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Letter to the Editor

Lithium-rich Cepheid V470 Cas*

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ABSTRACT

Aims. In this Letter, we report the discovery of a new lithium-rich yellow supergiant star – the Cepheid V470 Cas – that has a high lithium abundance, $\log A(\mathrm{Li}) = 3.29$. This is highly unusual for supergiant stars. V470 Cas is joining a very select group of lithium-rich Cepheids, with only nine members known to date in our Galaxy.

Methods. For the analysis of our high-resolution echelle spectrum obtained at the Canada-France-Hawaii Telescope, methods based on both local thermodynamic equilibrium (LTE) and non-local thermodynamic equilibrium (NLTE) assumptions were applied. In particular, the lithium abundance was derived by analysing the equivalent width of the 6707 Å line.

Results. Most lithium-rich Cepheids are located near the blue edge of the instability strip near the bottom of the Hertzsprung-Russell diagram. Their main sequence progenitors are distributed over a mass range of three to five solar masses. Of the nine lithium-rich Cepheids known, six are double-mode pulsators, including our programme Cepheid. It is very likely that the stars of this small group are entering the instability strip for the first time and have not yet passed the red giant phase. Therefore, they have not experienced the large-scale mixing event that could destroy lithium in their convective zones.

Key words. stars: variables: Cepheids

1. Introduction

Classical Cepheids are important for establishing the cosmological distance ladder and for studying stellar evolution but also for accurately mapping the chemical composition across our Galaxy. During the early analysis phase of an ongoing study on the abundances in Galactic Cepheids, we noticed one star (V470 Cas) with a remarkably large lithium equivalent width (EW). Strong lithium lines are very rarely seen in yellow supergiant spectra. While evolving from the main sequence (MS) and after exhausting the hydrogen fuel in its core, a B star expands and rapidly moves to the cooler region of the Hertzsprung-Russell (HR) diagram. Here the star approaches the blue edge of the instability strip (IS) and, upon entering this region, becomes a so-called first-crossing (of the IS) Cepheid. At a later phase, the star leaves the IS and continues its evolution as a red giant. The next stages of evolution include the core helium burning and the formation of the shell source. The star is then experiencing its second and third crossing of the IS. These evolutionary phases, as well as the previous stage as a red giant, are associated with dredge-up episodes. The deep mixing process occurring during these phases brings the surface material to the high temperature zone, where notably lithium nuclei can be "destroyed" in thermonuclear reactions with protons. As a result, the material returned to the stellar surface is ultimately depleted in lithium. Thus, for the great majority of Cepheids after the red giant stage, one can expect the lithium line to remain undetected in their spectra. This conclusion is confirmed by numerous spectroscopic studies of Cepheids. Nevertheless, very few Cepheids and non-variable yellow supergiants exhibit fairly strong lithium lines in their spectra (see text below). In this Letter, we present our analysis on the chemical composition of such a Cepheid, V470 Cas, focussing in particular on its large lithium abundance.

2. Programme Cepheid and observation details

V470 Cas was first classified as an eclipsing binary star (e.g. Hoffmeister 1964; see also Avvakumova et al. 2013). This classification was re-examined later on by Agerer et al. (1996) following a detailed study using charge coupled device (CCD) observations and Sonneberg sky patrol plates, leading them to propose a new classification for this star as a RRab variable with a pulsation period of 0.8744654 d. This classification was also adopted in the General Catalogue of Variable Stars. Later, this star was reclassified again. For example, in a very recent paper by Shah et al. (2022), the authors reported on their search of double-mode Cepheids from the Zwicky Transient Facility Survey. They found 72 new objects of this type, among them ZTF J013218.14+562958.1b (V470 Cas).

* Based on observations 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.

According to these authors, V470 Cas pulsates in two overtones (first and second) with periods of 0.87454 d and 0.70218 d, respectively (with a period ratio of 0.80291).

