DISCOVERY OF TWO LITHIUM CEPHEIDS IN THE GALAXY

V.V. Kovtyukh[1] , G. Wallerstein[2], and S.M. Andrievsky[1]

[1] Department of Astronomy, Odessa State University
T.G.Shevchenko Park, Odessa 65014 Ukraine, *val@deneb.odessa.ua*

[2] Department of Astronomy, University of Washington, Seattle, WA 98195

ABSTRACT. We report about the discovery of two lithium Cepheids in the Galaxy, based on observations made with the echelle spectrograph of the Apache Point Observatory. We have used high-resolution, high signal-to-noise spectra to determine abundances of chemical elements in 16 classical Cepheids. Only two of our program stars show a lithium line, RX Aur and YZ Aur (RX Aur has been also classified by us as a new non-radial pulsator). For the others, including the stars with [N/C]<0.2, Li is depleted up to <logN(Li)=1.0 or somewhat less. Hence it appears that mixing depletes Li before stars enter the instability strip. According to stellar models the main mixing event takes place when $T_{\rm eff}$ drops below 4000 K, which is outside the red edge of the instability strip; i.e. after stars have crossed the instability strip for the first time.

Key words: Stars: abundances; stars: lithium; cepheids: non-radial pulsation; Cepheids:instability strip.

1. Introduction

The study of lithium content as a function of effective temperature, rotation and deepening of the convective zone is a key problem for our understanding of stellar convective mixing.

Cepheids have masses of roughly 3–9 $M_\odot$. Hence they are relatively young stars. After leaving the main sequence they evolve to the right in the HR diagram. In so doing they pass through the instability strip (IS). As they evolve toward even cooler temperatures they reach an effective temperature ($T_{\rm eff}$) of 4000 K, near which their convective envelopes reach down to the level at which they have depleted their lithium and scooped up material that had been subjected to the reactions of the CN cycle. After this "first dredge-up" the N/C ratio rises significantly, about a factor of 4. Since the IS does not reach $T_{\rm eff}$ values as low as 4000 K, stars that are crossing the instbility region for the first time should not show the enhanced lithium abundance that is expected for stars that have mixed.

2. Observations and data reduction

The new spectra were obtained with the echelle spectrograph of the Apache Point Observatory (APO). By using a prism as cross-disperser the APO echelle covers all wavelengths from 3500 to 10 400 Å. The resolving power is about 35 000. Exposure times were usually about 10–30 minutes. We estimated the S/N ratio at the continuum level depending upon the wavelength interval to be about 80–150.

The continuum level placement, wavelength calibration and equivalent widths measurements were performed with DECH20 code (Galazutdinov, 1992).

3. The parameters and abundances

To determine the effective temperatures for our program stars we employed the method of Kovtyukh & Gorlova (2000) based on $T_{\rm eff}$– line depth relations. This technique allows the determination of $T_{\rm eff}$ with an exceptional precision. It relies on the ratio of the central depths of two lines that have very different functional dependences on $T_{\rm eff}$ (note that tens of pairs of lines are used in analysis). The method is independent of the interstellar reddening and only marginally dependent on individual characteristics of stars, such as rotation, microturbulence, metallicity and others.

The microturbulent velocities and gravities were found using modification of the standard analysis proposed by Kovtyukh & Andrievsky (1999). In this method the microturbulence is determined from Fe II lines (instead of Fe I lines, as used in classic abundance analyses).

Elemental abundances were calculated with the help of the Kurucz's WIDTH9 code. As usual, the reference abundances are adopted following Grevesse et al. (1996).

4. The lithium abundance in two cepheids

For a long time no classical Cepheids and supergiants were known to show a Li line. Luck (1982) found two lithium supergiants – HD 172365 and HD 174104 in the Galaxy. Luck & Lambert (1992) discovered lithium in the LMC Cepheid HV 5497.

