V1294 Aql = HD 184279: A bad boy among Be stars or an important clue to the Be phenomenon? ∗,†,‡

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ABSTRACT

A reliable determination of the basic physical properties and variability patterns of hot emission-line stars is important for understanding the Be phenomenon and ultimately, the evolutionary stage of Be stars. This study is devoted to one of the most remarkable Be stars, V1294 Aql = HD 184279. We collected and analysed spectroscopic and photometric observations covering a time interval of about 25000 d (68 yr). We present evidence that the object is a single-line 192.9 d spectroscopic binary and estimate that the secondary probably is a hot compact object with a mass of about 1.1-1.2 M⊙. We found and documented very complicated orbital and long-term spectral, light, and colour variations, which must arise from a combination of several distinct variability patterns. Attempts at modelling them are planned for a follow-up study. We place the time behaviour of V1294 Aql into context with variations known for some other systematically studied Be stars and discuss the current ideas about the nature of the Be phenomenon.

Key words. Stars: binaries: spectroscopic – Stars: emission-line, Be – Stars: fundamental parameters – Stars: individual: V1294 Aql, V2048 Oph, V744 Her, EW Lac, γ Cas, η And, V696 Mon

1 Introduction

The B0.5IV star V1294 Aql (also known as HD 184279, BD+03°4065, HIP 96196, SAO 124788, MWC 319; \(\alpha_{2000.0} = 19^h33^m36^s9191, \delta_{2000.0} = +03\deg45'40.779\)) is one of a few Be stars for which photometric variations over a few decades are rather well documented. This is so thanks to the curious fact that the star was recommended as a secondary standard for UBV photometry by Johnson & Harris (1954) and Johnson (1955) and therefore was relatively often observed by various observers. When Dahn & Guetter (1973) and Tempesti & Patriarca (1976) reported pronounced light variations of this "secondary standard", other research teams reanalysed their photometric observations to document the variations further. This early history has been summarised in detail by Horn et al. (1982), who confirmed an earlier suspicion by Ballereau & Hubert-Delplace (1982) that a correlation exists between light and spectral changes. They collected the records about the presence of Balmer emission and compared them to the light and colour variations based on historical records and based also on their new UBV photometry from Hvar Observatory. They noted that the observed cyclic long-term variability contradicts what is usually observed for the long-term

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Table 1. Journal of electronic spectra.

| Spg. No. | Time interval (HJD-2450000) | No. of RVs | Wavelength range (Å) | Spectral resolution |
|----------|-----------------------------|------------|----------------------|---------------------|
| 1        | 1370.4                      | 1          | 6520–6600            | 2500                |
| 2        | 2420.53–2777.67             | 2          | 6340–6860            | 6000                |
| 3        | 2860.40–2870.48             | 3          | 6530–6965            | 6000                |
| 4        | 2918.34                      | 1          | 6570–6645            | 6000                |
| 5        | 3431.34                      | 1          | 6470–6730            | 60000               |
| 6        | 4653.48                      | 1          | 4750–6900            | 10000               |
| 7        | 4944.64                      | 1          | 4270–6910            | 10000               |
| 8        | 2461.85                      | 1          | 3770–9220            | 48000               |
| 9        | 2749.62–6152.49             | 58         | 6255–6767            | 12700               |
| 10       | 6475.49–9483.31             | 66         | 6260–6735            | 12700               |
| 11       | 2771.92–4443.60             | 21         | 6170–6760            | 21700               |
| 12       | 9070.86–9499.64             | 4          | 6325–6930            | 21700               |
| 13       | 5057.59–6890.56             | 9          | 3800–8750            | 40000               |
| 14       | 6105.50–9480.39             | 8          | various              | > 10000             |
| 15       | 9489.51–9526.50             | 3          | 4500–8900            | 79000               |

Notes. Column “Spg. No.”:
1...Castanet-Tolosan T190 instrument, observer C. Buil – see http://www.astrosurf.com/buil/us/bestar.htm
2...Castanet-Tolosan T121; 3...Castanet-Tolosan (T128; 4...Castanet-Tolosan T280+Lhires III; 5...Castanet-Tolosan C11+eShel+Audine KAF1600; 6...Castanet-Tolosan C11+eShel+QSI152; 7...ESO 1.5 m reflector, FEROS spectrograph; 8...Onrdjef 2.0 m reflector, coudé grating spectrograph, CCD ST16s 2050x800 pixel detector; 9...Onrdjef 2.0 m reflector, coudé grating spectrograph, CCD Pylon Excelor 2048x512 pixel detector; 10...DAO 1.22 m reflector, coudé grating McKellar spectrograph, CCD Site4 detector; 11...HTP 1.5 m reflector, BESO echelle spectrograph; 12...Amateur spectra from the BeSS database http://basebe.obspm.fr/basebe/; 13...Cerro Tololo 1.5 m reflector, CHIRON echelle spectrograph.

V/R changes of the Balmer emission lines and expressed doubts about their interpretation by the model of a revolving elongated disk. Comparing the light curve of V1294 Aql to similar light curves of BU Tau and V744 Her, they noted that the development of a new shell phase in all three objects was accompanied by a pronounced light decrease. This type of variability was later classified as an inverse correlation between the brightness and emission strength by Harmance [1983] and was interpreted as an essentially geometrical effect for situations in which the circumstellar envelope in question is seen more or less equator-on. A study of the disk models, which grow in size and/or density with time, by Sigut & Patel (2013) basically confirmed this conjecture. The correlation was documented by Horn et al. (1983) throughout the entire interval of 50 years covered by spectral records with the help of a long series of photographic magnitudes.

The first detailed spectroscopic study of V1294 Aql was published in two papers by Ballereau & Chauville (1987) and Ballereau & Chauville (1989). They demonstrated the presence of cyclic long-term V/R variations of the double Balmer emission lines with a cycle length of some 6 yr and concluded that they are caused by a slow revolution of an elongated envelope (the model of McLaughlin [1961b]). They also investigated the possibility whether the star might be a spectroscopic binary, but found no evidence for it. Moujoudi et al. [1998] studied the correlation of the second Balmer jump with visual brightness and long-term radial-velocity (RV) changes for a number of Be stars. For V1294 Aql, they concluded that the Balmer jump parameter D correlates with both these quantities, attaining maximum in 1979, when the long-term cyclic RV variations were also at maximum.