Our new spectroscopic observations of V470 Cas, as part of a survey focussing on Cepheids located near the Perseus arm, were carried out at the Canada-France-Hawaii Telescope (CFHT) on December 2, 2023. The fibre-fed ESPaDOnS echelle spectrograph equipped with the e2v 2048 × 4608 Olapa CCD (binned 1 × 1) was used with its star-only spectroscopy mode under queue observing. With this configuration, the resolving power is about 80 000 and the spectral range extends from about 3700 to 10 500 Å. A single exposure of 1400 s was obtained under a seeing of about 0.7″, photometric skies and an airmass of 1.27. The spectrum was processed by the CFHT ESPaDOnS Libre–Esprit pipeline. The resulting signal-to-noise ratio (S/N) at the continuum level depends upon the wavelength interval, but it is in the 50–80 range.

3. Parameters for V470 Cas and abundance calculations

The stellar atmosphere parameters ($T_{\rm eff}$, log g, and $V_{\rm t}$) were determined from standard procedures: (1) by avoiding any dependence between the iron abundance derived from the neutral iron lines and their EWs, ($V_{\rm t}$); (2) by using the line-depth ratio method proposed by Kovtyukh (2007), ($T_{\rm eff}$); and (3) by preserving the ionisation balance condition for iron abundance as derived from neutral and single ionised lines, (log g). The following results were obtained for V470 Cas: $T_{\rm eff} = 6157 \pm 87$ K, log $g = 2.2$, and $V_{\rm t} = 2.4$ km s^{-1}.

As a verification step, the effective temperature was also determined by avoiding the dependence between the iron abundance derived from the individual neutral iron lines and their excitation potentials. A value of $T_{\rm eff} = 6185 \pm 93$ K was obtained, very similar to the value above.

The abundances in V470 Cas were derived from both the local thermodynamic equilibrium (LTE) and non-local thermodynamic equilibrium (NLTE) approximations using stellar atmosphere models directly calculated from the ATLAS9 code by Castelli & Kurucz (2003) using the atmosphere parameters derived for our programme star. The oscillator strengths, log g, were adopted from the Vienna Atomic Line Database (VALD, Ryabchikova et al. 2015, version 2023). The reference solar abundances were taken from Asplund et al. (2009) for LTE abundances, and calculated by us using the solar spectrum and NLTE programme (relevant data are available in the papers listed below).

For the NLTE calculations we applied atomic models that have been described in several papers, namely:

- Carbon: Andrievsky et al. (2001), Lyubimkov et al. (2015).
- Nitrogen: Lyubimkov et al. (2011), Andrievsky et al. (2021).
- Oxygen: Mishenina et al. (2000), Korotin et al. (2014).
- Sodium: Korotin & Mishenina (1999), Dobrovolskas et al. (2014).
- Magnesium: Mishenina et al. (2004), Černiauskas et al. (2017).
- Aluminium: Andrievsky et al. (2008), Caffau et al. (2019).
- Sulphur: Korotin (2009).
- Potassium: Andrievsky et al. (2010), Korotin et al. (2020).
- Calcium: Spite et al. (2012), Caffau et al. (2019).
- Copper: Andrievsky et al. (2018).
- Strontium: Andrievsky et al. (2011).
- Barium: Andrievsky et al. (2009).

Table 1. LTE elemental abundances in V470 Cas.

Ion	Code	[El/H]	σ	NL	(El/H)
Li I	3.00	+2.13	–	1	3.29
C I	6.00	–0.32	0.16	8	8.24
N I	7.00	–0.19	0.32	5	7.96
Na I	11.00	–0.11	0.22	2	6.22
Mg I	12.00	–0.38	0.30	2	7.30
Al I	13.00	–0.09	0.12	4	6.21
Si I	14.00	–0.52	0.14	9	7.08
Ca I	20.00	–0.15	0.09	6	6.23
Sc II	21.01	–0.35	0.17	3	2.90
Ti I	22.00	–0.19	0.09	6	4.84
Ti II	22.01	–0.35	0.22	5	4.68
V I	23.00	–0.05	–	1	4.06
Cr I	24.00	–0.43	0.12	3	5.33
Cr II	24.01	–0.22	0.08	5	5.54
Mn I	25.00	–0.52	0.07	3	5.02
Fe I	26.00	–0.48	0.07	84	7.10
Fe II	26.01	–0.48	0.06	20	7.10
Ni I	28.00	–0.44	0.12	10	5.86
Y II	39.01	+0.10	0.11	7	2.29
Zr II	40.01	–0.05	0.05	2	2.84
La II	57.01	+0.13	0.12	6	1.46
Ce II	58.01	–0.06	0.08	5	1.65
Nd II	60.01	–0.14	0.17	6	1.38
Sm II	62.01	–0.22	0.04	3	0.88
Eu II	63.01	–0.09	–	1	0.87

