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Letter to the Editor

Periodic mass-loss episodes due to an oscillation mode with variable amplitude in the hot supergiant HD 50064*

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ABSTRACT

Aims. We aim to interpret the photometric and spectroscopic variability of the luminous blue variable supergiant HD 50064 ($V = 8.21$).
Methods. CoRoT space photometry and follow-up high-resolution spectroscopy with a time base of 137 d and 169 d, respectively, was gathered, analysed, and interpreted using standard time series analysis and light curve modelling methods, as well as spectral line diagnostics.
Results. The space photometry reveals one period of 37 d, which undergoes a sudden amplitude change with a factor 1.6. The pulsation period is confirmed in the spectroscopy, which additionally reveals metal line radial velocity values differing by ~ 30 km s^{-1} depending on the spectral line and on the epoch. We estimate $T_{\rm eff}\sim 13\,500$ K, $\log g \sim 1.5$ from the equivalent width of Si lines. The Balmer lines reveal that the star undergoes episodes of changing mass loss on a time scale similar to the changes in the photometric and spectroscopic variability, with an average value of $\log \dot{M} \simeq -5$ (in M$_\odot$ yr^{-1}). We tentatively interpret the 37 d period as the result of a strange mode oscillation.

Key words. Stars: oscillations – Stars: winds, outflows – Stars: individual: HD 50064 – Stars: atmospheres – Asteroseismology – Stars: supergiants

1. Introduction

One of the goals of the asteroseismology programme (Michel et al. 2006) of the CoRoT satellite (Baglin et al. 2006) is to explore the Hertzsprung-Russell diagram (HRD) through uninterrupted time series of white-light photometry of unprecedented precision. In this context, numerous non-radial pulsators of various kind have been observed and analysed, among which massive stars on the main sequence (e.g., Degroote et al. 2009; Neiner et al. 2009). With the goals of mapping the uppermost part of the HRD and understanding the role of oscillations in the mass loss of evolved massive stars, a hot supergiant was observed in the seismology programme of the satellite.

The B-type supergiant HD 50064 (V mag of 8.21) has not been studied in detail. Its spectral type assignments range from B1Ia (Jacoby & Hunter 1984) to B6Ia (Blanco et al. 1970). It was monitored by CoRoT, whose performance not only delivers two orders of magnitude better precision than any ground-based photometry, but, even more importantly for supergiant stars, also guarantees uninterrupted data during several months. This is essential for progress in understanding massive evolved stars, because ground-based data for supergiants have so far suffered severely from very low duty cycles.

The oscillations of evolved massive stars known so far essentially come in two flavours. Classical gravity mode oscillations with periods of a few days, excited by the κ mechanism, have recently been found from space photometry (Saio et al. 2006; Lefever et al. 2007a). On the other hand, theory predicts so-called strange modes with periods between roughly 10 and 100 d in stars with masses above 40 M$_\odot$. These strange modes, which can be both radial and non-radial in nature, are modes trapped in a cavity caused by a density inversion in the very outer, highly non-adiabatic envelope of stars with a high L/M ratio whose radiation pressure dominates over the gas pressure (Glatzel & Kiriakidis 1993; Saio et al. 1998; Glatzel et al. 1999; Dorfi & Gautschy 2000). This type of oscillation has been claimed to be responsible for the mass-loss episodes of luminous stars, such as luminous blue variables (LBVs), e.g. Glatzel & Kiriakidis (1993), but observational proof of the occurrence of strange modes has not been established so far. Our data of HD 50064 suggests that the star undergoes a strange mode oscillation.

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* Based on high-resolution spectroscopy assembled with the CORALIE spectrograph attached to the 1.2m Euler telescope at La Silla, Chile and on CoRoT space-based photometry. The CoRoT space mission was developed and is operated by the French space agency CNES, with the participation of ESA's RSSD and Science Programmes, Austria, Belgium, Brazil, Germany, and Spain.