Mennickent et al. [1997] discussed possible observational tests of the models of long-term cyclic variations of the Be star disks. Investigating spectral, light, and colour variations of V1294 Aql over the time interval from JD 2440000 to 2450000, they noted that the brightness extrema corresponded to the phase transitions of the V/R variations from V/R > 1 to V/R < 1 and vice versa, but admitted that this behaviour was not seen during the third V/R transition over the investigated interval of time. They tentatively concluded, however, that the disk of V1294 Aql is seen more or less equator-on (in agreement with Horn et al. [1982] and that the revolution of its elongated structure (“one-armed global oscillation”) projected against the star during the phase transitions causes the observed light decreases through attenuation of the stellar flux.

Chini et al. [2012] carried out a spectroscopic survey of 249 O-type and 581 B-type stars in a search for the duplicity. Based on variable RV, they reported that V1294 Aql is a single-line spectroscopic binary. In a search for hot subdwarf companions to Be stars in the spectra obtained by the International Ultraviolet Explorer (IUE), Wang et al. [2018] reported a null detection for such a companion to V1294 Aql. Brandt (2021) cross-correlated the Hipparcos and Gaia catalogues in an effort to identify astrometrically accelerating objects. V1294 Aql was identified as a candidate for a system with a faint companion.

2. Observations and reductions

2.1. Spectroscopy

New electronic spectra were obtained at four observatories: with the Onrdjef 2.0 m reflector (OND) and a coudé spectrograph, with the Dominion Astrophysical Observatory 1.22 m reflector (DAO) and a coudé spectrograph, with the Cerro Armazones 1.5 m Hexapod Telescope (HPT), the Bochum Echelle Spectroscopic Observer (BESO) spectrograph, which is similar to FEROS (Fuhrmann et al. [2011]), and with the Cerro Tololo Inter-American Observatory (CTIO) 1.5 m reflector with the CHIRON echelle spectrograph (Tokovinin et al. [2013]). We also used one archival ESO FEROS echelle spectrum (Kaufer et al. [1997]). Kaufer & Pasquali [1999], the medium-resolution CCD spectra obtained and published by Christian Buil [1998] and a selection of amateur CCD spectra with resolutions better than 10000 from the BeSS spectroscopic database (Neiner et al. [2011]). Table [1] lists a journal of all spectral observations used.

The initial reduction of all Onrdjef and DAO spectra (bias subtraction, flat-fielding, creation of 1D spectra, and wavelength calibration) was carried out in IRAF. Initial reduction of the HTP and CTIO spectra was carried out at the respective observatories. Rectification, removal of residual cosmics and flaps, and RV measurements of all spectra were carried out with the Pascal program SPEFO (Horn et al. [1996]). Skodai [1996], namely the latest version 2.63 developed by J. Krpata (Krpata [1999]).

1 For normal stars, the Balmer jump parameter D, which is defined as log of the flux shortward 3700 Å divided by the flux shortward 3700 Å, is a good measure of the stellar effective temperature. The presence of circumstellar matter can cause the second Balmer jump, which is occasionally seen in emission.

2 For the description of his instrumentation and data reduction, see http://www.astrosurf.com/buil/us/bestar.htm.
were completed was a new program for spectral reduction
line was then used here. Only after these RV measurements
measurements were intercompared, the larger deviations were
the Hα studied the spectra as a part of his student’s research project. In
were carried out independently by PH and also by AH, who
slide to achieve a precise overlapping of the parts of the profile
2008).
SPEFO displays direct and flipped traces of the line
profiles superimposed on the computer screen that the user can
slide to achieve a precise overlapping of the parts of the profile
for which the RV is to be measured. All RV measurements
were secured with the 0.84 m reflector and Cuenta-pulsos photometer; 34... Lick 0.61 m Boller & Chivens telescope, refrigerated S20 tube; 37... US Naval
Observatory Ritchey-Chretien 1.0 m reflector, EMI 9524B tube; 92... Stefanion ESO Netherlands Van Straaten 0.40 m reflector, EMI 6256B tube;
30... 43382.85–43690.85 6 13C all-sky Alvarez & Schuster (1982)
34... 43401–43796** 2 VRI all-sky Cousins & Dean (1978)
1... 44073.40–48128.39 406 UBV 183324 / 183227 this paper
20... 45099.81–49951.73 90 B V 183324 / 183227 this paper
12... 45249.56–49591.69 121 ubvy all-sky Schuster & Guichard (1984)
30... 45451.00–45451.98 2 VRI all-sky this paper
3... 52060.81–52752.94 45 UBV 183324 / 183227 this paper
1... 52076.49–56475.46 624 UBV 183324 / 183227 this paper
66... 52763.49–52764.54 10 UBV 183324 / 183227 this paper
89... 52850.40–53309.29 69 UBV 183324 / 183227 this paper
1... 56488.41–59483.27 590 UBV 183324 / 183227 this paper
2... 57297.27–58089.25 533/555/549 BVR 183324 / 184663 this paper

Notes. * Inaccurate Julian dates; ** Julian dates uncertain by ±15 d
In the column “Station”, the individual observing stations are identified by the running numbers from the Praha/Zagreb photometric archives:
1... Hvar 0.65 m reflector, EMI tubes; 2... Brno private observatory of P. Svoboda, Sonnar 0.034 m refractor with a CCD camera; 4... Ondřejov
0.65 m reflector, EMI tube; 12... La Silla 0.50 m Danish reflector: Part 1 are all-sky observations, the rest are differential observations secured
during a long-term campaign. The original ubvy observations were transformed to UBV; 20... Toronto 0.40 m reflector, EMI 6094 tube; 26... Haute
Provence 0.60 m reflector, Lallemand tube; 30... San Pedro Mártir 0.84 m and 1.50 m reflectors (13C photometry), more recent UBV observations
were secured with the 0.84 m reflector and Cuenta-pulsos photometer; 34... Lick 0.61 m Boller & Chivens telescope, refrigerated S20 tube; 37... Jungfraujoch Sphinx mountain station 0.40 m reflector, Geneva photometer; 44... MtPalomar 0.51 m reflector, EMI 6094 tube; 59... Cape Town
photometry transformed into Johnson UBVR magnitudes. For comparison purposes we used the magnitudes of Cousins (1973) and Cousins &
Dean (1978) as a standard set.

