Revealing the Nature of HD 63401

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HD 63401 is a known magnetic chemically peculiar (mCP) star that is rotating slowly and probably possesses a hydrodynamically stable stellar atmosphere. In the latter case the atomic diffusion mechanism enforced by the magnetic field can lead to a stratification of elemental abundances with optical depth. HD 63401 was recently observed with the space telescope *TESS*, and its light curve shows distinct variability, which is usually detected in the α^2 CVn type stars. Based on the analysis of the light curve we derived a rotational period of $P = 2.414 \pm 0.018\,\mathrm{d}$ and studied the variability of the effective temperature on this period. The estimates of the effective temperature and surface gravity were obtained from the best fit of Balmer line profiles observed in seven high-resolution spectra of the star acquired with the spectropolarimeter ESPaDOnS. The same spectra were used to perform an abundance analysis employing the modified ZEEMAN2 code. We have found that He, C, P, V, Y, and Dy are deficient in the atmosphere of HD 63401, while Na, Al, Si, Fe, Zn, and Sr are significantly overabundant.

1 Introduction

HD 63401 is a relatively bright chemically peculiar (CP) star of spectral type B9 (Renson et al., 1991) with a significant magnetic field (Bagnulo et al., 2006; Kochukhov & Bagnulo, 2006). Bailey et al. (2014) estimated its stellar parameters and estimated an age of $\log t = 7.7 \pm 0.1$ based on the fact that it is a member of the open cluster NGC 2451. These authors also detected the enhanced abundance of Si, Ti, Cr, Fe, and Pr in its atmosphere, while He, O and Mg seem to be deficient. They concluded that the abundance peculiarities observed for different chemical elements may change with the stellar evolution on the main sequence.

Based on an analysis of *Hipparcos* photometric data, Adelman et al. (2000) reported the detection of photometric variability of HD 63401 with an amplitude of 60 ± 2 mmag. By analyzing uvby-photometry Hensberge et al. (1976) derived a rotation period of $P = 2.41 \pm 0.02\,\mathrm{d}$ for the object. This star has recently been observed with the Transiting Exoplanet Survey Satellite (*TESS*) (Ricker et al., 2015) which provided short cadence (2 min) photometric measurements. HD 63401 was included in our list of relatively bright CP stars that show photometric variability related to stellar rotation (Kobzar et al., 2020). This star (TIC 175604551) was observed in *TESS* sectors 7 and 8.

2 Analysis of the *TESS* Data

The photometric data obtained with *TESS* for HD 63401 were downloaded from the Mikulski Archive for Space Telescopes[1] (MAST) and are publicly available. To

[1] `https://archive.stsci.edu/tess/bulk_downloads.html`

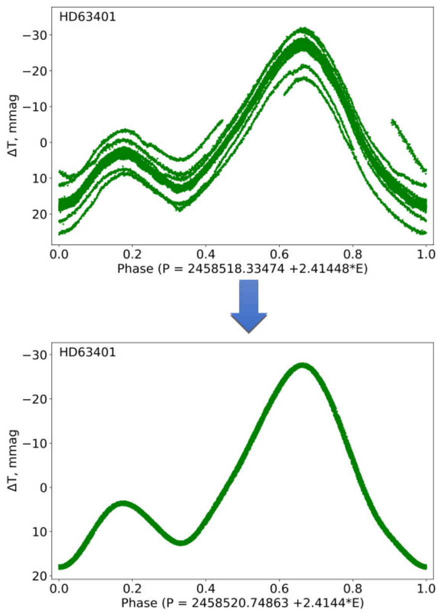

Fig. 1: The *TESS* photometric data phased with the period derived from the Fourier analysis (upper panel) and the reduced LC phase diagram (lower panel) produced by the code Period D&P for HD 63401 using the refined period.

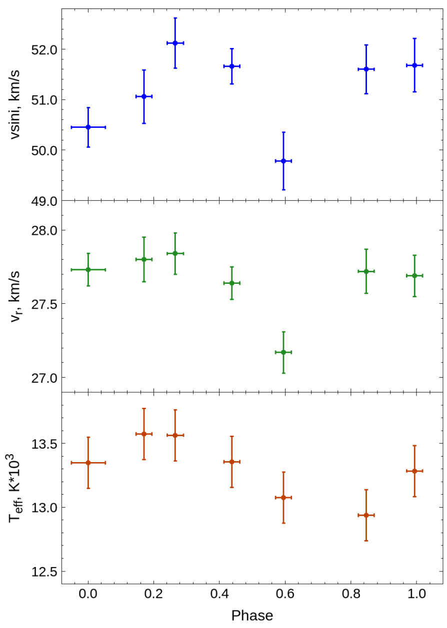

Fig. 2: The $\mathrm{v}\sin i$, $\mathrm{v_r}$, and $\mathrm{T_{eff}}$ were obtained from the spectral analysis. Their rotational phases were calculated according to the derived period.

