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PHOTOMETRIC AND SPECTROSCOPIC VARIATIONS OF THE Be STAR HD 112999[†]

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1 Introduction

Be stars were defined as "non-supergiant B-type stars whose spectrum have or had at a time, one or more Balmer lines in emission" by Jaschek et al. (1981). This class of stars has circumstellar disks that originate emission in hydrogen, helium, and/or metal lines. These disks seem to be mainly generated by rapid rotation and/or binarity, combined with non-radial pulsations (Huat et al., 2009; Neiner et al., 2012). These phenomena occur as an episode during the evolution of hot B-type stars.

One of the most intriguing properties of Be stars is their long-term variability, which seems to be related to disk growth or loss events (Hubert & Floquet, 1998). These events produce spectroscopic and photometric effects, i.e. changes from emission to absorption lines (and vice versa), and also flux and color variations. Given the great variety of observed events, many open questions remain unanswered (see the review by Porter & Rivinius, 2003, and references therein), which raises the importance of studying these objects. As the same authors state "Be stars are in a unique position to make contributions to several important branches of stellar physics, e.g., asymmetric mass loss processes, stellar angular momentum distribution evolution, asteroseismology, and magnetic field evolution".

The primary goal of this paper is to present the analysis carried out on a new possible transient Be star, labelled HD 112999 (α_{J2000} =13:01:35, δ_{J2000} = −60:40:16). This star was observed by one of us (MAC) while trying to identify possible members of the Centaurus OB1 (CenOB1) stellar association (Corti & Orellana, 2013). The spectral classification of this star varies depending on the bibliography available. It was first reported as a Be star by Bidelman & MacConnell (1973). Other authors reported different spectral types, i.e. Cannon & Pickering (B8; 1920), Houk & Cowley (B6 III (N); 1975), and

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Table 1: Instrumental configurations used

run	Observat.	Epoch(s)	HJD 2400000+	Telesc. [m]	Spectrograph	Rec. disp. [Å px^{-1}]	$\Delta\lambda$ [Å]	exp. time [sec]	S/N
A	La Silla/ESO	2008 May	54603.68	2.2	FEROS	0.03	3700-8600	600	70-120
B	CASLEO	2009 Apr.	54941.70	2.1	REOSC CD	0.2	3700-6000	1200	20-50
C	CASLEO	2012 Jan.	55930.86	2.1	REOSC CD	0.2	3700-6000	1200	20-50
D	CASLEO	2012 Apr.	56047.66	2.1	REOSC SD	1.6	5900-7400	700	150-200
E	CASLEO	2012 June	56086.00	2.1	Boller&Chivens	2.7	3500-5000	150	160-250

Garrison et al. (B6 V; 1977). Nowadays, HD 112999 is listed in the BeSS catalogue[1] as B6 III ne (Neiner et al., 2011). This star prompted further attention because our optical spectrum, taken on 2009, was very different from those classified before. We consulted spectral and photometric databases and found that HD 112999 is a variable Be star which seems to have experimented disk − loss and growth − events over the last decades. In the following sections, we describe these facts.

2 Observational Data

2.1 Spectroscopic data

The observational material belongs to different program runs obtained at the Complejo Astronómico El Leoncito (CASLEO), Argentina and La Silla Observatory, Chile. Different instrumental configurations, detailed in Table 1, were used in these runs.

For CASLEO observations, comparison arc images were observed in the same sky position where the stellar images were located immediately after or before the stellar exposures, being Th−Ar for the echelle mode of the REOSC spectrograph, Cu−Ar for the simple mode, and He−Ne−Ar if the B&C was used. Moreover, bias frames, standard stars of radial velocity, and spectral type were observed every night, the latter only during run B. We also took the spectrum of the standard of rotational velocity, τ Sco (Slettebak et al., 1975), during run C. These spectra were processed and analysed with IRAF[2] routines.

The spectrum retrieved from the ESO database was obtained with the FEROS spectrograph and processed with the MIDAS pipeline. The radial velocities were obtained by simple cross-correlation of the echelle orders of the HD 112999 star and of the simultaneous calibration fiber with regard to the pertinent reference spectrum.

2.2 Photometric data

The photometric data were taken from two sources: the Epoch Photometry Annex of Hipparcos Astrometry Mission (Perryman & ESA, 1997) and The All Sky Automated Survey (ASAS) (Pojmanski, 1997).

The Hipparcos data consist of 214 observations made between December 1989 and January 1993. The measurements are in the interval $7.31 < H_p < 7.48$; the errors of the individual measurements range from 0.007 to 0.020 mag. According to the criteria adopted when Hipparcos data were analysed, this star was classified as an "unsolved variable"[3]. Following the Hipparcos calibration for a star with colour index $V - I = 0.070$, as in this case, the relation $H_p - V_J = 0.025$ should hold, where V_J is the magnitude in the V filter of the Johnson photometric system.