2.2. Photometry
We attempted to collect all available observations with known
dates of observations. Basic information about all data sets can be found in Table 2 and the details of the photometric reductions and
standardisation are described in Appendix A.

For the convenience of other investigators, we also publish all our individual observations together with their HJDs. All measured RVs are listed in Table 3, spectrophotometric quantities are provided in Table 4, and photometric observations are collected in Table 5. These three tables are available in
electronic form only.

Table 2. Journal of available photometry with known dates of observations.

| Station                  | Time interval (HJD) | No. of obs. | Passbands | HD of comparison / check star | Source                              |
|-------------------------|---------------------|-------------|-----------|-------------------------------|------------------------------------|
| 44                      | 36431.77–36462.78   | 42          | V         | 184663                         | Lynds (1959); see the text         |
| 59                      | 36795 – 41544**     | 3           | UBV       | all-sky                        | Cousins & Stoy (1963); Cousins (1973) |
| 34                      | 39370 ±30°         | 1           | UBV       | all-sky                        | Moreno (1971)                      |
| 90                      | 39928 – 42988*      | 40          | BV        | all-sky                        | Temperati & Patriarchetti (1976)   |
| 26                      | 40449.4 – 40452.4*  | 2           | UBV       | 183227                         | Haupt & Schroll (1974) & priv.com. |
| 92                      | 40453.5°           | 1           | UBV       | all-sky                        | van der Waal et al. (1972)        |
| 91                      | 41230.7°           | 1           | UBV       | all-sky                        | Dahn & Guetter (1973)             |
| 37                      | 42894.92–43391.55   | 3           | Geneva    | all-sky                        | Burki (priv.com.)                 |
| 30                      | 43382.85–43690.85   | 6           | 13C       | all-sky                        | Alvarez & Schuster (1982)          |
| 43                      | 43401 – 43796**     | 2           | VRI       | all-sky                        | Cousins & Dean (1978)             |

Table 2 is published in color online.

Notes. Inaccurate Julian dates; Julian dates uncertain by ±15 d
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3. Long-term spectral, light, and colour changes of V1294 Aql

As mentioned above, we attempted to collect and homogenise all available photometric observations and measurements of RVs and line strengths from the records with known dates of observations. Long-term behaviour of these quantities and their mutual correlations are discussed in the following sub-sections.

3.1. Value of visual estimates of brightness

The visual estimates of brightness by skilful amateur observers are commonly used to determine the times of minima (or maxima) of periodic variables and to monitor light changes of variables with a large amplitude (over several magnitudes). The scatter band of visual estimates is typically about 0.1 to 0.15, but it can be pushed down by talented individuals who, moreover, follow a few principles: (a) to perform only one visual estimate per night (without recalling the previous one), and (b) to reduce the estimates to Johnson V magnitudes of the comparison stars (known to one thousandth of a magnitude), not to the Harvard scale of magnitudes, which is only accurate to 0.1. One of us (SO) contacted the first author of this study back in 2003 to inform him that he had observed another light decrease of V1294 Aql for about 0.3. We then agreed to test his ability to obtain accurate visual estimates via parallel photoelectric observations at Hvar, San Pedro Mártir (SPM), Tubitak National Observatory (TUG), and Çanakkale. Figure 1 shows the comparison of visual estimates and Johnson V photoelectric photometry from several stations over the time interval covered by visual estimates. The visual estimates agree very well with the general trend of variations that were recorded via photoelectric photometry, but the deep light minimum appears broader than that recorded by photoelectric photometry. One possible reason is that the minimum was observed close to the end of visibility of the star in the sky and the visual estimates were not corrected for the differential extinction.

3.2. Correlation between the long-term light and spectral changes in time

Figure 2 is a time plot of all available observations secured in or transformed into the Johnson UBV magnitudes. The top panel shows that the usual brightness level in V is occasionally disturbed by rapid light decreases of different durations. Moreover, we note that there is also a secular, steady slow light decrease of the undisturbed brightness of the star outside the more rapid light decreases until about HJD 2455000, when it suddenly changed to a steeper secular light increase. We return to this new phenomenon in a separate section below. The second panel of Fig. 2 shows that the B−V index followed the brightness changes, but with a small amplitude, while the U−B index showed a similar pattern of changes, but with a larger amplitude and with a more or less steady secular reddening.

An enlarged Fig. 3 covers only the more recent time interval, when electronic spectra became available. It shows that the B−V index followed the brightness changes, but with a small amplitude, while the U−B index showed a similar pattern of changes, but with a larger amplitude and with a more or less steady secular reddening.

Figure 4 shows the V/R changes of Si ii 6347 Å line. It reveals a pattern similar to that observed for Hα, but the time cov-
Time plot showing the correlation between the secular brightness and colour variations in the $V$ -band magnitudes and $B-V$ and $U-B$ colour indices (black shows all-sky and blue shows differential observations), and the $V/R$ changes, $EW$, and strength of the H$\alpha$ emission for the more recent electronic spectra. The colour symbols for spectra from different sources are the same as in Fig. 2.

Figure 5 shows the variation of the shell absorption RVs (characterised by He I RVs, for which data are also published by Ballereau & Chauville [1989]) and emission-line RVs measured on the wings of the H$\alpha$ line in electronic spectra. We note that while the shell RVs show large cyclic changes that have also been observed for a number of other Be stars, the RVs measured on the wings of the H$\alpha$ emission are secularly stable and show only mild changes on a shorter timescale.

