HP Lyr – possibly the hottest RV Tau type object

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ABSTRACT

We report Johnson's $UBVRI$ photometric and optical spectroscopic observations of a long period variable HP Lyr which up to now has been considered an eclipsing binary with a period of 140 days. The spectral type changes continually from A2-3 at maxima to A7-F2 at minima. We propose that the brightness changes are caused by the pulsation of the star with two periods: $P_1 = 69.35$ days and $P_2 = 2 \times P_1 = 138.7$ days. These periods decreased by more than 1\% between 1960 and 1980. The spectral luminosity class determination gives an A type supergiant Iab. HP Lyr is also the optical counterpart of the infrared source IRAS 19199+3950. Relatively high galactic latitude ($b = +11.7^\circ$) and high radial velocity ($-113$ km/s) indicate that HP Lyr is an evolved, most likely post-AGB star. All presented features argue that this star is an RV Tau type object.

Key words: binaries: eclipsing – variable: RV Tau stars – individual: HP Lyr

1 Introduction

The star HP Lyr is a poorly known long-period variable discovered by Morgenroth (1935). The photographic photometry showed the light curve of a semiregular type with the amplitude of brightness variations $\Delta m_{pg} = 0.5$ and the period of 70.4 days (Sandig 1939). The brightness at maximum was $10^m 5$ in $m_{pg}$ and no secular changes of it were reported. Wenzel (1960) determined the spectral type of the variable as A6 and proposed that HP Lyr be an eclipsing binary consisting of a pair of A6 stars orbiting in a circular orbit with the period of $\sim 140$ days. He classified the light curve as a $\beta$ Lyrae type with both minima of similar depth.
Table 1: Journal of the spectroscopic observations of HP Lyr

| Date          | JD        | Phase | Exp. (min) | λ λ (nm) | Disp. (Å/pix) | Spec. class | T eff (K) | Rad. vel. (km/s) | N° | O° |
|---------------|-----------|-------|------------|----------|--------------|-------------|-----------|------------------|----|----|
| 26/27.08.00   | 1783.375  | 0.693 | 30         | 375-480  | 2.0          | A4          | 8500      | -81 ± 8         | 3  | T  |
| 05/06.09.00   | 1793.375  | 0.765 | 40         | "        | "           | A5          | 8200      | -112 ± 15       | 3  | T  |
| 09/10.09.00   | 1797.374  | 0.794 | 30         | "        | "           | A5          | 8200      | -102 ± 10       | 3  | T  |
| 17/18.09.00   | 1805.377  | 0.851 | 60         | 625-665  | 0.8          | -          | -122 ± 2   | 14 T            |    |    |
| 19/20.10.00   | 1837.258  | 0.081 | 60         | "        | "           | -          | -135 ± 4   | 11 T            |    |    |
| 27/28.11.00   | 1876.189  | 0.362 | 60         | 625-665  | 0.8          | -          | -123 ± 3   | 13 T            |    |    |
| 02/03.05.01   | 2032.433  | 0.489 | 20         | 350-550  | 2.0          | F2          | 7000      | -88 ± 8         | 5  | P  |
| 08/09.05.01   | 2038.388  | 0.529 | 60         | 625-665  | 0.8          | -          | -106 ± 5   | 15 T            |    |    |
| 24/25.05.01   | 2054.538  | 0.648 | 10         | 350-550  | 2.0          | A3          | 8800      | -135 ± 9        | 5  | P  |

\(a\) The number of lines

\(b\) T – Tartu Observatory, P – Piwnice Observatory

2 Observations

HP Lyr was one of the targets in our project of UBVRI photometric monitoring of long period binaries in Piwnice Observatory of Nicolaus Copernicus University in Toruń (Poland). The photometry was carried out during 1998 and 1999 using a one-channel photometer on the 60-cm Cassegrain telescope equipped with EM19585B photomultiplier. As a comparison star, we chose a very close to HP Lyr A0V star HD 182592 (\(V=8.01, \, U - B=0.06, \, B - V=0.07, \, V - R=0.07, \, R - I=0.01\)). The effective wavelengths of our instrumental \(ri\) bands were significantly shorter than those of Johnson’s system: 6390 Å and 7420 Å, respectively. Nevertheless, for a single star we can use the formal transformation, found by observations of Johnson’s standards: \((R-I) = 1.40(r-i)\), and \(R = r - 0.37(R-I)\). Our original data are presented on Fig. 1. The mean observational errors were 0.04, 0.03, 0.01, 0.01, 0.03 in particular UBVri bands, respectively.