** Postdoctoral Fellow of the Fund for Scientific Research of Flanders (FWO), Belgium

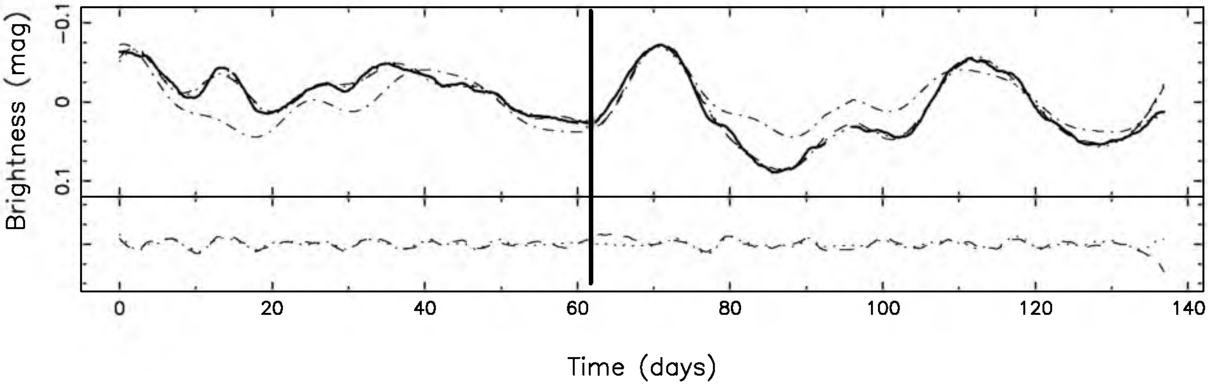

Fig. 1. The CoRoT light curve of HD 50064 corrected for a linear downward trend (full line). For an explanation of the fits in different linestyles, see text. The *y*-axis of the lower panel is reduced by a factor 2 compared with the one in the upper panel.

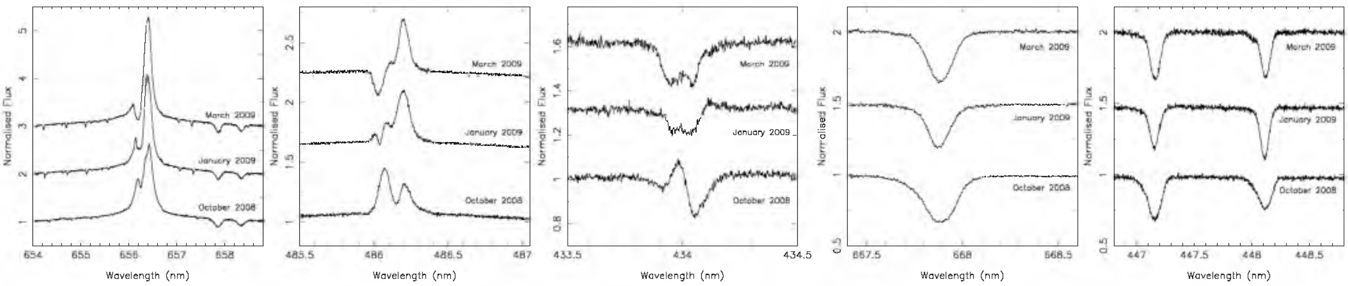

Fig. 2. Average profiles at three epochs of H, He, and an Mg line of HD 50064 (from left to right: Hα, Hβ. Hγ. He I at 6678Å, and He I at 4471Å, as well as Mg II at 4481Å).

2. Data description

2.1. The CoRoT data

HD 50064 was observed by CoRoT during a long run in the anticentre direction (LRa01) for 136.9 days. It is the only hot supergiant among the seismology targets so far. The CoRoT light curve contains 319 913 datapoints, with a time sampling of 32 s, after deleting the measurements suffering from hot pixels during the passage through the South Atlantic Anomaly. In order to compare the space photometry behaviour of HD 50064 with the one reported in the literature (Halbedel 1990), we transferred the CoRoT fluxes to white-light magnitudes.