3.3. Unusual colour variations

Many systematically studied Be stars are known to exhibit always the same and a rather clear type of either a positive or an inverse correlation between the long-term brightness variations, a characteristic type of behaviour in the colour-colour diagram, and the Balmer emission-line strength as defined by Harmanec [1983, 2000]. He identified these two types of correlation as an aspect effect. For Be stars with an inverse type of correlation, light decreases are followed by the rise of the Balmer emission-line strength and by a shift along the main sequence towards later spectral subclasses in the $U-B$ versus $B-V$ diagram. For a positive type of correlation, the brightenings are followed by the rise of the emission strength and a shift from the main sequence towards the supergiant sequence in the $U-B$ versus $B-V$ diagram. The inverse correlation is observed for stars that are seen more or less equator-on (a growing gaseous envelope is attenuating the light of the central object), while the positive correlation is observed for stars that are seen more pole-on (inner optically thick parts of the growing envelope mimic an apparent increase in the stellar radius). Several examples of both types of correlation in
the colour-colour diagram can be found, for instance, in Fig. 2 of Božić et al. (2013).

The situation is dramatically different for V1294 Aql. The $UBV$ observations accumulated over several decades cover a large part of the whole colour-colour diagram, with a single clear pattern.

To understand better what is going on, we investigated the colour-colour diagrams for different segments of the long-term changes. Figure 6 shows the colour changes separately for the old data secured before JD 2450000, for more recent data from the secular brightness increase (observations after JD 2457000), and for observations covering two episodes of a rapid increase and decrease in the $H\alpha$ emission associated with sharp light decreases. The pattern is remarkably similar for both these episodes. Formally, it looks like a positive correlation. However, the phases of minimum brightness and maximum strength of the

Fig. 6. $U-B$ vs. $B-V$ diagram for several distinct data subsets. Top panels: Older data until JD 2450000 (left). All-sky observations are shown as black circles, and data from stations defined in Table 2 are denoted as follows: 01 (blue), 04 (green), 12 (red), and 26 (magenta). More recent data from the interval of secular light brightening, all from station 01 (blue) (right). The bottom panels show $UBV$ observations from the two sharp increases in the emission-line strength accompanied by light decreases. Time interval JD 2452741 – 2453309, which covers the first sharp light decrease (left, cf. Figs. 1 and 3.) Data from the time interval JD 2455357 – 2456094 corresponding to the second sharp increase in the emission-line strength (right). Data from stations 1, 30, 66, and 89 of Table 2 are shown by blue, red, green, and magenta dots, respectively. The main sequence and the supergiant sequence based on data from Golay (1974) (pp. 79-80) are shown, as is the reddening line.

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Table 6. Orbital solutions based on the Hα emission RVs.

| Element | All RVs | Hi-res. spectra only |
|---------|---------|----------------------|
| P (d)   | 192.91 ± 0.18 | 192.91 fixed |
| T' super conj. | 56318.5 ± 2.2 | 56316.2 ± 2.9 |
| e       | 0.0 fixed | 0.0 fixed |
| γ (km s⁻¹) | −6.27 ± 0.31 | −5.52 ± 0.44 |
| K₁ (km s⁻¹) | 6.33 ± 0.41 | 6.26 ± 0.61 |
| No. of RVs | 172 | 38 |
| rms (km s⁻¹) | 3.92 | 2.63 |

Notes. *) All epochs are in HJD-2400000.

Fig. 7. Radial-velocity curve corresponding to the orbital solution, based on RVs measured on the steep wings of the Hα emission, plotted for phases from ephemeris (top). Orbital curve based on RV of the H I 6678 Å shell line prewhitened for the long-term changes, plotted for the same ephemeris (bottom). Data from individual instruments are shown by different symbols. The circles are the same as in Fig. 2, and black triangle shows CTIO.

4. Duplicity of V1294 Aql

The idea that duplicity can be an important factor for the very existence of the Be phenomenon is not new. Plavec & Horn (1969), Kříž (1969) and Plavec (1970) have argued that at least some Be stars could be binaries that are observed in the later phases of mass exchange between the binary components. Kříž & Harmanec (1975) and Harmanec & Kříž (1976) formulated the general hypothesis that Be stars are mass-accreting components of binaries and showed that this idea can also explain several types of time variations observed for Be stars. Additional arguments were provided by Plavec (1976b) and Peters (1976). However, as pointed out already by Plavec (1976a), if all Be stars have Roche-lobe filling secondaries, more eclipsing binaries should be observed among them. Later investigations also led to the finding that the presence of Roche-lobe filling secondaries can be excluded for some Be stars that were found to be spectroscopic binaries, such as V744 Her = 88 Her (Doazan et al. 1982b) or V439 Her = 4 Her (Heard et al. 1975; Harmanec et al. 1976). This led Pols et al. (1991) to suggest that many Be stars might be objects created by large-scale mass transfer that were observed in phases after the mass transfer ceased. The expected secondaries of such objects would be hot compact stars, white dwarfs in some cases. These are the most easily detectable in far-UV spectra. Evidence for a hot secondary to the well-known Be binary ϕ Per was found first from the antiphase variation in the H α 4686 Å emission seen in the photographic spectra (Poeckert 1981) and later from the H I 6678 Å emission in the electronic spectra obtained by Gies et al. (1993). Its ultimate direct detection as an O VI subdwarf came from the study of the far-UV spectra from the Hubble Space Telescope by Gies et al. (1998). The secondary was then resolved with optical spectro-interferometry by Mourard et al. (2013). Detections for several other systems followed. Wang et al. (2018) carried out a systematic search for the presence of hot secondaries and summarised our knowledge of already known cases. Wang et al. (2021) detected nine new Be+sdO binaries from analyses of the Hubble Space Observatory spectra, and Klement et al. (2022) reported the first interferometric detection and signatures of the orbital motion for three known Be+sdO systems. On the other hand, Bodensteiner et al. (2020) carried out a systematic search for Be stars with main-sequence secondaries, with a completely null result. This constitutes indirect evidence that the mass exchange is or was behind the formation of binaries with Be primaries. Hastings et al. (2021) carried out evolutionary calculations of mass exchange in binaries in an effort to set some limits on the fraction of Be stars produced by binary interaction. They found that under certain conditions, this fraction can be quite high.

