomenon. This is also an argument that pulsations are not observed in the Kepler light curves: pulsation occurs at distinct frequencies. Even if it was stochastic, it can only appear and disappear at stellar eigenmode frequencies. Therefore, one would expect to see at least some peaks standing out in the periodogram of the SC data (Fig. 3), which is not the case. However, we cannot claim that pulsations are not present at all because the photometry contains little flux that originates in the stellar photosphere.

We evaluate the time-scales of possible central star pulsations. From the most suitable sequence of envelope models by Gautschy (1993) with respect to NGC 6826 we estimate a pulsation constant $Q = P \sqrt{\rho/\rho_\odot} = 0.042$ d for the fundamental radial mode, that is excited by the $\kappa$-mechanism in almost all of these models. This pulsation constant corresponds to a period of the radial fundamental mode of NGC 6826 of 2.7 h. Given the uncertainties in the stellar parameters and models, this can only be seen as a rough estimate. We note that envelope models do not allow the computation of non-radial modes, but the presence of strange modes with similar periods as the radial pulsations were noted in the models by Gautschy (1993).

It is important to constrain under which circumstances we would have missed the detection of binary-induced variability. A binary would reveal itself through radial velocity or light variability. The photometric noise level in our data is 0.072 mmag at worst. This translates into a detection threshold for periodic signals of 0.29 mmag. Given the dilution of any given variability signal due to the presence of the nebula (Section 2.1), we conservatively estimate
that we would have detected any periodic signal with an intrinsic amplitude exceeding 1.5 mmag in our data.

Morris (1985) derived expressions for the amplitude of ellipsoidal light variations. We applied these in combination with the limb darkening and gravity brightening coefficients for the Kepler bandpass by Claret & Bloemen (2011), and adopting a central star mass of 0.74 M⊙ (Kudritzki et al. 2006). This resulted in the constraint that we could have detected binaries with orbital periods shorter than 7 days under favourable inclinations. However, a stellar (M ≥ 0.08 M⊙) companion in a 1.238 d orbit would only have escaped our detection in combination with an orbital inclination below 26°.

Under the assumption of a random orientation of the orbital plane in space, the probability that it is observed below a certain inclination angle is

\[ p(< i) = 1 \cos i. \]

Further assuming that the CSPN rotation axis is normal to this orbital plane, this probability can be written as

\[ p(< i) = \frac{(1 - \cos i)}{\sqrt{1 - (\cos i)^2}} \quad i \geq \sin^{-1}\left(\frac{v_i}{v_b}\right) \]

\[ p(< i) = 0 \quad 0 \leq i < \sin^{-1}\left(\frac{v_i}{v_b}\right), \]

where \( v_b \) is the stellar rotational break-up velocity (see Bernacca (1970) for a detailed discussion).

We can estimate the break-up velocity of the CSPN by using the spectroscopic parameters quoted earlier and

\[ P_{\text{crit}} = \frac{2\pi R_{\text{eq}}^{3/2}}{(GM)^{1/2}}, \]

where \( R_{\text{eq}} \) is the equatorial radius of the star. Following Reid et al. (1993), \( R_{\text{eq}} = 1.5 R \), where \( R \) is the stellar radius in the non-rotating case. This calculation yields \( P_{\text{crit}} = 7.8 \) h, hence, \( v_b = 280 \) km s\(^{-1}\), hence, \( \sin^{-1}\left(\frac{v_i}{v_b}\right) = 10.3 \). With these values, probabilities calculated with equation (2) are only 1.6 per cent higher as if they were derived with equation (1). Returning to the hypothesized stellar companion in an orbit inclined by less than 26° discussed earlier, the probability that we missed its detection therefore becomes 10 per cent.

A stronger constraint arises from the lack of a detection of periodic radial velocity changes. We again used a central star mass of 0.74 M⊙, and a generous upper limit for its periodic radial velocity variations of 3.3 km s\(^{-1}\). For orbital periods shorter than 7 days (the length of our spectroscopic time series), we should have detected all stellar companions with an orbital inclination above 44°; for hypothesized companions exceeding 0.2 M⊙, the limit on the orbital inclination is \( i < 31° \), corresponding to a 14 per cent probability of missing a detection. A stellar companion in a 1.238 d orbit would not have been detected in radial velocity with an orbital inclination below 10°. However, in that case the CSPN rotation axis cannot be normal to the orbital plane because the central star would have to rotate above break-up speed.

The referee remarked that the shape of the NGC 6826 nebula and the presence of fast low-ionization emission regions in it (Balick et al. 1994) suggest that the orbital plane of a hypothetical binary causing these features would be at low inclination. Whereas such an interpretation cannot be ruled out completely, it needs to be reconciled with the orientation of the CSPN’s rotation axis keeping in mind its critical rotation rate. Furthermore, such a low inclination is inconsistent with our interpretation of the 1.238 d variation in terms of a rotational modulation originating from the central star, unless one postulates a rotation axis significantly deviating from the normal to the orbital plane.

5 Interpretable

Following their analysis of one year of Kepler LC data on NGC 6826, Jevtić et al. (2012) suggested that a combination of stellar pulsation and interaction with a close companion is a possible explanation of the central star’s variability. According to our results, such a scenario is very unlikely. Our measurements rather support another possibility mentioned by Jevtić et al. (2012), variable features on the central star’s surface in combination with inhomogeneities and variations in the density structure of its wind. Such variability is observationally well established in massive hot stars (e.g. Fullerton 2003).