We have obtained some CCD spectrograms of this star in Tartu Observatory in Estonia and two spectra in Piwnice Observatory. The observations were carried out using the Cassegrain grating spectrographs attached to 1.5m (Tartu) and 0.9m (Piwnice) telescopes. Table 1 presents the journal of all our spectroscopic observations and results of the radial velocity measurements and the spectral class classification. The spectra were reduced under the IRAF and the MIDAS packages.

3 Period searching

We have performed frequency analysis of our photometric observations using the Lomb-Scargle periodograms (Lomb 1976, Scargle 1982). In each band we
Figure 1: Johnson's $UBV$ and instrumental $\Delta r$, $\Delta i$ light curves of HP Lyr in 1998/99 obtained in Piwnice Observatory. The filled squares denote a part of the light curves where the amplitude of the brightness changes was typical for HP Lyr i.e. 0.5 mag in $V$ band. B light curve was shifted by -0.1 mag for clarity of the picture.
detected a strong peak at the frequency of about $f_1 = 0.0144$ (69.5 days) and the second one at a frequency $f_2 = 0.0072$ (139 days), whereas two sidelobes around $f_1$ signal reflect the shape of the spectral window (Fig. 2). These two detected signals $f_1$ and $f_2$ are in the 2:1 resonance. The mean period derived from $f_1$ frequency obtained in all filters and assuming a 2:1 resonance is $P = 139.4 \pm 0.7$ days, i.e. about 1% less than the previous estimations (Wenzel 1960, Kreiner et al. 2001).

Looking for the ephemeris of HP Lyr we have carried out the timing analysis of observed minima. The Wenzel’s (1960) original ephemeris:

$$\text{Min I} = \text{JD} 2426910 + 140.75E.$$  \hspace{1cm} (1)

was based on 66 independent moments of 56 photographically observed minima between 1931 and 1959. His O-C’s residua are shown in Fig.3 for $E < 72$. During 1960-1980 there were no observations mentioned in the literature. Since 1981 several moments of minima, estimated visually, were observed by Tristram Brelstaff (JD 2444817, 2444893, 2445171, 2445240, 2445510, 2445587, 2446217, 2447807) and published in a number of BAA VSS circulars (Markham and Pickard 2001). The next set of minima dates was collected by Kreiner et al. (2001). These data contain photometric and visual observations done by
Figure 3: O-C diagram for "primary" (dots) and "secondary" (open circles) minima calculated according to the original Wenzel’s ephemeris (Eq. 1). Two straight dashed lines correspond to the abrupt period change solution (Eq. 1 and 3) and the dashed-dotted line correspond to the cubic solution: Eq. 2.

W. Braune et al. (JD 2445236.5, 2445309.2) and J. Heubscher et al. (JD 2445516, 2445565.6, 2449464.0, 244953.0, 2450998.2, 2451062.6) and were published in several issues of B.A.V.Mitt. We have also added two moments of minima from our observations: JD 2425062.0 and JD 2451341.0 (Fig. 1).

All data after 1980 ($E > 120$) show significant deviation from Wenzel’s ephemeris (Fig. 3). We found a satisfactory, cubic solution connecting all minima which is presented in Fig. 3:

$$\text{Min I} = \text{JD 2 426 907} + 140^{d}74^{m} E - 0^{d}0043 E^2 - 4^{d}9 \cdot 10^{-5} E^3 \quad (2)$$

However the second possibility – the linear equation for the later data – gives a slightly better fit assuming the existence of an abrupt period decrease:

$$\text{Min I} = \text{JD 2 444 893} + 138^{d}66^{m} (E - 128). \quad (3)$$

The numbers $E$ are the same as in Wenzel’s ephemeris (Eq. 1). Epoch $E = 128$ corresponds to the first observed "primary" minimum after the 1960-1980 gap. If the abrupt period change is real, it should most probably occur in 1974 at the 112th cycle according to Wenzel’s ephemeris. Observations should soon distinguish between the cubic and the linear ephemeris.
4  Eclipsing or pulsating star?

