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Detailed follow up studies of three ultracompact sdB binaries

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Abstract

We present follow-up studies of three ultracompact hot subdwarf binaries. Using data from the Zwicky Transient Facility, we find orbital periods of 33.6, 37.3, and 36.9 minutes for ZTF 1946+3203, ZTF 0640+1738, and ZTF 0643+0318 respectively. The light curves show ellipsoidal variability of the hot subdwarf star with potential eclipses of an accretion disc. Phase-resolved spectroscopic observations with Keck were used to measure a radial velocity curve and atmospheric parameters of the hot subdwarf stars. ZTF J0643 shows evidence of accretion disc emission lines in the average spectrum. Combining light curve and spectroscopic fits will allow us to measure precise system properties such as masses, to determine the evolutionary history and future evolution of the system.

1. Introduction

Most hot subdwarf B stars (sdBs) are core helium burning stars with masses around 0.5 $M_\odot$ and thin hydrogen envelopes [1, 2, 3]. A large number of sdB stars are in close orbits with orbital periods of $P_{\rm orb} < 10$ days [4, 5], with the most compact systems reaching orbital periods of < 1 hour [6, 7, 8, 9, 10, 11].

SdB binaries with white dwarf (WD) companions which exit the common envelope phase at $P_{\rm orb} < 2$ hours will reach contact while the sdB is still burning helium [12]. Once the sdB fills its Roche Lobe, helium-rich material will be transferred to the WD companion. After the WD accretes $\approx 0.1\,M_\odot$, helium burning is predicted to be ignited unstably in the accreted helium layer on the WD surface [13, 14]. This could either disrupt the WD even when the mass is significantly below the Chandrasekhar mass, a so-called double detonation supernova [15, 16, 17, 18, 19, 20, 21] or just detonate the He-shell without disrupting the WD which results in a faint and fast .Ia supernova with subsequent weaker He-flashes [22, 13].

In this work we present follow-up studies of three ultracompact hot subdwarf binaries which were first discovered by Burdge et al. 2020 [23]. The objects are ZTF 1946+3203 (ZTF J1946), ZTF 0640+1738 (ZTF J0640), and ZTF 0643+0318 (ZTF J0643). They show periods of 34, 37, and 37 minutes based on their photometric variability, making them the most

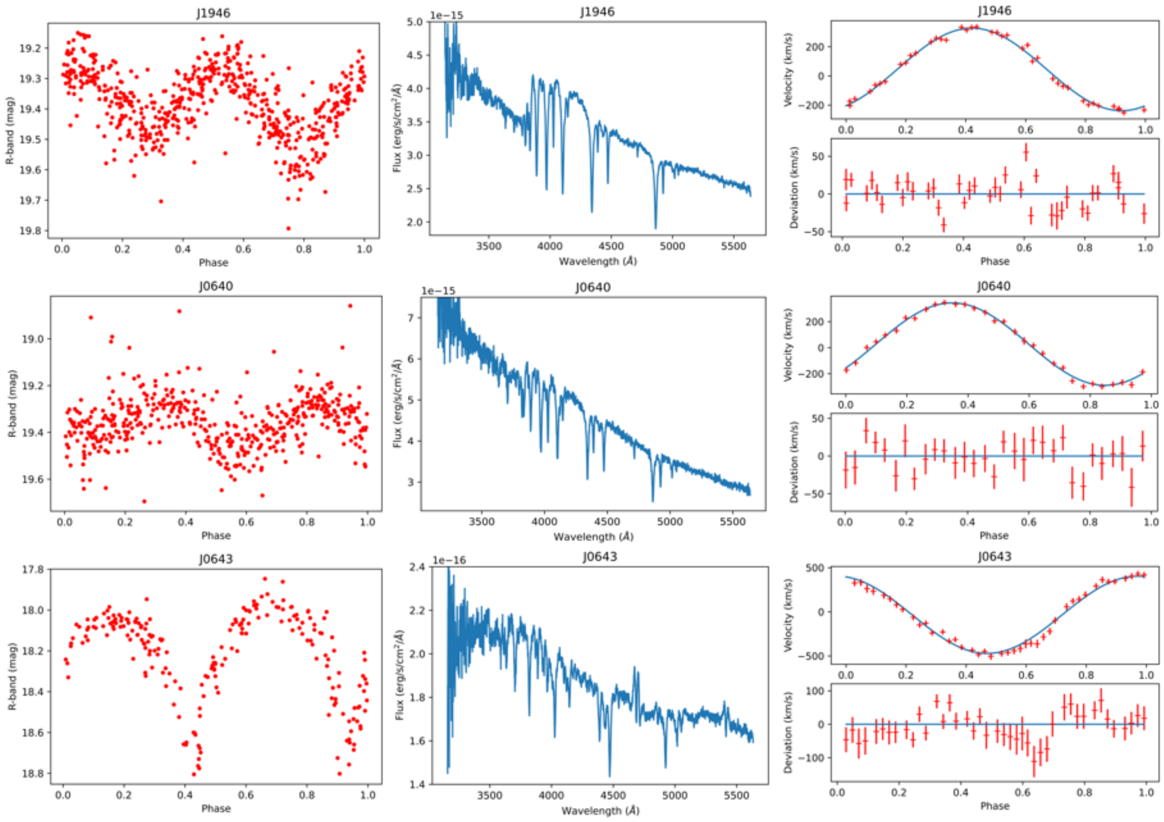

Figure 1: Left Column: Phase folded ZTF light curves. Middle Column: Spectra from Keck LRIS with 600/4000 grating. Right Column:(Top) Velocity curves with accompanying sine-fit. (Bottom) Residuals of the fit

compact hot subdwarf binaries known today. As such they are ideal candidates to be type Ia supernova progenitors. One of the systems has signs of an accretion disc, making it the first candidate with spectral signatures for an accretion disk.