perform the analysis of its light curve (LC) an automatic procedure, *TESS*-AP (Khalack et al., 2019), was used to estimate the frequencies, amplitudes and phases of the photometry. *TESS*-AP consists of several scripts and programs, including Period04 (Lenz & Breger, 2005), and was designed for automatic data analysis. The code Period D&P[2] was developed in Python and employed to refine the value of the stellar rotation period. The program uses the photometric observations to construct a phase curve, and fits it with the following Fourier series:

$$m_j = A_0 + \sum_{n=1}^{N} A_n \cdot \cos\left(\frac{2\pi n \cdot t_j}{P} + \phi_n\right), \tag{1}$$

where m_j is an individual observed magnitude and t_j the corresponding time of observation, N is the number of harmonics, P is the rotation period, and A_n and ϕ_n are the amplitudes and phases of the harmonic series. To derive the best fit parameters we used the method of non-linear least squares approximation (Marquardt, 1963). The code Period D&P calculates a value of the rotation period and its precision, and plots a phase curve. The light curve may contain trends, flares and other features. The trends occur mainly at the beginning or end of each continuous sequence of

[2]GitHub: `https://pawakawko.github.io/Period-D-P`

Tab. 1: Average abundances calculated for elements analysed in seven spectra of HD 63401.

El.	[X/H]	El.	[X/H]	El.	[X/H]	El.	[X/H]
He	-1.25 ± 0.28	P	-1.54 ± 0.71	Ba	0.44 ± 0.28	Ce	-0.39 ± 0.08
C	-0.94 ± 0.21	Ca	-0.20 ± 0.16	Co	1.38 ± 0.95	Pr	0.72 ± 0.28
N	-0.09 ± 0.18	Sc	0.42 ± 0.08	Ni	0.08 ± 0.37	Nd	0.16 ± 0.17
O	-0.31 ± 0.19	Ti	0.44 ± 0.12	Cu	-0.19 ± 0.04	Sm	-0.37 ± 0.06
Ne	-0.24 ± 0.03	V	-1.75 ± 0.05	Zn	2.60 ± 0.17	Gd	-0.05 ± 0.13
Na	1.63 ± 0.48	Cr	0.83 ± 0.17	Sr	1.16 ± 0.45	Dy	-0.72 ± 0.52
Al	1.74 ± 0.65	Mn	0.55 ± 0.17	Y	-0.64 ± 0.06		
Si	1.07 ± 0.61	Fe	1.57 ± 0.18	Zr	-0.28 ± 0.10		

TESS observations and do not repeat on the rotation period. To exclude a contribution of the trends the code Period D&P cuts off all measurements that have a large deviation from the current best fit and repeats the fitting procedure (see Fig. 1). This procedure resulted in an estimate of the rotation period of $P = 2.414 \pm 0.018$ d for HD 63401.

3 Spectral Analysis

We have performed a spectral analysis of seven high-resolution ($R = 65000$) and high signal-to-noise ratio Stokes I and V spectra recently obtained with the spectropolarimeter ESPaDOnS at the CFHT. The dedicated software package Libre-ESpRIT (Donati et al., 1997) was employed to reduce the data. The unnormalized spectra were used when fitting the Balmer lines observed in the Stokes I spectra to theoretical profiles calculated with the FITSB2 code (Napiwotzki et al., 2004) and grids of stellar atmosphere models (Khalack & LeBlanc, 2015). The best fit values of the $T_{\rm eff}$ derived from the analysis of each observed spectrum obtained at different rotational phases are shown in the lower panel of Fig. 2.

The Stokes I and V spectra were normalized to conduct an abundance analysis with the help of the ZEEMAN2 code (Landstreet, 1988). An automatic procedure (Khalack, 2018) was used to select blended and unblended line profiles suitable for the abundance analysis. A model of the stellar atmosphere was calculated for the derived average parameters, $T_{\rm eff} = 13360 \pm 200$ K, $\log g = 4.1 \pm 0.2$, and metallicity $M = 0$ with the assistance of the PHOENIX-15 code (Hauschildt et al., 1997). This model atmosphere was used as input for ZEEMAN2 to fit the selected observed line profiles with synthetic ones. The average abundance of elements in the atmosphere of HD 63401 was estimated for each rotational phase as were the values of $v \sin i$ and radial velocity $v_{\rm r}$ (upper two panels in Fig. 2). The abundance estimates averaged over seven phases for each chemical element examined are presented in Tab. 1.