Our photometry shows that initially the amplitude of the light variations was about 0.05 in V band, slightly smaller in red ri filters and was raising in blue filters up to 1.0 (U band). But, after about JD 2451150, all amplitudes decreased by a factor of two, whereas the mean brightness remained unchanged (Fig. 1). This is rather not typical behaviour for an eclipsing binary and we decided to show the mean light curves using V − R and R − I transformed Johnson colours (Fig. 4). Our V light curve in Fig. 4 resembles the β Lyr type curve with a slightly deeper "primary" minimum at phase 0.5. However, we have a gap in observations around phase 1.0. Also, the colour index curves seem to be deeper at phase 0.5. This fact is confirmed by our spectral observations which give earlier spectral type and higher temperature around phase 1.0 than around phase 0.5 (Fig. 5). Wenzel (1960) reported that both minima are of similar depth but the inspection of his photographic light curve shows that the minimum numbered by him as 1 (phase 0.0) may be slightly deeper. This alternation between the depth of minima is very difficult to understand in a binary system. It is real if the cubic solution (Eq. 2) is a valid model of both sets of the data in Fig. 3. On the other hand, if the binary consists of two similar stars, then any mass loss or exchange of matter should lead to an increase (not a decrease) of the orbital period.

In order to rule out definitively the binary hypothesis we have calculated synthetic light curves using WD code (Wilson & Devinney 1971). In general, only the ellipsoidal variations in a binary system can produce reddening of both minima. Especially in early type stars with radiative envelopes, a significant gravitational reddening effect should be expected following von Zeipel's (1924) theorem. We have tested two possible models with extreme von Zeipel's effect: 1) an overcontact binary with two similar and evolved A6 components and 2) a semidetached binary consisting of an A6 star filling its Roche-lobe and massive, compact, optically invisible companion. Both ellipsoidal models can roughly reproduce the V band light curve but failed to reproduce the colour variations – Fig. 4. No binary model can explain the observed reddening with the amplitude about Δ(B − V) ≈ 0.3 during both minima.

Changes of colours create complex loops on the U − B, B − V diagram (Fig. 6). However, they show a general trend to align with the supergiant sequence from A2 at maximum to F0 at minimum with constant E(B − V) = 0.42. Nearly the same spectral changes from A3 at maximum to F2 at minimum (Fig. 8), were obtained from our blue spectra (Table 1) using MK criteria by Morgan et al. (1978). The temperature changes derived from Straizys' (1982) calibration strictly follow the light and colour variations (Fig. 5). The most probable explanation of this behaviour is pulsations of a single star. Although our radial velocity data are insufficient for interpretation in terms of pulsations, they can preclude the binary model. It is not possible to join the four radial velocity points obtained from metallic lines (Fig. 5) by one sinusoidal line with the con-
Figure 4: $V$ photometry and colour indices folded up according to Eq. (3). The fits with the extremal gravitation darkening effect are shown with $V$ and $B - V$ data. Continuous line: overcontact model for two A6 giants ($\Omega_1=\Omega_2=3.27$, $i=62^\circ$), dashed one: semidetached model with invisible companion ($q=M_{A6}/M_{inv}=0.2$, $i=90^\circ$).

Figure 5: Upper panel: radial velocities of HP Lyr from Balmer lines (blue spectra – open circles) and metallic lines (red spectra – filled circles). Bottom: the effective temperature resulting from derived spectral type.
Figure 6: $U - B$, $B - V$ colour-colour diagram of our photometry of HP Lyr. Main sequence and supergiant theoretical colours are marked by continuous lines (Straizys 1977). Dashed lines – the reddenings of the maxima and the minima correspond to $E(B-V) \sim 0.42$. Filled squares and open circles have the same meaning as in Fig. 1.

dition of crossing the barycentric velocity close to spectroscopic conjunctions (“eclipses” at phases 0.0 and 0.5).