Notes. Only lines with EW < 110 mÅ were used. NL is the number of lines used, [El/H] is the abundance relative to the solar value, and (El/H) is the absolute abundance value on a scale where the hydrogen abundance is 12.00.

In order to find the atomic level populations for the ions of interest, we employed the code MULTI (Carlsson 1986). This programme was modified by Korotin et al. (1999). MULTI enables calculations of a single NLTE line profile. When the line of interest is blended, we performed the following procedure: with the help of MULTI, we first calculated the departure coefficients for those atomic levels that are responsible for the formation of the considered line. Afterward, we included these coefficients in the LTE synthetic spectrum code SYNTHV (Tsymbal et al. 2019). This allowed us to calculate the source function and opacity for each line investigated. Simultaneously, the blending lines were calculated in LTE with the help of the line list and corresponding atomic data from the VALD database (Ryabchikova et al. 2015) in the wavelength range of the line under study.

4. V470 Cas chemical composition

The results from the LTE and NLTE abundance calculations for V470 Cas are presented in Tables 1 and 2, respectively. We note that in some cases the number of lines used for the NLTE analysis is greater than that of the LTE analysis. The reason for this is the following. In the LTE analysis, we only used line EWs less than 110 mÅ, while in the NLTE analysis (line profile synthesis) this limitation is absent. For some elements (e.g. Sr and Ba) with very strong lines in the V470 Cas spectrum, we used only the NLTE analysis. The NLTE abundances of some elements listed in Table 2 further stress how sensitive they may be to NLTE effects. A striking example is

Table 2. NLTE elemental abundances in V470 Cas and corresponding LTE abundances derived using the same line and MULTI code in the regime of the LTE approximation.

Ion	Code	[El/H]	σ	NL	$(El/H)_{NLTE}$	$(El/H)_{LTE}$
C I	6.00	−0.30	0.12	8	8.16	8.51
N I	7.00	−0.28	0.10	8	7.58	7.78
O I	8.00	+0.00	0.10	4	8.71	9.61
Na I	11.00	−0.26	0.10	4	5.99	6.41
Mg I	12.00	−0.22	0.08	10	7.32	7.30
Al I	13.00	−0.33	0.10	4	6.10	6.04
S I	16.00	−0.26	0.12	7	6.90	7.11
K I	19.00	−0.27	0.10	2	4.84	6.00
Ca I	20.00	−0.13	0.08	17	6.18	6.32
Cu I	29.00	−0.18	0.12	3	4.07	3.78
Sr II	38.01	+0.68	0.20	2	3.60	3.82
Ba II	56.01	+0.71	0.10	4	2.88	2.98

Notes. NL is the number of lines used, [El/H] is the abundance relative to the solar value, $(El/H)_{NLTE}$ is the absolute NLTE abundance value on a scale where the hydrogen abundance is 12.00, and $(El/H)_{LTE}$ is the LTE abundance obtained using the same lines as in NLTE. We have calculated the NLTE abundances in the Sun as the zero point for NLTE differential [X/H].

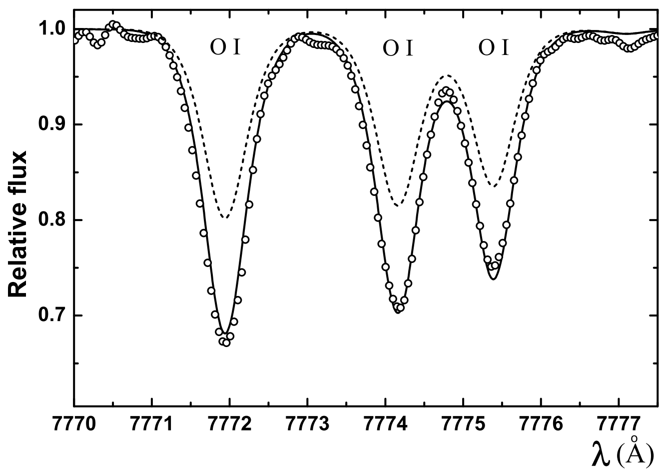

Fig. 1. NLTE synthetic profiles of O I 7771−5 Å triplet lines (solid line) and observed profiles (open circles). LTE profiles were calculated with the same abundances as NLTE profiles (dashed line).