One always has to be cautious when analysing binaries with clear signatures of the presence of circumstellar matter in the system. The experience from our previous studies of individual Be stars (Božić et al. 1995; Koubský et al. 1997; Harmanec et al. 2000, 2002b; Linnell et al. 2006; Ruždjak et al. 2009) shows that the binary nature of particular Be stars is most easily detected via periodic RV variations of the steep emission wings of the Hα line and often also via the periodic changes in the V/R ratio of the double Balmer emission lines.

Period analyses of all Hα emission-line RVs of V1294 Aql, using both the Deeming (1975) and Stellingwerf (1978) methods, revealed that the RV of the Hα emission wings varies with a period of 193 d and a semi-amplitude of ~ 5 km s⁻¹. The same periodicity is also detected in the RV of the Hα absorption core and in the absorption RVs of Si II doublet at 6347 and 6371 Å and Fe II 6456 Å after long-term changes are removed.
Fig. 8. Three Ondřejov Hα profiles. They are mutually shifted in ordinate by 1.0 of the continuum level for better clarity. Profiles from HJD 2457128.5976 and 2457137.5762 have anomalously positive RVs of the emission wings, which stem from the episode of a large strengthening of the emission. The next profile, from HJD 2457154.5435, has a normal orbital RV.

Table 7. Possible properties of the binary system: Mass of the secondary $M_2$, mass ratio $M_2/M_1$, semi-amplitude of the RV curve of the secondary $K_2$, and the semi-major axis $a$ for several possible orbital inclinations $i$. The mass of the primary was assumed to be $M_1 = 16.9 M_\odot$ after Zorec et al. (2016).

| $i$ (°) | $M_2$ ($M_\odot$) | $M_2/M_1$ | $K_2$ (km s$^{-1}$) | $a$ ($R_\odot$) |
|--------|-----------------|----------|-----------------|-------------|
| 90.0   | 1.171           | 0.0693   | 90.43           | 368.69      |
| 85.0   | 1.175           | 0.0695   | 90.07           | 368.72      |
| 80.0   | 1.189           | 0.0704   | 88.99           | 368.82      |
| 70.0   | 1.249           | 0.0739   | 84.73           | 369.23      |
| 60.0   | 1.361           | 0.0805   | 77.77           | 369.98      |

Notes. We express the values of masses and radii in the nominal values $M_\odot$ and $R_\odot$ as defined by Prša et al. (2016).

Using the program FOTEL (Hadrava 1990, 2004), we derived the circular-orbit orbital elements for all Hα emission-wing RVs and for those from the high-resolution spectra alone. The mutual agreement of the two solutions is very satisfactory. They are presented in Table 6 and the corresponding RV curve is plotted in Fig. 7. In the rest of this study, we adopt the following linear ephemeris:

$$T_{\text{super conj.}} = \text{HJD 2456318.5} + 192491 \times E$$

based on the solution for all spectra.

To be fair, we note that some deviations from the mean RV curve in the upper panel of Fig. 7 are rather large. This is, for instance, the case of two Ondřejov spectra taken on HJD 2457128.6 and 2457137.6, when a very steep rise of the emission strength had occurred. We remeasured these spectra several times, but the result was the same. Their RVs are almost in anti-phase to the orbital RV curve near phase 0.3. We show the corresponding line profiles in Fig. 8 together with another profile, taken about two weeks later, which already gives a RV in accord with the orbital motion. The two peculiar RVs were given zero weight in the orbital solution.

5. Correlations between orbital and long-term changes

Inspection of the light, colour, and emission-line strength variations seems to indicate that the rapid episodes of large changes such as those near JD 2452900 or JD 2457300 occurred during one binary orbital period. To investigate the problem, we plot phase diagrams of the variability of the $V$ magnitude for several more recent shorter time intervals in Fig. 9. The two large light decreases that are accompanied by strong increases in the Hα emission-line strength apparently occurred around phases of
elangements, with the Be primary receding from us. At the same
time, the plot shows that in another observing season, brighten-
ings were observed around similar orbital phases. The same is
also confirmed by a phase plot of the Hα emission-line strength;
see Fig. 10.

We also investigated the time behaviour of the V/R ratio of
the double Hα emission. In this case as well, V1294 Aql appears
to be quite unusual. As Figs. 2 and 3 show, the V/R variations
are different in different time intervals and do not recall either
the long-term cyclic changes known for Be stars with one-armed
global oscillations or phase-locked changes. In several panels
of Fig. 11 we show enlarged plots of the V/R changes. Instants
of expected phase-locked V/R maxima predicted by the orbital
ephemeris (1) are shown by vertical lines.

6. Rapid changes

Although we collected a large number of photometric observa-
tions of V1294 Aql, their time distribution is not suitable for
a search for rapid periodic changes. Perhaps the only observa-
tions suitable for such a search are the early V observations
by Lynds (1959). He himself concluded that his observations
definitively indicate variations in brightness, which appear to
be somewhat erratic, however, and no period could be found.
The observations were secured within one month during a time
interval that was not affected by secular variations. Our period
analysis revealed sinusoidal variations with a semi-amplitude of
0.0139(29). A least-squares fit led to ephemeris (2), the rms of
one observation being 0.0067. The corresponding phase plot is
shown in Fig. 12.

\[ T_{\text{light min.}} = \text{HJD } 2436450.8053(92) + 0.064827(50) \times E. \] (2)

This indicates that a scatter of at least 0.03 is to be expected in
individual observations on longer timescales.

Lefèvre et al. (2009) carried out an automatic period search
in the Hipparcos Hα photometry to find new periodic variables
among OB stars. They identified V1294 Aql as a possible slowly
pulsating B star (SPB) with a period of 71752. We cannot con-
firm their result. They apparently did not take the secular light
change in Hα photometry into account; see the upper panel of
Fig. 1 here.

