K2 spots rotation in the helium star HD144941

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ABSTRACT

HD144941 is an evolved early-type metal-poor low-mass star with a hydrogen-poor surface. It is frequently associated with other intermediate helium-rich subdwarfs and extreme helium stars. Previous photometric studies have failed to detect any variability. New observations with the *K2* mission show complex but periodic variations with a full amplitude of 4 parts per thousand. It is proposed that these are due to an inhomogeneous surface brightness distribution (spots) superimposed on a rotation period of 13.9±0.2 d. The cause of the surface inhomogeneity is not identified, although an oblique dipolar magnetic field origin is plausible.

Key words: stars: chemically peculiar, stars: individual (HD 144941), stars: rotation, starspots

1 INTRODUCTION

HD144941 was reported helium-rich by MacConnell et al. (1970). The spectrum was shown to be metal-poor with a helium/hydrogen ratio ≈ 10 (Hunger & Kaufmann 1973; Harrison & Jeffery 1997; Jeffery & Harrison 1997; Beauchamp et al. 1997; Przybilla et al. 2005; Pandey & Lambert 2017). Its effective temperature and surface gravity are appropriate for a main-sequence B star, but it is 6 magnitudes too faint to be associated with the Sco-Cen OB2 association within which it lies (MacConnell et al. 1970). It has subsequently been compared with extreme helium stars, including the pulsating helium star V652 Her (Jeffery et al. 2001), which is known to be a low-mass evolved star.

Given their power for yielding distance-independent radii and masses, Jeffery & Hill (1996) sought evidence for pulsations in HD144941. Their failure to find light variations with semi-amplitudes > 0.0053 mag. on timescales between 8 hours and 50 days, or with semi-amplitudes > 0.0023 mag. on timescales between 6 minutes and 5 hours, was important. Like V652 Her, HD144941 has a temperature and radius within the instability zone for pulsations driven by an opacity bump associated with iron-group elements. Pulsation instability is enhanced by a deficiency in hydrogen, but reduced by a deficiency in metals (Saio 1993; Jeffery et al. 1999; Jeffery & Saio 2016). Thus the low metallicity in HD144941 is consistent with the absence of pulsations. Taken together, V652 Her and HD144941 con-

firmed the rôle of metals in driving pulsations in early-type helium stars.

A subsequent space-based photometric study of HD144941 using the *STEREO* satellites failed to detect any variability (Wraight et al. 2012).

HD144941 = EPIC 203109319 was observed during the *Kepler* follow-up mission *K2* and reported to show "other periodic or quasiperiodic variability" with a period of ≈ 7 d (Armstrong et al. 2016). Given the unusual properties of HD144941, the question arises as to the nature and cause of this variability. This paper presents the light curve (§ 2), examines its form in more detail (§ 3), and discusses the origin and implications of its variability (§ 4).

2 OBSERVATIONS

HD 144941 was selected as a target for *K2* (Howell et al. 2014) in Campaign 2 by Papics (GO 2010) as part of a wider project to study single B-type stars. It was observed in long cadence mode (one photometric point per 29.4 min) without significant interruption between 2014 Aug 23 and 2014 Nov 10 (MJD=56893.8–56971.3). During the course of a *K2* campaign, tiny adjustments are made to the spacecraft pointing. A number of groups have developed tools to mitigate the effects of these adjustments and have made 'cleaned' photometry publicly available. We have taken the light curve of HD 144941 as extracted by Vanderburg & Johnson (2014). To remove any residual long term trends in the light curve we detrended using a 3rd order polynomial. This light curve is shown in Fig. 1.
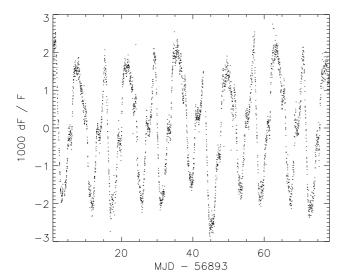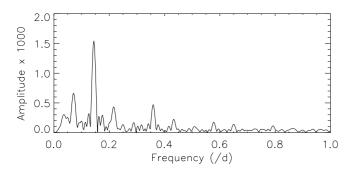
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Figure 1. The *K2* light-curve of HD144941 made between 2014 Aug 23 and 2014 Nov 10. The cadence is one photometric point per 29.4 min. We have normalised it so that the mean count rate is zero and the deviations are given in parts per thousand. We have also lightly detrended the light curve to remove residual long term variations.
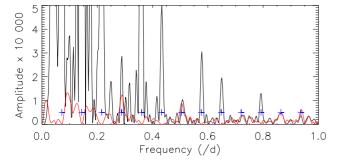