the oxygen abundance. In Figs. 1 and 2 we show the NLTE synthetic fit for the infrared oxygen lines in the V470 Cas spectrum.

It is important to note that the abundances of carbon and nitrogen do not show a sign of the deep mixing characteristics of Cepheids (after that carbon becomes deficient, while nitrogen is overabundant) affected by dredge-up (see, for example, the recent paper by Luck 2018). The lines of Ba and Sr are strong (more than 200 mÅ and more than 350 mÅ, respectively; for example the range of the EWs for the oxygen triplet lines is 120−150 mÅ). Therefore their abundances in V470 Cas should be taken with caution, despite those abundances being derived using the NLTE approximation. The problem may lie in the sensitivity of the abundance of these elements to the adopted microturbulent velocity.

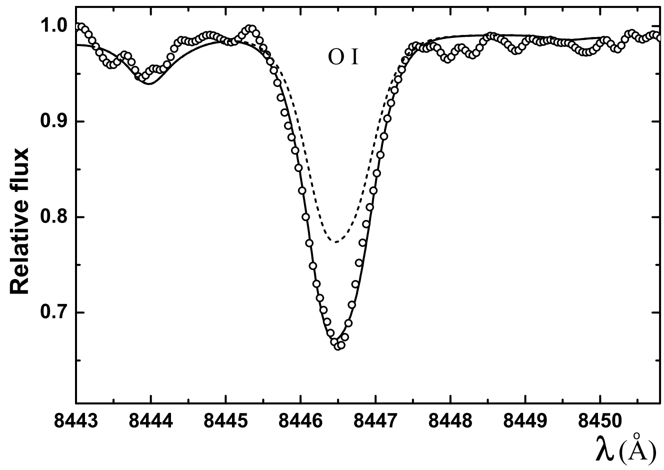

Fig. 2. NLTE synthetic profile of the O I 8446.5 Å blend (solid line) and observed profile (open circles). LTE profiles were calculated with the same abundances as the NLTE profile (dashed line).

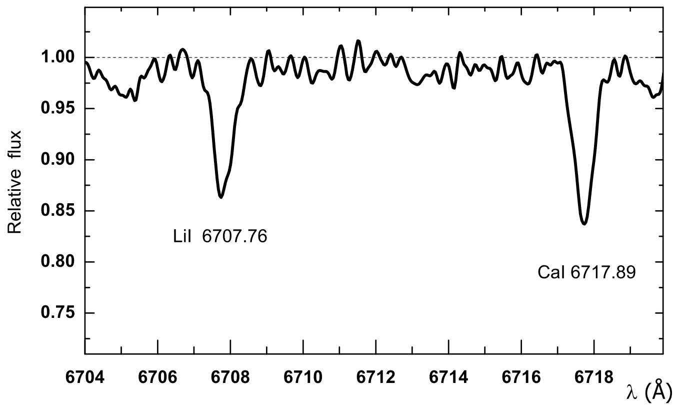

Fig. 3. Lithium line in the spectrum of V470 Cas.

5. Lithium in V470 Cas and other lithium-rich Cepheids

Figure 3 shows the lithium line in the spectrum of V470 Cas. As mentioned above, a rather strong lithium line was also detected in the spectra of a few other Cepheids in previous studies. Table 3 lists those stars, as well as some of their properties.