Zorec et al. (2016) estimated the following physical proper-
ties of the Be component:

\[ T_{\text{eff}} = (30120 \pm 2540) \text{ K}, \log g = (4.08 \pm 0.40) \text{ [cgs]}, \text{ mass } M = \]
\[(16.9 \pm 2.7) \text{ M}_\odot, v \sin i = (207 \pm 18) \text{ km s}^{-1}, \text{ critical rotational ve-
locity } v = (517 \pm 64) \text{ km s}^{-1}, \text{ and the inclination of the rotational}
axis } i = (37^\circ \pm 9^\circ). \text{ For these values, the period 0.0648 appears as}
a reasonable rotation period of the Be component. In passing we

\[ T_{\text{light min.}} = \text{HJD } 2436450.8053(92) + 0.064827(50) \times E. \] (2)

\[ T_{\text{light min.}} = \text{HJD } 2436450.8053(92) + 0.064827(50) \times E. \] (2)

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note that at the time of writing, the star has not been observed by
the TESS satellite.

7. Fourth timescale

Harmanec (1998b) has called attention to the fact that the bright-
ness of the Be star ω CMa outside of the episodes of brightenings
accompanied by the growth of emission-line strength (typical
of the positive correlation discussed above) has been decreasing
secularly. His observation was later confirmed with more recent
photometry (Ghoreyshi et al. 2018, 2021). These authors and also
Marr et al. (2021), who studied another Be star, V2048 Oph = 66 Oph, modelled the secular variability and the episodes of
brightening and increases in the Balmer emission-line strength
with some success, estimating the required viscosity values for
individual episodes, and also discussing some limitations of their
effort. The yellow light curve of V2048 Oph is shown in the
upper panel of Fig. 1 of Marr et al. (2021). It shows a secular
light decrease between 1980 and 2000, occasionally interrupted
by brightenings reminiscent of a positive correlation. However,
the strength of the Hα emission is near its maximum over the
same time interval of about 20 years, and only then does it gradu-
ally decrease. No emission has been observed since about 2010.
However, as Marr et al. (2021) pointed out, the outer parts of the
disk are still seen in the radio wavelengths.

We collected and homogenised the V photometry of
V2048 Oph from the archive of UBV photometry provided by
J.R. Percy, from Hvar, SPM, Johnson et al. (1966), Haupt &
Schroll (1974) and Kozok (1985) and transformed the Hipparcos
H (Perryman & ESA 1997) photometry into Johnson
V and the
observations of Hill et al. (1976) secured in the DAO photomet-
ric system into
UBV using the transformation formulæ provided
by Harmanec & Božić (2001). The V light curve of V2048 Oph
based on the above-mentioned data sets is shown in the upper
panel of Fig. 13.

A similar secular light decrease has also been reported for
V744 Her = 88 Her, a Be star with an inverse type of correla-
tion (Harmanec & Božić 2013). We show its light curve comple-
mented by more recent observations, adapted from Božić et al.
in prep.) in Fig. 13 as well. In the same figure, we also show
the V and B light curves of the Be star EW Lac = HD 217050
from another study in preparation. In this case, a secular increase
in brightness is observed. We note that the large scatter around
the mean trend is related to the known rapid light variability of
EW Lac on a timescale shorter than one day. The fourth panel of
Fig. 13 shows the plot of Hvar V photometry of ϕ And, another
Be star with a positive type of correlation. A mild light decrease
over several decades of observations is visible.

Searching the literature, we found a few more examples. A
secular light increase has also been observed for the Be star with
a positive correlation γ Cas (Harmanec 2002, Fig. 5) over nearly
30000 days.

Finally, as we have shown here, the secular light decrease of
V1294 Aql has recently changed to a secular light increase. All
this shows the large variety of different possible evolutions of the
circumstellar disk, its replenishment, and a gradual dissipation.

8. Discussion

In spite of the effort of several generations of stellar astronomers,
the engine leading to the occasional formation of circumstellar
disks around Be stars has not been firmly identified so far. One
possible explanation is based on the idea that Be stars are rapidly
rotating non-radial pulsators (NRP) and that the additional force
needed to facilitate the outflow of gas and angular momentum
transfer from the stellar equator arises from a constructive in-
terference of two or more NRP modes (Rivinius et al. 1998b,a;
Baade et al. 2017a,b; Baade & Rivinius 2020; Borre et al. 2020;
Labadie-Bartz et al. 2021). Especially the systematic photome-
tries from space observatories were used and analysed to support
this conjecture. Confirmation of this scenario would require the
creation of new, self-consistent models, however, which would
show that Be stars are indeed pulsationally unstable over the
peak of a relatively faint He emission. This is best illustrated (a temporarily elongated envelope?) and apparently weakens the sequence of the fact that the He shell RV becomes very negative variations for both lines are in phase, while in the second inter-
changes of the Be component.
leads to phase-locked \( V \) can be, we compare the \( V \) and \( R \) changes as global oscillations in the phase-locked \( V \) and He \( I \) 6678 profiles for two dates are shown.

This study of V1294 Aql demonstrates very clearly how hard it is to identify and understand mutually coexisting and overlapping variability patterns governing the observed spectral, light, and colour changes. Attempts at modelling them quantitatively, planned for a continuation of this study, are expected to shed more light on the mysterious Be phenomenon. We also suggest that further monitoring of the object with systematic photometry, high-resolution spectroscopy, and especially with the optical inter-
ferometry could help to reveal the secrets of this intriguing Be binary, or possibly a multiple system, as indicated by the analysis of the astrometric data (Brandi 2021).

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Fig. 14. Apparent V/R changes observed for the Hα and He I 6678 emission lines intercompared for two time segments. The variation in the shell He RV is also shown. An apparently anti-phase behavior is observed in the second time interval, when the shell RV becomes quite negative and the He shell line blends with the V peak of the faint He emission. The same colours as in the previous time plots are used to distinguish spectra from individual observatories.