Figure 2. The amplitude spectrum of the *K2* light-curve of HD144941. Top and bottom: the amplitude spectrum of the complete data (black). Bottom: data prewhitened (red) by nine strongest harmonics and a contribution from low-frequency noise, together with locations of the fundamental period and eleven harmonics (blue crosses).
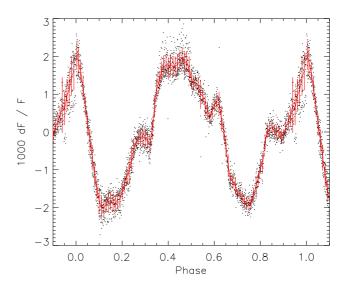

Figure 3. The *K2* light-curve of HD144941 folded on a period of 13.93 d (black dots) and binned (red symbols; error bars are standard deviations of data within each phase bin).

Table 1. Fourier decomposition of *K2* light curve of HD144941.

n	f (d^{-1})	a (‰)
1	0.07180(0613)	0.636
2	0.14403(0216)	1.531
3	0.21600(0778)	0.454
4	0.28814(2298)	0.142
5	0.35994(0700)	0.459
6	0.43217(1961)	0.163
8	0.57655(1918)	0.167
9	0.64886(2471)	0.129
11	0.79237(3024)	0.105
–	0.03240(1227)	0.284
–	0.05167(1754)	0.218

3 ANALYSIS

The *K2* light-curve in Fig. 1 suggests an apparent period of $\approx$ 7 d. Closer inspection shows that alternate cycles are more similar than consecutive cycles. Fourier analysis (Fig. 2) demonstrates a highly-structured singly-periodic signal, with a fundamental period of 13.9±0.2 d and multiple harmonics. Some low frequency power is also present, which is probably red noise. Prewhitening the data by the fundamental period, 8 harmonics and a red-noise contribution gives the residual amplitude spectrum shown in Fig. 2. The adopted frequencies (f in cycles per day) and amplitudes (a in parts per thousand - ‰) are shown in Table 1, with harmonics labelled as n. Detrending the red-noise signals allows the data to be phase folded, whilst phase binning at intervals of 0.01 cycles brings the light curve structure into sharper focus (Fig. 3).

Defining zero phase by the sharper of the two light maxima, the 13.9 d cycle shows two similar minima at phases 0.2 and 0.75, and shoulders on the ascending branches at phases

0.3 and 0.85. The two maxima are quite different in character. The segments which appear most similar are separated by ≈ 0.6 cycles and not an exact half cycle.

4 INTERPRETATION

This is the first high-definition light curve obtained for *any* strongly hydrogen-deficient star, albeit one having 10% hydrogen on its surface. At 4‰, the full-amplitude of the variation is less than half the lower limit for periods longer than one third of a day measured by Jeffery & Hill (1996). The period of 13.9 d is a factor of 100 too long to associate with radial pulsations such as seen in the comparable extreme helium star V652 Her, or in main-sequence β Cepheid variables (Aerts et al. 2010). A non-radial g-mode pulsation is unlikely on similar grounds. In either case, the highly-structured light curve is not anticipated from a small-amplitude pulsation, where a more sinusoidal form is anticipated.