[1] http://basebe.obspm.fr

[2] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[3] cf. The Hipparcos and Tycho Catalogues, Vol. 1, Introduction and Guide to the Data, Sec. 1.3 App. 2.

The ASAS data include 1030 magnitude determinations obtained between November 2000 and December 2009. ASAS provides aperture photometry with several apertures. For this study, the aperture labeled as MAG 1 in the dataset was selected because larger apertures could be contaminated by a neighbor star. The errors of individual measurements are up to 0.120 mag, with a typical value $\mathrm{err}_{ASAS} = 0.040$ mag. Since $\mathrm{err}_{ASAS} > (H_p - V_J)$, no zero-point correction was applied to compare the two datasets.

3 Results

3.1 Spectral Analysis

The FEROS spectrum (labelled A in Table 1) shows typical Be features such as the Balmer lines Hγ, Hβ and Hα in emission (see Fig 2). There, at least one additional emission line, Fe I λ4328 bluer than Hγ, and two additional emission lines, Fe I λ4849 and Fe I λ4875 of Hβ, can be observed. The spectrum also presents other metallic lines, i.e. O II, Fe II, Cr II, Ti III, C III, etc, as weak emissions, some of them shown in Fig 1. All of these emission lines could be originated in a disk. A Be star with mid inclination angle might cause the double structure observed in Hα emission lines. The rotation of the disk plus a possible absorption ("reversal" of the emission) against the edge of the star or disk cause such profiles of double structure. Other features as He I, λ4009, 4026, 4144, 4387, 4471, 4921, 5875, 6678 and 7065, Si II $\lambda\lambda$4128-30 and Mg II λ4481 can be observed in absorption. These lines are thought to be originated in the stellar photosphere. This composite spectrum indicates that the HD 112999's disk was thick and extended during 2008 May.

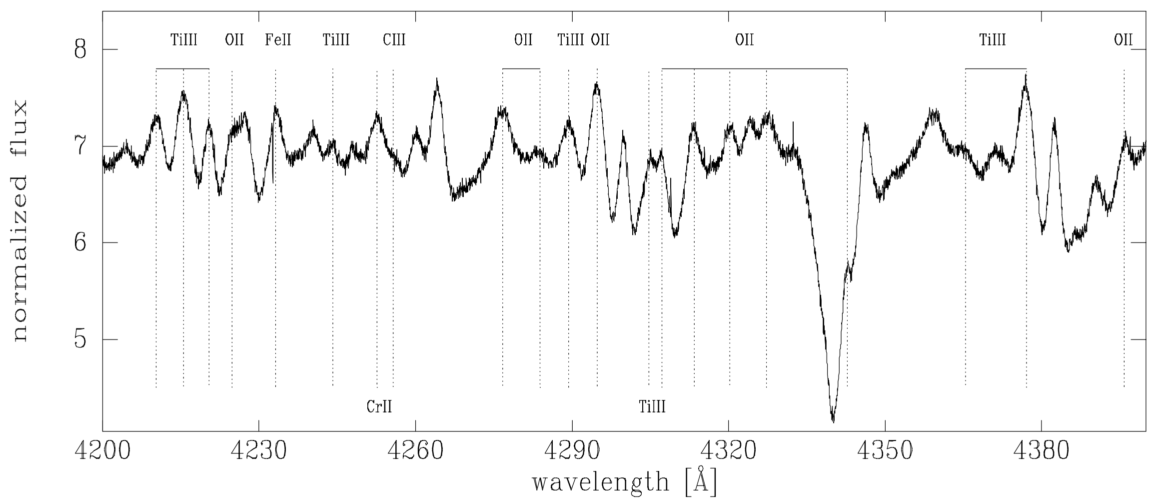

Figure 1. Some metallic emission lines in the FEROS spectrum.

Our B spectrum, obtained about one year later than A, shows a very weak emission contribution in the Hβ profile and an almost marginal one in the Hγ line. The metallic lines (seen as weak emissions in A) have not been detected in this spectrum. We think that this is not due to the fact that the B spectrum has a poorer S/N ratio than A. The absorption lines, which would result from the stellar photosphere in the A spectrum, can also be observed here.

Three years later, the C spectrum presented the Balmer lines Hγ and Hβ as pure absorption, i.e. there were no traces of emission contribution in these lines (see Fig. 2).

The D spectrum was obtained by one of us (WAW) to see the profile of the Hα line, as neither B nor C spectra included it in their spectral ranges. Thus, we proved that Hα is a conspicuous absorption line in the spectrum taken in April 2012 (see Fig. 2).