2. Photometric analysis

All three objects were observed as part of the Zwicky Transient Facility (ZTF) public survey [24, 25]. Image processing of ZTF data is described in full detail in Masci et al. 2019 [26]. The number of ZTF epochs range from 413 to 1004 points over three years for each object. To measure the orbital period we performed a Lomb-Scargle analysis on each data set using the Astropy Lomb-Scargle periodogram module[1] [27, 28].

We find orbital periods of 33.6 min, 37.3 min, and 36.9 min for ZTF J1946, ZTF 0640, and ZTF 0643 respectively. This is in agreement with previous the studies [23]. The phase folded light curves show strong periodic ellipsoidal variability. ZTF J1946 shows a deep eclipse which is also seen in the known sdOBs with a confirmed accretion disc [10, 11]. ZTF J0643 shows equally deep eclipses leading to the conclusion that the second component, most likely the

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[1] https://docs.astropy.org/en/stable/timeseries/lombscargle.html

accretion disc, has a similar brightness than the hot subdwarf primary (see left panels in Fig. 1).

3. Spectroscopic analysis

Phase resolved spectroscopy was taken with Keck and the Low Resolution Imaging Spectrometer (LRIS; [29]). ZTF J1946, ZTF J0640, and ZTF J0643 has 31, 40, and 42 phase resolved spectra respectively covering a full orbit for each objects. To measure the radial velocities, we used the cross correlation `rvsao` package implemented in `IRAF`. We then performed a sine-fit to the individual radial velocities to measure the radial velocity semi-amplitude for each object. We find a radial velocity semi-amplitudes of $282.6 \pm 18.7\,\mathrm{km\,s^{-1}}$, $316.7 \pm 26.8\,\mathrm{km\,s^{-1}}$ and $437.4 \pm 84.7\,\mathrm{km\,s^{-1}}$ for ZTF J1946, ZTF J0640, and ZTF J0643 respectively (see right panels in Fig. 1). The large error for the radial velocity semi-amplitude in ZTF J0643 is likely originating from the contamination from the accretion disc.

The average spectra were constructed from the sum of the individual rest-wavelength corrected spectra. ZTF J1946 and ZTF J0640 show typical hot subdwarf spectra with strong hydrogen and helium absorption features. ZTF J0643 shows a spectrum of a He-sdO with strong helium and weak hydrogen absorption lines as well as double peaked emission lines in He II 4686 Å and He II 5411 Å indicating emission from an accretion disc (see middle panels in Fig. 1). This makes ZTF J0643 the first hot subdwarf binary with spectral signatures of an accretion disc.

We use spectral models to fit the co-added spectra of ZTF J1946 and ZTF J0640 which were constructed using a hybrid LTE/NLTE approach described in detail in Przybilla et al. 2011 [30] and Irrgang et al. 2021 [31]. The grid of spectral models covers a typical range of hot subdwarf $T_{\rm eff}$ and $\log g$ up to modest helium abundances (Heber et al., these proceedings). ZTF J0643 shows strong helium features and requires larger helium abundances. Therefore, for ZTF J0643 we use spectral models computed with TLUSTY/SYNSPEC [32] covering helium dominated atmospheres. The approach and the models are described in detail in Dorsch et al. 2022 [33]. Using the spectral modelling tool SPAS [34], the co-added spectra were fitted for effective temperature ($T_{\rm eff}$), surface gravity ($\log g$), and helium abundance ($\log(y) = \log \frac{n(He)}{n(H)}$) using atmospheric models. For ZTF J1946, we find $T_{\rm eff}= 27{,}500 \pm 1000\,\mathrm{K}$, $\log g= 5.90 \pm 0.10$, and $\log(y) = -1.11 \pm 0.10$. For ZTF J0640 we find $T_{\rm eff}= 30{,}500 \pm 1000\,\mathrm{K}$, $\log g= 5.70 \pm 0.15$, and $\log(y) = -0.38 \pm 0.20$. Finally for ZTF J0643 we find $T_{\rm eff}= 42{,}500 \pm 2000\,\mathrm{K}$, $\log g= 6.15 \pm 0.30$, and $\log(y) = +1.8^{+\infty}_{-0.3}$.

4. Conclusion and summary

We present detailed follow-up observations of three new ultracompact hot subdwarf binaries with orbital periods below 40min, making them the most compact hot subdwarfs known today. ZTF J0640 shows ellipsoidal deformation whereas ZTF J1946 and ZTF J0643 show light curve shapes typical for mass transferring systems with a deep eclipse on top of ellipsoidal deformation indicating the presence of an accretion disc. ZTF J0643 presents double peaked helium emission features from an accretion disc providing the first direct evidence for an accretion disc in a hot subdwarf binary as well as a low-hydrogen content. The low hydrogen content suggests that the system has lost a large fraction of its hydrogen envelope and potentially shows an advanced stage of mass-transferring hot subdwarfs [12].

To continue this study, we will create light curve models using the light curve modelling code LCURVE [35] with prior information from spectroscopy, and calculate system properties such as masses, radii and inclination angle to be able to fully constrain the evolutionary history of each system.

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Further Information

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Author contributions

ES extracted the ZTF light curves, performed the period analysis and radial velocity measurements, supported the interpretation of the spectra as well as led the writing of the manuscript. TK performed the spectral modelling with SPAS and supported the writing of this manuscript. MD supported the spectral fitting and some of the spectral models used in this work.

Conflicts of interest

The authors declare no conflict of interest.

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