In Table 3 we see that V470 Cas has the third highest lithium content among all lithium-rich Cepheid stars discovered thus far. The lithium lines in the spectra of the Cepheids listed in Table 3 are described in Kovtyukh et al. (in prep.) and Kovtyukh (2023). Since we do not have the NLTE atomic model for lithium, we estimated the NLTE correction by interpolation within the grid of Lind et al. (2009). For the stellar parameters as derived earlier for V470 Cas, the corresponding correction is very small: −0.09 dex. In Fig. 4 the locations of all the known lithium-rich Cepheids are displayed in a HR diagram.

6. Conclusion

We have discovered a new lithium-rich Cepheid, V470 Cas, thereby increasing the number of such known yellow pulsating supergiants with a high lithium content to nine stars. Six of the nine discovered Li-rich stars are double-mode pulsators. All of these Cepheids are located at or near the blue edge of the IS. Thus, it can be concluded that after a short evolutionary

Table 3. Properties of the lithium-rich classical Cepheids and supergiants.

Star	Mode	Period (days)	$T_{\rm eff}$ (K)	log g	$V_{\rm t}$ (km s^{-1})	[Fe/H]	(Li/H)	Remarks
Galaxy:								
OGLE GD-CEP-0516	P2/P1	0.394959 (P1)	6526	2.4	1.4	0.01	3.60	Kovtyukh (2023)
ASAS 075842–2536.1	P2/P1	0.41013 (P1)	6295	2.4	2.4	−0.16	2.84	Kovtyukh et al. (2019)
V363 Cas	P2/P1	0.546597 (P1)	6660	2.0	2.2	−0.30	2.86	Catanzaro et al. (2020)
V470 Cas	P2/P1	0.87454 (P1)	6157	2.2	2.4	−0.48	3.29	This work
ASAS 131714–6605.0	P2/P1	0.913165 (P1)	6308	2.4	3.0	0.05	2.96	Kovtyukh et al. (2019)
V371 Per	P1/P0	1.738 (P0)	5973	2.2	3.7	−0.42	3.35	Kovtyukh et al. (2016)
V1033 Cyg	P0	4.9375119	5819	1.9	2.7	0.01	3.20	Luck & Lambert (2011)
V708 Car	P0	51.403084	5206	1.3	4.3	−0.40	1.95	Kovtyukh et al. (in prep.)
Non-variable supergiants								
HD 174104			5854	2.6	5.0	+0.16	3.46	Luck (1982), Andrievsky et al. (1999)
HD 172365			5978	1.3	7.5	−0.07	2.90	Luck (1982)
LMC:								
HV 5497	P0	99.156076	4850	0.53	4.0	−0.20	1.64	Luck & Lambert (1992)

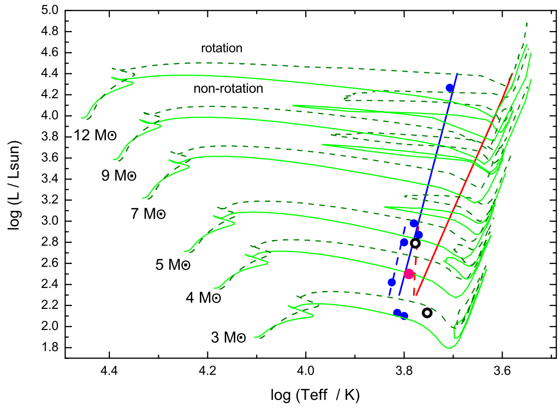

Fig. 4. HR diagram displaying the location of our programme Cepheid V470 Cas (red circle) and the other lithium-rich Cepheids described in the literature (blue circles). Evolutionary tracks are from Ekström et al. (2012) for 3−12 solar masses with and without rotation. The blue and red lines denote the blue and red boundaries of the IS for classic Cepheids (solid lines) and first-overtone Cepheids (dashed lines). Open circles indicate the positions of the lithium-rich non-variable supergiants.

transition between the MS as a B star to the blue edge of the IS, the newborn Cepheid retains its primordial lithium content, and this is confirmed by spectroscopic analysis. However, the question remains open as to why do other low-luminosity Cepheids, presumably crossing the IS for the first time and not going through the red giant phase with subsequent large-scale mixing, do not similarly show a large lithium abundance? This is an important question for the theory of stellar evolution, and it has no answer yet.

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