The E spectrum is the one we have been able to obtain more recently (Fig. 3). It shows the same absorption spectral lines than the other spectra, plus a very narrow absorption line at 4233 Å, which we have identified as Fe II. We argue that this line seems to have originated in a shell because its FWHM is

Table 2: Radial velocities measured in the high resolution spectra

Line	run A [km s^{-1}]	run B [km s^{-1}]	run C [km s^{-1}]
He I 4026	−20	5	7
He I 4471	−35	−15	−31
Mg II 4481	−92	−5	−2
He I 5876	−20	36	−19
Na I 5890-96	4.5	5.5	2.5

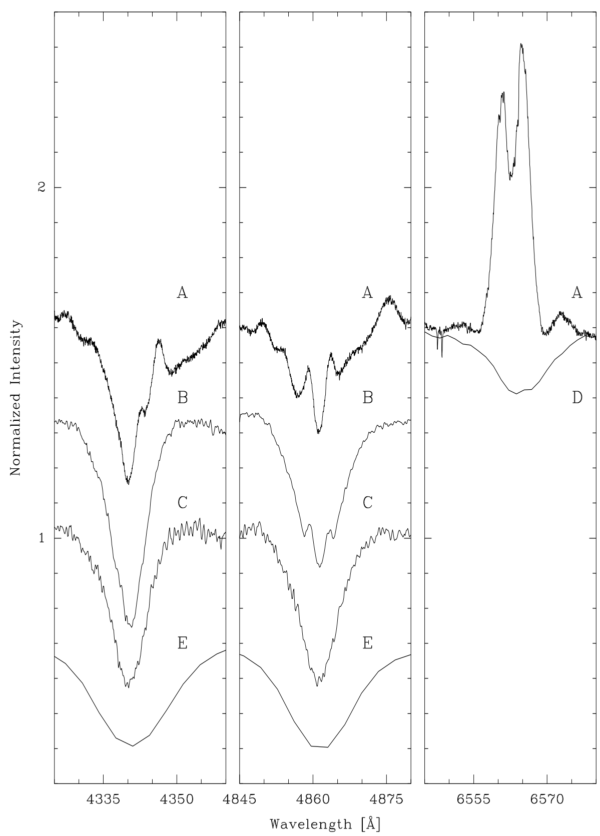

Figure 2. Variations of the Hγ, Hβ and Hα lines from spectra obtained in different runs (see Table 1). Other emission lines identified as Fe I λ 4328 (in the Hγ region), Fe I λ 4849 and λ 4875 (Hβ region), and Fe I λ 6574 (Hα region) can also be observed.

~ 2.5 Å compared to the FWHM ~ 8 Å of the photospheric He I absorption lines. This assumption is in good agreement with the fact that the forming region of Fe II lines is located close to the central star (Arias et al. 2006).

We classified the Be-type spectra A, B, and E as B2−3 V, following the criteria of Walborn & Fitzpatrick (1990), i.e. the ratio between Si III λ4552 and Si IV λ4089, the declining strengths of the C III+O II blends at $\lambda\lambda$4070 and 4650, and the weakness of all the Si II-III features. From the spectral type B2 to B3, Si II $\lambda\lambda$4128-30, C II λ4267 and Mg II λ4481 increase in prominence. The very large He I $\lambda\lambda$4144/4121 ratio is a characteristic of the B2 V spectra and the principal luminosity criterion is Si III λ4552/ He I λ4387.

The projected rotational velocity ($v \sin i$) in this class of stars is an important parameter. To estimate it, we used the spectrum of the star τ Sco, which was convolved with rotation line profiles calculated for different projected rotational velocities, and the $FWHM$ of the absorption line He I λ5015 was measured for each velocity. Then, a linear relation between $FWHM$ and the $v \sin i$ was fitted. This empirical relation was used to translate the $FWHM$ of the line in the spectrum of HD 112999 into a $v \sin i$ estimation. In this way we obtained $v \sin i = 170 \pm 40$ km s^{-1}, the error being so large because of the low S/N ratio of the spectrum and the weakness of the line.

The B star becomes a Be star exhibiting rapid rotation probably as the result of disk instabilities caused by the spun up by binary mass transfer (McSwain et al., 2009). In order to know if this is the case for HD 112999 star, we measured the radial velocities in its three high-resolution spectra (A, B, and C). For this, we fitted Gaussian profiles to the selected spectral lines, i.e. He I $\lambda\lambda$4026, 4471 and 5876, and Mg II λ4481, as well as the interstellar lines of Na I. A comparison of the values of Na I showed no systematic differences between the spectrographs used (within an error of 3 km s^{-1}), nevertheless, the He I and Mg II λ4481 absorption lines present discrepancies within one spectrum which are much larger than for any of these lines between different spectra. The observed differences between spectra cannot be exploited to speculate a possible binarity, because the different values are expected from one spectrum to another in the case of a binary star and all the lines should vary in the same way within one spectrum. We provide the radial velocity measurements in Table 2 for future reference.