All seismology targets of LRa01 are subject to a small downward trend of instrumental origin. In the case of HD 50064, the trend is clearly stronger and probably intrinsic to the star. It was corrected for by a linear approximation. This detrended light curve is shown as the thick line in the upper panel of Fig. 1. Large variations occur, with peak-to-peak values of $\sim$ 0.2 mag and with a time scale of about one month. This is compatible with the scarce data in Halbedel (1990). The light curve also reveals a sudden rise in amplitude near day 62.

2.2. Follow-up spectroscopy

Halbedel (1990) took one spectrum of HD 50064 and found a P Cyg Hα profile with a V/R ratio of 0.23 and a maximum red emission peak value of 4.2 continuum units. A few low-resolution low signal-to-noise UV spectra taken in 1979 with the IUE satellite are also available, but they do not allow quantitative estimates of the stellar parameters to be derived. We assembled 14 high-resolution échelle spectra of the star with the CORALIE spectrograph attached to the 1.2m Euler telescope in La Silla, Chile, at three epochs (5, 5, 4 spread over 6, 8, 6 nights in Oct. 08, Jan. 09, Mar. 09, respectively), after the CoRoT data revealed the star's variability. The integration time was 30 min, leading to an S/N level of about 50. The usable parts of the spectrum have wavelengths between 4000Å and 7000Å.

The average profile of some selected lines for the three epochs are shown in Fig. 2. The Balmer lines point towards mass loss that is variable on the same time scale as the CoRoT photometry. The He and Mg lines are also variable on this time scale. We cannot exclude additional spectroscopic variability with periods below a day.

2.3. Interferometry

Given that the star is surrounded by circumstellar matter, as the Balmer lines reveal, we observed HD 50064 with the near-IR interferometric instrument VLTI/AMBER (Petrov et al. 2007) during Belgian GTO time in March 2009[1]. The measurement was performed on the closed triangle A0-K0-G1, providing baselines of 90, 80, and 125 m, respectively. Our analyses show that the target was *not* resolved. Based on the spread on the data, we find that the target's half-light radius must be less than 1 milli-arcsec. For the distance estimate of $\gtrsim$ 2900pc (Halbedel 1990), this upper limit of 1 milli-arcsec translates to 650 $R_\odot$ for the disk or a disk-to-star flux ratio below 7% in the covered wavelength range (1.2 – 2.5 μm) when assuming a simple model of a circumstellar disk around an unresolved star.

[1] program ID 083.D-0028

3. Analyses of the data

3.1. Modelling of the CoRoT light curve

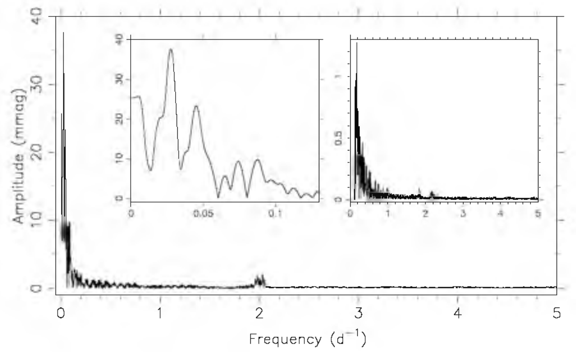

Fig. 3. Amplitude spectrum of the CoRoT data of HD 50064, up to 5 d^{-1} (57.87μHz). At higher frequencies, only harmonics of the satellite orbit of 6184 s occur, with an amplitude below 1 mmag. The insets show an enlarged section at low frequencies (left) and the amplitude spectrum of the residuals after prewhitening with the dominant frequency and six of its (sub)harmonics (right).

A first look at the detrended light curve immediately revealed large non-sinusoidal variations in amplitudes of several hundredth of a magnitude, with periodicity of tens of days (Fig. 1). The data is thus highly oversampled. We binned the light curve by averaging 101 consecutive data points. All the results we list are for this binned light curve, containing 3167 points and having a Rayleigh limit of 0.0073 d^{-1}. The reference epoch we adopted is t_0 = HJD 2454391.970406.