Fig. 15. Apparent V/R changes observed for the Hα and He I 6678 emission lines intercompared for two dates. An apparently anti-phase behaviour is observed for the later date, when the He I 6678 shell RV becomes quite negative and the He shell line blends with the V peak of the faint He emission.
Appendix A: Details of photometric observations and their reduction and homogenisation

Differential observations from Hvar, Ondřejov, San Pedro Martir, Tubitak, and Canakkale were all reduced and carefully transformed into the standard Johnson UBV system with the help of the reduction program HEC22; see Harmanec et al. (1994) and Harmanec & Horn (1998) for the observational strategy and details of the data reduction. The latest HEC22 rel.18 version was used. It allows the use of non-linear transformation formulæ, includes the colour extinction coefficient among the seasonal transformation coefficients, and allows the time variation of linear extinction coefficients to be modelled in the course of the observing nights. Our standard strategy is to observe the check star as frequently as the variable to determine the real data quality. This also permitted replacing the originally selected comparison by the check star when the former was found to be micromoving after some time. This was indeed the case of observations of V1294 Aql. Our original comparison 35 Aql = HD 183324 was reported to be a \( \lambda \) Boo microparameter with a period of 0.0211 and a full amplitude of 0.02 by Kuschnig et al. (1994) and received the variable star name V1431 Aql. We now use our original check star HR 7397 = HD 183227 as the comparison, but we note that because our observing sequences usually consisted of three to five cycles of individual observations, they are typically some 0.05\( \pm \) 0.006 long and the variability of 35 Aql is in a sense smeared out. We therefore retained some series of observations relative to 35 Aql, where the change to the new comparison HR 7397 would decrease the quality of differential observations.

Below, we provide some details of the individual data sets defined in Table A.2 and their reductions.

- **Station 01 – Hvar**: These differential observations have been secured by a number of observers over many years, with HR 7397 and HR 7438 as the comparison and check star, respectively, within the framework of the long-term program of monitoring the light and colour variations of bright Be stars. The all-sky magnitudes from Hvar were carefully homogenised and serve as our primary source of UBV and UBVR magnitudes. The Hvar mean values, which were always added to magnitude differences from all stations, are listed in Table A.1. Since the summer of 2013, the \( R \) filter was installed to the Hvar photometer, and UBVR observations were collected. We note that the transparency curve of the \( R \) filter closely corresponds to that of the standard Cousins \( R \) filter. However, because we were not able to find enough northern bright standard stars with the Cousins \( V - R \) values, we derived robust mean values of Johnson \( V - R \) indices from Johnson et al. (1966) and reduced our observations to the Johnson system.

  - **Station 02 – Brno**: These BVR observations were secured by P. Svoboda in his private observatory with a Sonnar 0.34 m refractor and a CCD camera. They were reduced to the form of magnitude differences by the author. The Hvar all-sky values of the comparison star were then added to them.

  - **Station 04 – Ondřejov**: UBV observations secured with the 0.65 m Ondřejov reflector and a photometer with an EMI tube and transformed into the standard Johnson system.

  - **Station 12 – La Silla ESO**: There are two independent observation sets. The early observations are all-sky uvby observations published by Kozó (1985). The rest are differential uvby observations obtained with the Danish 0.50 m reflector (later called Strömgren Automatic Telescope (SAT)) (see Manfroid et al. 1991, Sterken et al. 1993, Manfroid et al. 1994 Sterken et al. 1995 for the published data and details of the observations and reduction) relative to 35 Aql. HD 7397 being used as the check star. We then used the transformation from the Strömgren into the Johnson system derived by Harmanec & Božič (2001) to obtain values that can be directly compared to other UBV datasets.

  - **Station 20 – Toronto**: Differential BV observations secured during the international campaign on bright Be stars by John Percy, who kindly placed them at our disposal. They were transformed into the standard Johnson system via linear transformations by the author, and the Hvar all-sky values of the comparison star were added to the magnitude differences.

  - **Station 26 – Haute Provence**: Two UBV observations were secured by Hautp & Schroll (1974). Individual observations were kindly provided by H. Hautp upon our request and corrected to our adopted values for the comparison star.

  - **Station 30: SPM 1.50 m and 0.84 m reflectors**: The early all-sky observations (before JD 2446000) were secured at the 1.50 m reflector in the 13C system and reduced by their authors (Alvarez & Schuster 1982; Schuster & Guichard 1984). They were then transformed into the standard Johnson UBV system with the help of transformation formulæ derived by Harmanec & Božič (2001). More recent differential UBV observations were secured by MW with the 0.84 m reflector and Cuenta-pulsos photon-counting photometer. Variable extinction during the nights was monitored, and the data were reduced to the standard UBV system.

  - **Station 37 – Jungfraujoch**: These all-sky seven-colour (7-C) observations were secured in the Geneva photometric system at the Jungfraujoch Sphinx mountain station 0.40 m reflector and kindly placed at our disposal by G. Burki. They were transformed into the standard Johnson UBV system with the help of transformations derived by Harmanec & Božič (2001).

  - **Station 44: Mt Palomar 0.51 m reflector**: Lynds (1959) carried out numerous differential observations of early-type stars classified as giants, including V1294 Aql. He observed in yellow light, with a Corning 3384 filter and an EMI 6094 tube. Most of his observations are only published in the form of time plots of the data, variable minus comparison. In Table A.2, we compare the mean magnitude differences between the respective stars for all his microvariables with the mean differences in the standard Johnson \( V \) filter. It is obvious that for all practical purposes, the yellow filter used by

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Table A.1. Standard UBVR magnitudes of the stars used by different observers as comparison stars in their differential observations of V1294 Aql.

| Star     | HD       | \( V \) (mag.) | \( B-V \) (mag.) | \( U-B \) (mag.) | \( V-R \) (mag.) |
|----------|----------|----------------|-----------------|-----------------|-----------------|
| V1431 Aql| 183324   | 5.799          | 0.089           | 0.057           | 0.100           |
| HR 7397  | 183227   | 5.844          | 0.017           | -0.380          | 0.087           |
| HR 7438  | 184663   | 6.373          | 0.408           | -0.033          | 0.388           |

Notes. All tabulated UBVR magnitudes of these stars are based on numerous all-sky observations secured at Hvar.