We have detected the Li I 6707.8 Å line in two stars – RX Aur and YZ Aur. In Figs. 1, 2 we show the Li region in several spectra of RX Aur and YZ Aur, also we show this region in spectrum of usual Cepheid δ Cep without lithium line. For RX Aur the mean value of logN(Li) = 1.81 ±0.09, while for YZ Aur logN(Li) = 1.66 ±0.06. These estimates can be compared to the solar system lithium content: logN(Li) = 1.1 for the Sun and 3.3 in meteorites (Lodders, 2003). Assuming that Cepheids started with the meteoritic abundance, the bulk of the Cepheids have depleted their lithium by at least 2.3 dex while RX Aur and YZ Aur – by only 1.6 dex. According to the theory (see de Laverny et al. 2003), the lithium depletion begins when a star of about 3 $M_\odot$ reaches $T_{\rm eff}$ = 6400, and lithium abundance becomes logN(Li) = 1.0 at about $T_{\rm eff}$ = 5500 K. This agrees with our observation that the upper limit on logN(Li) = 1.0 for the great majority of our program stars.

The first dredge-up is expected to occur at nearly $T_{\rm eff}$ = 4000 K which lies outside the IS (Petroni et al., 2003). It seems that the mixing processes that involve Li in this stars was more complicated than in the standard models.

Also RX Aur and YZ Aur have broadened spectral lines of all elements. Altogether this could be a sign that these two Cepheids are crossing the IS for the first time (Bersier & Burki, 1996). Another example of the first-crossing Cepheid is SV Vul (Luck et al. 2001). RX Aur, YZ Aur and SV Vul show the following common peculiarities:

1. The width of the spectral lines in RX Aur and YZ Aur are larger than in other Cepheids (rotation? macroturbulence? non-radial pulsation?). But it should be noted that at the same time the spectra SV Vul show sharp lines (maybe we see a polar region of SV Vul).

2. Pulsational period is about constant for RX Aur and YZ Aur or even decreasing (SV Vul), but the evolutionary calculations predict a rapid increase of period for the first-crossing Cepheids (see, for example, Bono et al. 2000, Turner & Berdnikov 2004).

Nevertheless such predictions cannot be considered as being reliably grounded and definitive. Really, just before entering the red giant phase the first crossing Cepheid suffers a sudden decrease of luminosity. During this stage its radius does not increase, on the contrary it can even decrease, causing the period decreasing. For example, observational data of Szabados (1978) testify against an observed increase of pulsational periods in the first crossing Cepheids. Standard evolutionary models do not describe adequately period changes in galactic Cepheids, as well as in Magellanic Cloud Cepheids (Pietrukowich 2001, 2002, 2003).

Our results may indicate that mixing begins long before the red giant stage. In fact the strength of convection could be much higher than it is predicted by

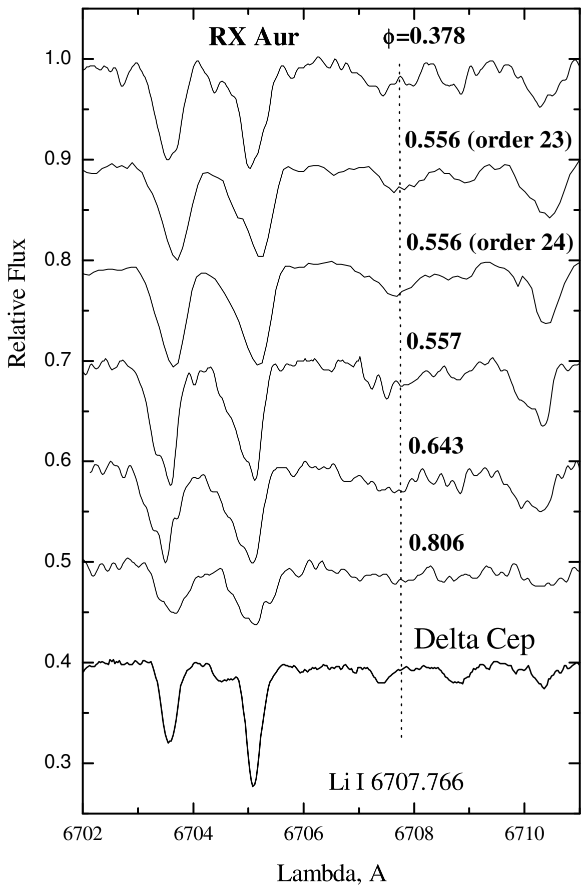

Figure 1: The Li region in RX Aur spectrum. Pulsational phases are shown. For the sake of clarity the continuum level is equally shifted. We see also unusual line profiles with small blue-shifted sharp bumps in some phases, that could be explained by non-radial pulsations excited in this Cepheid (see text for details). The resolving power is R=35000 for ϕ=0.556 and R=80000 for others phases.