5 Evolutionary status

The supergiant luminosity class Ib-Iab was derived by comparison with the spectra of the MK standards – Fig. 7. However, relatively high galactic latitude ($b = +11.7^\circ$) and high radial velocity ($-113$ km/s) indicates that HP Lyr is most likely an evolved star of Intermediate Population II. The massive young object of Population I stars should be expected close to the Galactic plane. The spatial distribution of the interstellar extinction at the same galactic longitude ($l = 70^\circ - 75^\circ$), but lower latitude ($b = 5^\circ - 6^\circ$) shows practically constant extinction $A_v = 1.2 - 1.6$ above a distance of about 1.5 kpc (Neckel & Klare 1980, Mikolajewska & Mikolajewski 1980). This value of $A_v$ corresponds well to $E(B-V)$ for HP Lyr and gives a limit for the absolute magnitude $M_v < -1^m5$.

A comparison between the spectra in the $H_\alpha$ region 6420 - 6600 Å obtained during two descending branches of the light curve is presented in Fig. 9. There are numerous metallic absorption lines used for radial velocity measurements (Table 1). On the blue spectra, only three Balmer lines (and additionally CaII K and FeII 5169 Å at Piwnice) were measured. The mean heliocentric radial velocity measured from the Balmer lines is $-104 \pm 5$ km/s and from metallic lines $-122 \pm 5$ km/s. It seems that all extremely sharp Balmer absorptions are affected by the P Cyg emission components related to shock expanding in the
Figure 7: The luminosity sequence of A-type stars in profiles of H\(\delta\) and H\(\gamma\) lines. Dotted lines: HD 178187 (A4III) - the broadest absorption profiles and HD 186177 (A5Ib). The spectrum of HP Lyr – continuous line – was taken on 24/25 May 2001 (at maximum) and indicates A3 Ia-Iab class. Note sharp Balmer lines and intensive Fe II and Ti II blend at 4172-8 Å and Fe II 4233 line in the HP Lyr spectrum.

Figure 8: The comparison between two spectra, obtained on 2/3 May 2001 exactly at the minimum (F2 type, solid line) and 24/25 May 2001 at the maximum (A3 type dotted line). Note the increasing of CaII and metallic lines, together with the appearance of the G-band in F2 spectrum, and significant increasing of Balmer absorption in A3 spectrum.
atmosphere. Such weak emission is clearly visible in the $H_\alpha$ profile in Fig. 9. HP Lyr was positionally associated with IRAS source 19199+3950 by Friedemann et al. (1996), but they rejected this identification because of its early spectral type. HP Lyr has the very good positional coincidence $3''$ with an IRAS source (it is much better than most identified IRAS sources in their catalog), whereas the weak red star which Friedemann et al. suggested as a possible optical counterpart lies 8 times further (i.e., at the distance $24''$). We found HP Lyr in maps of the Two Micron All Sky Survey\textsuperscript{1} with $J = 8.98$, $H = 8.44$ and $K = 7.73$. Within a radius of $60''$ around HP Lyr there is no other $JHK$ source. We conclude that HP Lyr is the only counterpart of the IRAS infrared source. Such infrared excess is typical for evolved Population II stars.

6 HP Lyr as the RV Tau variable

The $\beta$ Lyr type shape of the light curve and the other observed photometric and spectroscopic properties of HP Lyr show many important similarities with RV Tau group of variables. The RV Tau stars are luminous, pulsating variables located in the brightest part of the Population II instability strip and overlap in the Hertzsprung-Russell diagram with the W Vir type II Cepheids (Wahlgren 1992). Typical members have spectral type between F and K, luminosity class Ia-II, periods of their light variations in the range from about 30 to 150 days, large spectral and colour changes from maxima to minima. Alternating deep and shallow minima are caused by two dominant frequencies in their power spectra in 2:1 resonance with the ratio of their amplitudes close or smaller than

\textsuperscript{1}The 2MASS Internet Archive is available at the webpage http://www.ipac.caltech.edu/2mass
unity. There is general agreement that RV Tau stars are pulsating low-mass post-AGB stars in the transition into the planetary nebulae phase (Jura 1986, Giridhar et al. 2000).