4 The whole program suite with a detailed manual, examples of data, auxiliary data files, and results is available at [http://astro.troja.mff.cuni.cz/ftp/hec/PHOJ1](http://astro.troja.mff.cuni.cz/ftp/hec/PHOJ1).
Lynds measures magnitudes that are very close to the Johnson V filter. The largest $\Delta (dV – dy)$ difference was found for V373 Cas, which is now known to be a Be star and a spectroscopic binary (Lyubimkov et al. 1998). The Hipparcos $H_p$ magnitude has a 0.1 range of variations (Perryman & ESA 1997). We therefore digitised the yellow observations of V1294 Aql from the enlarged Fig. 13 of Lynds (1959) and derived HJDs and magnitude differences that were then added to the V magnitude of the comparison star HR 7438 from Table A.1. We estimate that the HJDs are accurate to $\pm 0.0003$, which is very satisfactory.

Station 61 – Hipparcos: These all-sky observations were reduced to the standard V magnitude via the transformation formula derived by Harmanec (1998a). To derive this transformation, the correct values of the Johnson $B – V$ and $U – B$ indices are required. We checked the overlapping Hvar $UBV$ photometry to find that the $B – V$ index remained basically constant over the time interval covered by the $H_p$ photometry at a value of 0.011. The $U – B$ index varied from $-0.077$ to $-0.064$, but we verified that these extremes cause an error of only about 0.001 in the transformation into Johnson V. We therefore used $B – V = -0.010$ and $U – B = -0.070$ to transform $H_p$ into V.

Station 66 – Tubitak: These differential $UBV$ observations were secured with the 0.40 m reflector of the Turkish national observatory and an SSP-5A solid-state photometer and were transformed into the standard system.

Station 89 – Çanakkale: These differential $UBV$ observations were secured at Çanakkale mountain station with a 0.40 m reflector and an SSP-5 solid-state photometer and were transformed into the standard system.

Station 93 – ASAS3 V photometry: We extracted these all-sky observations from the ASAS3 public archive (Pojmanski 2002), using the data for diaphragm 1, which has the lowest rms errors on average. We omitted all observations of grade D and observations with rms errors larger than 0.034. We also omitted a strongly deviating observation at HJD 2452662.6863.

### Table A.2. Lynds (1959) versus standard Johnson magnitude differences for all suitable microvariables observed by Lynds. The mean $UBV$ values of all considered stars were taken (with one exception) from the General Catalogue of Photometric Data (see Mermilliod et al. 1997). The yellow magnitude differences ‘variable minus comparison’ of Lynds are denoted by $d_y$. The $UBV$ magnitudes of the corresponding comparison are always listed below each program star.

| Star | HD | V (mag.) | $B – V$ (mag.) | $U – B$ (mag.) | $d_y$ (mag.) | $d_V$ (mag.) | $\Delta (dV – dy)$ (mag.) | $\Delta (B – V)$ (mag.) | Notes |
|------|----|----------|----------------|----------------|-------------|-------------|--------------------------|--------------------------|------|
| KP Per | 21803 | 6.405 | 0.028 | -0.713 | 1.100 | 1.093 | -0.007 | -0.373 | |
| HR 1182 | 21770 | 5.312 | 0.401 | -0.020 | |
| o Per | 23180 | 3.833 | 0.049 | -0.741 | -2.827 | -2.826 | -0.001 | -0.027 | |
| BD+31 649 | 23478 | 6.659 | 0.076 | -0.566 | |
| BD+52 714 | 23675 | 6.727 | 0.448 | -0.542 | 0.020 | -0.012 | -0.032 | -2.076 | 1 |
| BD+52 726 | 24431 | 6.739 | 0.372 | -0.610 | |
| BD+52 715 | 23800 | 6.922 | 0.329 | -0.534 | 0.212 | 0.183 | -0.029 | -0.043 | 2 |
| BD+52 726 | 24431 | 6.739 | 0.372 | -0.610 | |
| V600 Her | 149881 | 7.03 | -0.19 | -0.97 | 0.632 | 0.65 | 0.018 | -0.103 | |
| V773 Her | 149822 | 6.380 | -0.087 | -0.188 | |
| V896 Oph | 165174 | 6.139 | -0.011 | -0.928 | 1.707 | 1.704 | -0.003 | -0.042 | |
| NSV10009 | 165477 | 4.435 | 0.031 | 0.009 | |
| ES Vul | 180968 | 5.432 | 0.038 | -0.773 | -1.460 | -1.475 | -0.015 | -0.134 | 2,3 |
| BD+21 3719 | 180889 | 6.907 | 0.172 | 0.162 | |
| V819 Cyg | 188439 | 6.293 | -0.116 | -0.914 | 0.058 | 0.083 | 0.025 | -0.474 | 4 |
| HD 7577 | 188074 | 6.210 | 0.358 | 0.032 | |
| V373 Cas | 224151 | 6.003 | 0.207 | -0.713 | -1.152 | -1.197 | -0.045 | 0.067 | 2 |
| BD+56 3127 | 224624 | 7.212 | 0.14 | 0.08 | |

Notes: 1...When adopting the mean $UBV$ values for this star, we omitted the deviating value $V = 6.88$ denoted as uncertain in the original study by Fernie (1983). 2...Be star; 3...The $UBV$ magnitudes of the corresponding comparison are always listed below each program star.

### Notes
- Station 61 – Hipparcos: These differential $UBV$ observations were secured at Çanakkale mountain station with a 0.40 m reflector and an SSP-5 solid-state photometer and were transformed into the standard system.
- Station 93 – ASAS3 V photometry: We extracted these all-sky observations from the ASAS3 public archive (Pojmanski 2002), using the data for diaphragm 1, which has the lowest rms errors on average. We omitted all observations of grade D and observations with rms errors larger than 0.034. We also omitted a strongly deviating observation at HJD 2452662.6863.