The amplitude spectrum of the binned data is shown in Fig. 3. All intrinsic variability due to the star occurs below 1 d^{-1}. The highest peak occurs at 0.027 d^{-1} (0.313μHz). corresponding to a period of 37 d, and reaches an overall amplitude of 38 mmag. We checked explicitly that the same result for the frequency is obtained for the full (un)detrended unbinned light curve. A harmonic fit with this frequency, with a constant value for the amplitude and phase of each harmonic, is not appropriate, even when considering numerous harmonics (dashed-dotted line in Fig. 1). This is due to the change of variability near day 62 (see Fig. 1), which cannot be an instrumental effect, as it does not occur for the other asteroseismology targets of LRa01. The variance in the light curve increases with a factor 1.6 after day 62.

We cut the binned data set into two parts, one until day 61.7 (set A) and another one after it (set B). The dominant frequencies for set A are 0.015 and 0.030 d^{-1}, while we find 0.024 d^{-1} for set B. These frequencies differ less or only slightly more than the Rayleigh limit from each other. Given the larger variability in set B, this data dominates the periodogram of the overall light curve, which leads us to conclude that there is only one clear periodicity in the CoRoT data, corresponding with a frequency of 0.027 d^{-1}, but with an amplitude and/or phase change near day 62. A separate harmonic fit with 0.027 d^{-1} fixed for sets A and B and including the (sub)harmonics nf_i, for $n = 1/2, 1, 3/2, 2, 5/2, 3$ is shown as a dashed line in Fig. 1. It leads to an amplitude and phase switch from 28 mmag to 46 mmag and from $\phi = 0.623$ to $\phi = 0.560$ (2π radians). Such a fit is not worse than one for which we allow the frequency to be optimised for sets A and B (dotted line in Fig. 1). The residuals in the bottom panel of Fig. 1 show variability at the 1 mmag level (inset in Fig. 3) caused by the higher harmonics of 0.027 d^{-1}, while no additional independent frequencies were found.

We conclude that the CoRoT light curve of HD 50064 can be characterised by a single period of 37 d with a sudden amplitude increase of a factor 1.6, which occurs once on a time scale of 137 d.

3.2. Spectroscopic behaviour

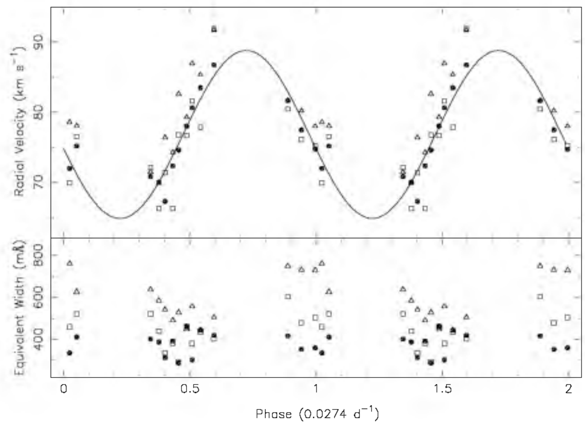

Fig. 4. Phase diagrams of the radial velocity and equivalent width of the three spectral lines He I 4471Å (squares), He I 6678Å (triangles), and Mg II 4481Å (filled dots). Each measurement occurs twice for visibility purposes.

Our spectroscopic data of HD 50064 is limited to 14 spectra of moderate S/N, but it spans 169 d (Rayleigh limit of 0.006 d^{-1}). We computed the centroid velocities (see Aerts et al. 1992) for the least blended spectral lines, as well as their Fourier transform. This led to *clear confirmation of the photometric period.* Phase diagrams for the He I 4471Å, He I 6678Å, and Mg II 4481Å lines are shown in Fig. 4. We find a consistent radial-velocity (RV) amplitude of 12±2 km s^{-1} from these three lines. This amplitude is similar to the one of B-type radial pulsators along the main sequence (e.g., Aerts & De Cat 2003). Large equivalent width (EW) variations occur for the three considered lines, with relative peak-to-peak values near 50% (see bottom panel of Fig. 4). These also reveal the 37 d period for the two He lines. The phase difference between the EW and RV variations amounts to 277° ± 14° for He I 4471Å and 246° ± 10° for He I 6678Å. Adiabatic pulsation modes would give rise to values of 90° or 270°, depending on the spectral line. Deviations thereof are usually interpreted as non-adiabatic effects (De Ridder et al. 2002).