It is proposed that the light curve in HD144941 is due to small-scale structure (or spots) on the stellar surface which rotates with a period of 13.9 d. This structure is dominated by a single dipole distribution, superimposed by small scale features which produce sharp jumps in total brightness as they appear onto or disappear from the visible hemisphere.

The difficulty is that HD144941 is a B-type star with an effective temperature of some 23 000 K (Harrison & Jeffery 1997). Since the surface layers should be completely radiative, it is difficult to explain how such structures should arise. A possible corollary is provided by the surfaces of other chemically peculiar B stars, notably the Bp(He) stars such as σ Ori E (Greenstein & Wallerstein 1958; Hesser et al. 1976; Walborn & Hesser 1976), where a strong magnetic field (≈ 7.5 kG, (Oksala et al. 2015)) modifies the local surface structure and emergent fluxes. Such stars show strong variations in light (0.2 mag in u, 0.1 mag in the *MOST* filter for σ Ori E) over the course of the rotation period (1.19 d) (Townsend et al. 2013). It is interesting that the HD144941 light curve is more structured than that of σ Ori E as measured from space with the *MOST* spacecraft (Townsend et al. 2013). With a much smaller amplitude ($\times 0.04$), HD144941 need only possess a weak, if complex, magnetic field in order to exhibit inhomogeneities sufficient to explain the *K2* light curve. If light amplitude scales with field strength, then a polar field of some 300 G would be sufficient, and detectable.

The question then becomes whether spots induced by magnetic fields are present on other evolved chemically peculiar stars. A magnetic-field origin for multi-periodic variability in the hydrogen-weak subdwarf LS IV-14 116 was suggested by Naslim et al. (2011), and ruled out by Green et al. (2011) and Randall et al. (2015). Long-term variability observed in the hydrogen-weak subdwarfs KIC1044976 (Jeffery et al. 2013) and UVO 0825+15 (Jeffery et al. 2017) has still to be explained.

An alternative line of thought has suggested that HD144941 might be a main-sequence Bp(He) star and not an evolved star, although the low metallicity ([Fe/H] $= -1.9 \pm 0.2$ Jeffery & Harrison (1997)) argues strongly against such a view. Given the apparent magnitude ($m_V = 10.14 \pm 0.01$), extinction ($E_{B-V} = 0.25 \pm 0.02$ (Jeffery et al. 1986)), effec-

tive temperature ($T_{eff} = 22\,000 \pm 1000$ K) and surface gravity ($\log g = 4.15 \pm 0.1$ (Przybilla et al. 2005)), only an accurate distance is necessary to estimate the mass. The TGAS survey provides a parallax for HD144941 = TYC 6788-284-1 of 0.00101 ± 0.00061" (Astraatmadja & Bailer-Jones 2016; Gaia Collaboration et al. 2016) which translates to a mass of $1.2 \pm 0.7\,M_\odot$. Although slightly large for the evolved star argument, this rules out the main-sequence star argument unless the distance is substantially increased in the second *Gaia* data release.

5 CONCLUSION

HD144941 has hitherto been known as a non-variable low-mass helium star with comparable dimensions to the pulsating helium star V652 Her. Its low metallicity accounts for the absence of pulsations, despite lying in the Z-bump instability strip.

Photometric observations with *K2* radically challenge this picture, demonstrating a 13.9 d light curve which can best be explained by the rotation of a star with an inhomogeneous surface brightness. Explaining the origin of the surface inhomogeneity presents major challenges. It will at least require spectroscopic evidence for a structured surface and a magnetic field on HD144941, data on the long-term behaviour of the light curve and evidence for similar phenomena on related hydrogen-deficient stars.

Whilst an alternative view of HD144941 as a chemically peculiar main-sequence star is convenient, the TGAS parallax measurement supports the argument for a low-mass evolved star. The *K2* observation has implications for interpreting the properties of other evolved hydrogen-deficient stars, including both extreme helium stars and hot subdwarfs; some of these must become targets for future space photometry missions.

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