4 Discussion

We have used photometric data provided by *TESS* for HD 63401 to derive its rotation period of $P = 2.414 \pm 0.018$ d, based on the assumption that the presence of overabundant patches of elements causes a redistribution of the emitted flux and hence produces brighter spots in the star's atmosphere. In the context of the oblique

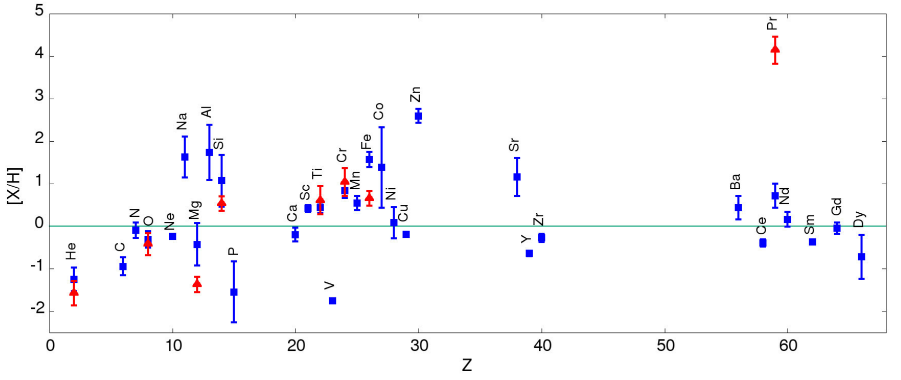

Fig. 3: Comparison of the derived average abundances of chemical elements (squares) in stellar atmosphere of HD 63401 with the data (triangles) reported by Bailey et al. (2014). The green line represents the solar abundance (Grevesse et al., 2015).

rotator model (Stibbs, 1950), the visibility of the patches and spots will change with rotational phase and lead to the observed flux variability (see David-Uraz et al. 2020). This hypothesis is in good agreement with the observed weak variability of the measured effective temperature with rotational phase. It may be noticed that the maxima of the LC phase diagram (lower panel of Fig. 1) have similar rotational phases as the extrema at the temperature variability (lower panel of Fig. 2). However, the minimum of the effective temperature corresponds closely to the maximum of the LC. The average values of $v \sin i$ and radial velocity derived from the analysis of over hundred line profiles examined in each spectrum also show a weak variability with rotational phase similar to that detected for $T_{\rm eff}$ (top two panels of Fig. 2).

Our estimates of the average (over seven phases) abundances of elements in HD 63401 are in relatively good agreement with the data published by Bailey et al. (2014) (see Fig. 3 and Tab. 1). We have found that He, C, P, V, Y, and Dy are significantly underabundant in the atmosphere of HD 63401, while Na, Al, Si, Fe, Zn, and Sr show strong overabundances. Our estimate of the Fe abundance appears to be significantly higher than that reported by Bailey et al. (2014). The abundance of Pr derived in this work is much lower than derived by Bailey et al. (2014). All analyzed rare earth elements, meanwhile, show abundances close to the solar abundance (Grevesse et al., 2015).

The detected variability of the light curve and $T_{\rm eff}$, and the strong overabundance of some chemical elements support the hypothesis of abundance patches existing in the atmosphere of HD 63401. These patches can be formed and supported by the effective action of atomic diffusion (Michaud, 1970). We assert that its atmosphere may be hydrodynamically stable and therefore plan to search for evidence of vertical abundance stratifications of chemical elements in the star.

Acknowledgements. P.K and D.T are thankful to the Mitacs Globalink Research Internship program for the support of this research. V.K. and M.P.-C. acknowledge support from the Natural Sciences and Engineering Research Council of Canada. M.P.-C., O.K. and V.K. are thankful to the Faculté des Études Supérieures et de la Recherche and to the Faculté des Sciences de l'Université de Moncton for financial support for this research. Some of the calculations were performed on the supercomputer *béluga* of the École de technologie supérieure in Montreal, under the guidance of Calcul Québec and Calcul Canada. The analysed spectra were obtained at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii. The operations at the Canada-France-Hawaii Telescope were conducted with care and respect from the summit of Maunakea which is a significant cultural and historic site. This paper includes data collected by the *TESS* mission. Funding for the *TESS* mission is provided by the NASA Explorer Program. This research used the SIMBAD database, operated at CDS, Strasbourg, France. Photometric data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST).

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