We computed an average spectrum for the three epochs after shifting each spectrum to the centroid velocity of the Mg II 4481Å line (Fig. 2). This reveals a range in centroid velocities of up to 50 km s^{-1} for lines formed at different optical depths. The V/R ratio of Hα is $\simeq$ 0.44 in Oct. 08, $\simeq$ 0.56 in Jan. 09, and $\simeq$ 0.73 in Mar. 09. Both Hα and Hβ evolve from a double-peaked emission profile to a P Cygni profile in that period, while Hγ transforms from an inverse P Cygni profile in Oct. 08 to a modest P Cygni profile in Jan. 09 and an absorption profile in Mar. 09, and Hδ is always in absorption. We interpret this behaviour in terms of radial motion of the atmosphere in the line forming region of Hα and Hβ in Oct. 08 while at the same time material recedes towards the stellar centre deeper in the atmosphere where Hγ and the He and metal lines are formed. This situation evolves to an expanding upper atmosphere in Jan. and Mar. 09, which are separated by two pulsation cycles.

We determined $T_{\rm eff}$ and $\log g$ from the EW of Si II and Si III lines, as well as He I lines, by comparing with the predictions for the extended grid of FASTWIND model atmospheres `BSTAR06` in Lefever et al. (2007b). The absence of He II and Si IV lines places a clear upper limit to $T_{\rm eff}$. Restricting the models to the solar Si abundance (Asplund et al. 2009) led to $T_{\rm eff} \simeq 13500$ K, $\log g \simeq 1.5$, where the differences for the three epochs were less than the typical uncertainties of 1000 K and 0.2 dex. The EW of the Balmer lines led to $\log Q = \log[\dot{M}(v_\infty R)^{-1.5}] \simeq -11.5$. On the other hand, the peak heights of Hα range from 1.5 in this study to 4 in Halbedel (1990) and this leads to the rough estimate $\dot{M} \sim 10^{-5} \mathrm{M}_\odot\,\mathrm{yr}^{-1}$ as an average mass-loss rate. This, combined with the value of $v_\infty \simeq 100\,\mathrm{km\,s^{-1}}$ derived from the blue wings of the Hα profiles, gives a radius estimate of $\simeq 200\,\mathrm{R}_\odot$ and a luminosity $\log(L/L_\odot) \simeq 6.1$.

4. Interpretation

The 37 d period found in the CoRoT photometry and in the spectroscopy is compatible with the radial fundamental mode for the parameters of HD 50064, assuming $M \sim 45\,\mathrm{M}_\odot$ (e.g., Lovy et al. 1984). The behaviour of the Balmer lines is hard to explain in terms of non-radial gravity modes as found in other B supergiants (Lefever et al. 2007a). While the overall morphology of the light curve with the sudden amplitude changes resembles the theoretically predicted modes by Dorfi & Gautschy (2000), their predicted periods are an order of magnitude too short, and they did not give rise to mass-loss episodes. We thus suggest that HD 50064 is subject to a radial strange mode oscillation.

The spectrum of HD 50064 shows a strong resemblance to that of LBVs with moderate mass loss, e.g. HD 160529 (Stahl et al. 2003). We thus suggest that HD 50064 is on its way to that stage, by building up a circumstellar envelope while pulsating. The main conclusion of our work is that its pulsation mode is clearly connected with its variable mass loss. With only three epochs of spectroscopy, we cannot make a detailed comparison of the spectroscopic and pulsational behaviour, but we suggest a coordinated action for long-term photometric and high S/N spectroscopic follow-up observations in order to understand the detailed behaviour of the (strange) mode(s) and the relation with the mass loss of this supergiant.

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