Large-scale variations in the wind structure are believed to be seated at the base of the wind, in so-called Co-Rotating Interaction Regions (CIRs; Mullan 1984). In brief, CIRs arise due to intensity variations on or near the stellar photosphere, such as spots or non-radial pulsation patterns. Such intensity or temperature variations modify the outflow velocity of the spherical wind. Hence, the parts of the wind originating at these locations are differently affected by the driving force, and collide with particles emitted from other surface regions. Due to stellar rotation, spiral-shaped density

![Figure 8. Simultaneous C IV radial velocities (upper panels) and Kepler photometry (lower panels) of NGC 6826. The non-overlapping parts of the light curves have been removed for easier comparison. The light and radial velocity variations do not correspond.](http://mnras.oxfordjournals.org/ Downloaded from at Nicolaus Copernicus Astronomical Center on May 7, 2013)
fluctuations in the wind arise and cause the spectroscopically observed DACs. These DACs occur on time-scales related to the stellar rotation period (several days), and drift slowly through the line profiles with respect to the wind velocity. As exemplary literature we refer to Fullerton et al. (1997) for an observational study and Cranmer & Oswcki (1996) and Lobel & Blomme (2008) for hydrodynamical model computations.

In addition to the DACs, ‘modulations’ have also been observed to move through the line profiles. They travel at a much faster rate than the DACs and have considerably shorter recurrence times (Fullerton et al. 1997). These ‘modulations’ alter the mean flux, as opposed to the DACs that are pure absorption features. Radiative transfer modelling (Lobel, Toal’d & Blomme 2011) implies that these are only slightly bowed large-scale density enhancements and local wind velocity variations that radially protrude into the equatorial wind. The density enhancement is of the order of 10 per cent, and can result from mechanical wave action at the base of the stellar wind, such as produced by non-radial pulsations (e.g. see Kaufer et al. 2006). The photospheric cause of these variations is called rotational modulation regions (RMRs).

The variability of some WR stars may be related to such variations, although they have been interpreted slightly differently. Periodic photometric variations with time-scales of days have been attributed to CIRs (e.g. Chené et al. 2011), and irregular short-term variations with time-scales of hours have been reported in addition. Their spectroscopic counterparts are believed to be moving features in optical profiles of wind-sensitive lines, observed not only in WR stars, but also in Of stars (e.g. Lépine & Moffat 2008) and are interpreted as clumps propagating in the wind.

The temporal behaviour of NGC 6826 conforms to these scenarios. Taking the photometric 1.237 99 d period to be due to rotation, the double-wave shape may be a manifestation of two corotating features. The recurrence time for DACs in the UV lines of NGC 6826 is not well constrained; Prinja et al. (2012a) reported the detection of two sequential features over ≈8 h. It is interesting to note however that we never see more than two strong CIRs in OB stars that have been monitored for one rotation period.

The time-scales of short-term light variations are consistent with RMRs or clumps moving within the wind. As our spectroscopy implies that the variations in the wind are not local, they are most likely attributable to large-scale features. Therefore, they may be associated with RMRs. The difficulty with this picture is that the spectroscopic data of massive stars, in which RMRs are manifested, imply that they occur quite regularly, whereas the short-term photometric variability is irregular in our case. Consequently, some periodically triggered mass-loss must have lost memory by the time it reaches the depth in the wind that the photometry samples.

Albeit the present observations do give some insight into the nature of the variability of NGC 6826 (and other ZZ Lep stars), more observational evidence is needed. Although observationally hard to obtain due to the faintness of the targets, spectroscopic evidence for wind clumping or eventual RMR presence in CSPN should be sought. On the other hand, photometric evidence for light variability on the RMR and CIR time-scales for massive stars, focusing on non-WR stars, would also be useful.

In this context, it is interesting to note that Blomme et al. (2011) analysed CoRoT light curves of three massive O-type stars and also found some apparently incoherent variability, in all three targets. The light curves, amplitude spectra and time-frequency analyses of these stars phenomenologically closely resemble what we report for NGC 6826. One may therefore speculate that this kind of variability is present in all hot stars [Blomme et al. (2011); Handler et al. (2012) discussed it in connection with massive OB stars], and that it is related to stellar wind variations.

6 SUMMARY

The observed photometric variability of the central star of NGC 6826 consists of a periodic modulation with a time-scale of 1.237 99 d and irregular light variations on time-scales of a few hours. Optical spectra imply line variability on a similar time-scale, with a possible period of 3.1 h. UV spectra show DACs with a recurrence time of about 8.5 h. The only possible correspondence between the photometric and spectroscopic variability may be the time-scale of the hourly changes.

The periodic photometric variation is best explained by rotational modulation. The 1.237 99 d period we derived is similar to asteroseismic rotation periods of single white dwarf stars (e.g. Winget et al. 1991). Time-series photometry of ZZ Lep stars may therefore reveal their rotation periods, but large data sets are needed to detect these periodicities due to the dominating short-term variability, that is due to changes in the stellar mass-loss. This behaviour is similar to what has already been observed in massive OB and WR stars, suggesting that the same mechanism may be responsible for the variations in all hot star winds.

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REFERENCES