Most photometric peculiarities of HP Lyr are also typical for RV Tau stars. The photometric study of Pollard et al. (1996) revealed several objects such as AR Pup which during the period of observations did not show any distinction between primary and secondary minima (just like HP Lyr). Since the mean brightness of HP Lyr remains unchanged, it belongs to the RVa subgroup of RV Tau stars. Possible alternation of the "primary" and the "secondary" minima observed in HP Lyr is also typical for RV Tau stars (e.g. R Sct). The asymmetric, "bowed" shape of the colour curves are typical for these variables.

Another spectacular feature observed in HP Lyr photometric behaviour was the period change(s). The pulsation period of the RV Tau stars often varies with a complex way in a long timescale. Their O–C diagrams show many period instabilities and abrupt changes when the period increases or decreases from 0.001$P$ to 0.01$P$ (Erleksova 1971, Percy et al. 1991). The timescale over which the period changes can be from 20 to over 100 cycles.

The observed spectroscopic features of HP Lyr correspond quite well to common spectroscopic characteristics of RV Tau stars (Pollard et al. 1997 and references therein). For example, from many $H\alpha$ profiles of some RV Tau stars, IW Car profiles are most similar to those of HP Lyr. IW Car itself was reported to be a binary system with spectral classification of A4 Ib-II: + F7/8 (Houk 1987), but the radial velocity measurements contradict this hypothesis.

Most of the RV Tau type stars have more prominent P Cyg profiles in the $H\alpha$ lines. It can be explained by their lower temperature and weaker photospheric components of the Balmer absorptions. One of our spectra of HP Lyr taken at a minimum (2/3 May) shows a weak CN I blend at 3883. Thus, in the spectroscopic subclassification scheme proposed by Preston et al. (1963), HP Lyr should belong to the the spectroscopic group "B" as an extremely hot pulsating RV Tau star (mean $T_{eff} \sim 7700$ K). The hottest RV Tau star known previously, IW Car, has the temperature $T_{eff} = 6700$ (Giridhar et al. 1994).

Many RV Tau stars also exhibit infrared excesses (Raveendran 1989) from, most probably, dusty circumstellar shells. The presence of infrared excess in the case of RV Tau stars may be a sign of their old evolutionary stage as AGB stars. On the R(12/25) – R(25/60) diagram HP Lyr lies in the area populated by RVB stars (Fig. 10). Also, the colours: $J – H = 0.54$ and $H – [25] = H + 2.5 \log(F_{25\mu m}) = 9.88$ of HP Lyr place it inside the well defined area populated by RV Tau stars at the near-far-infrared colour-colour diagram (Fujii et al. 2001).

Alcock et al. (1998) derived a single P-L relation for blue RV Tau stars in the Large Magellanic Cloud (Eq. 6 in their paper). If we apply this relation for the halfperiod of 70 days, we estimate the absolute magnitude of HP Lyr: $M_v \sim -4.5$. This value implies the distance to the star $\sim 5$ kpc and the distance from the galactic plane $z \sim 1$ kpc. The high absolute magnitude of HP Lyr implied by Alcock et al.’s P-L relation may not be correct. However, the
low amplitude of brightness changes in HP Lyr ($\Delta V = 0.5$ mag) is in a very good agreement with the slope of the relation $V$ amplitude-period in Fig. 7(b) of Alcock et al. (1998)

7 Conclusions

The results of the photometric and spectroscopic survey of the long period variable HP Lyr have been reported. The star has behaviour typical for RV Tau stars but is apparently hotter than any other known RV Tau object. It means that this star makes a substantial extension to the Type II Cepheids/RV Tau instability strip to higher temperatures. Thus HP Lyr can be very important from an evolutionary point of view. Further photometric monitoring is very interesting to follow the period changes.

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