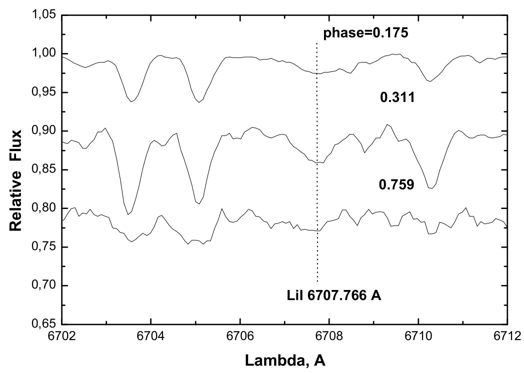

Figure 2: The same as Fig. 1, but for YZ Aur spectrum.

the standard stellar evolution theory. If one increases the convective mixing length, say, by two times, then the red giant branch appears to be shifted by several hundreds degrees towards the higher temperatures. At the same time this also shifts leftwards the region of the sharp luminosity decrease for the first-crossing Cepheids, and this region can fall on the IS (see Cordier et al. 2003). Since the both luminosity and temperature decrease within this region, this means that the Cepheid radius is about constant, and we will not be able to detect any significant period change.

5. RX Aur - a new non-radial pulsator

Unlike in the non-variable supergiants, the profiles of the Cepheids vary with phase. In the paper of Kovtyukh et al. (2003), among the 99 program stars the four unusual Cepheids were found (BG Cru, V1334 Cyg, EV Sct and X Sgr) that show interesting absorption bumps in the wings of spectral lines. Three of them (BG Cru, V1334 Cyg, EV Sct) are s-Cepheids (it is quite possible that X Sgr is s-Cepheid too). It was also noted that these four Cepheids have rather large widths of the spectral lines.

Kovtyukh et al. have suggested that the observed bumps in the line profiles in some Cepheid spectra can be considered as a combined effect of the rather high broadening (either due to rotation or macroturbulence) and a resonant interaction between the radial modes that produces the non-radial oscillations. The presence of non-radial pulsation effectively divides the visible surface of a star into sectors with different velocity fields and temperatures, and these regions redistribute the light in a rotationally broadened absorption profile to create the time-dependent bump pattern.

We have carefully re-examined available high-resolution spectra (R=80 000) of RX Aur, and found weak absorptional blue bumps at ϕ=0.557 (see Fig. 1). Note that RX Aur and X Sgr demonstrate an unusual similarity in the spectral line profiles at common phases near 0.55, where the non-radial effects are well seen. It should be noted that the effect is much more prominent in X Sgr than in RX Aur.

RX Aur has a larger period (P=11^d.6235) than the other five discussed Cepheids. Interestingly enough, unlike them, its pulsation amplitude is the smallest among the other 11 day fundamental Cepheids. This might be considered as additional confirmation of its status as a first-crossing Cepheid. Actually, having not reached the red giant phase, RX Aur did not experienced yet the dredge-up. Thus, it should have a smaller than ordinary Cepheids helium content, and therefore the smaller pulsational amplitude.

The total number of Cepheids with broadened lines which are known at present is 12. Only two of them, RX Aur and YZ Aur, show Li line. Five of them show obvious signs of the non-radial pulsations. The existence of the other seven Cepheids with measurable rotation but without visible bumps indicates that rotation is a necessary but not sufficient condition for an excitation of the non-radial pulsations. Looking at the common properties of the Cepheids with non-radial pulsations, one can note that among their similar features there are also small pulsation amplitude and period value that is close to the resonace between possible overtones and fundamental mode. For instance, RX Aur has its period value also near the well known 10 day resonance.

6. Summary

We discovered two lithium Cepheids in the Galaxy among more than 150 investigated program stars. These two cepheids (RX Aur and YZ Aur) show the presence of the resonance Li lines. They also show line broadening that indicates to their rather high rotation. Moreover, we conclude that RX Aur could be a non-radial pulsator.

Acknowledgements. The authors would like to thank Dr. R.E. Luck for the use of its spectroscopic data. The authors thank Drs. B. Carney and A. Fry for kindly provided KPNO spectra of RX Aur.

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