3.1.1 BCD fundamental parameters

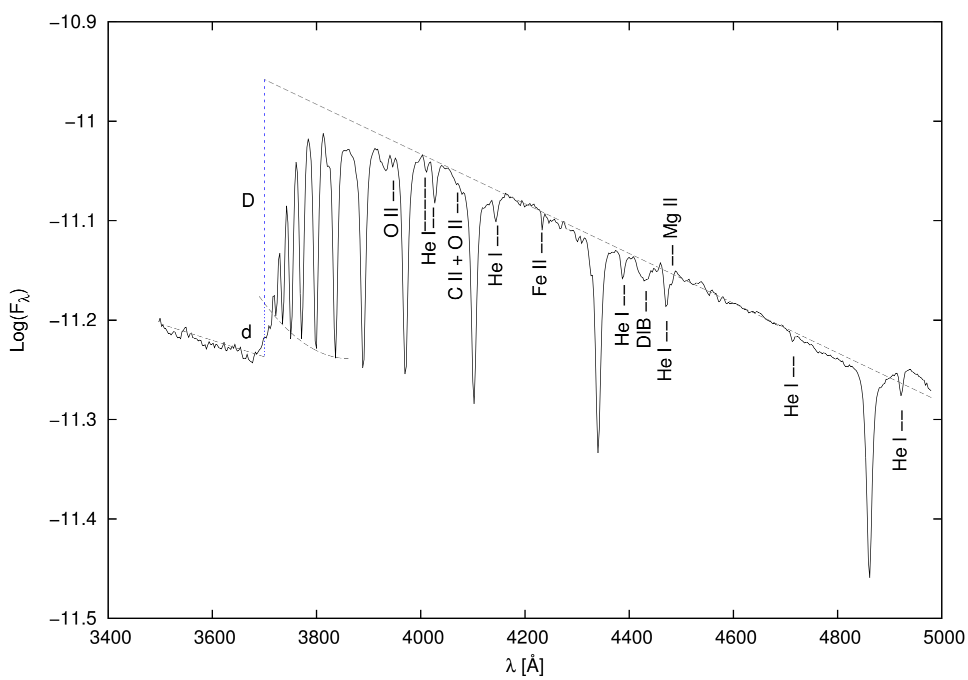

Figure 3. Balmer discontinuity: D is the first Balmer jump for normal B star, d is the second discontinuity in absorption, indicating the presence of the circumstellar envelope.

Some physical properties from the E spectrum of HD 112999 were derived by using the BCD (Barbier-Chalonge-Divan) spectrophotometric system (Chalonge & Divan, 1973, 1977). A detailed description of this method is presented in Zorec et al. (2009, Appendix A) and further applications to Be stars were made by Zorec et al. (2005) and Aidelman et al. (2012). This method is ideal for studying peculiar stars, and in particular Be stars, due to the fact that the parameters defined by the method are not affected by interstellar extinction and absorption/emission from the circumstellar envelope (Zorec & Briot, 1991). Then, we determined a B3 spectral type (with one subtype error) of luminosity class III, an effective temperature $T_{\rm eff} = 17\,500 \pm 1\,000$ K, a surface gravity $log\ g = 3.3\pm\ 0.5$, an absolute magnitude $M_V = -2.5\pm\ 0.5$ mag, and a color excess $E_{B-V} = 0.11\pm\ 0.07$ mag.

The presence of the second Balmer discontinuity in the E spectrum indicates that a circumstellar envelope can still be observed (Divan, 1979). Figure 3 shows this spectrum in the Balmer discontinuity region, where the first jump, D, corresponds to a normal B star while the second one, d, is originated by the envelope.

Later on, we estimated the distance from HD 112999 to the Sun, using its extreme V magnitudes, i.e. $7.3 \leq V \leq 7.5$ (see Fig. 4), corrected by colour excess $E_{B-V} = 0.11\pm\ 0.07$ mag and considering the standard selective absorption coefficient, $R_{\rm v} = 3.1$ (Schultz & Wiemer, 1975). We obtained a distance modulus of 9.5 ± 0.5 mag (790 ± 180 pc) and 9.7 ± 0.5 mag (870 ± 200 pc), respectively. These estimated distance values with their respective errors are slightly larger than the Hipparcos distance (654 pc). Then, HD 112999 is closer than the Cen OB1 association, $V_0 - M_v = 12$ mag (2500 pc) (Corti et al., 2012).

3.2 Light curve analysis

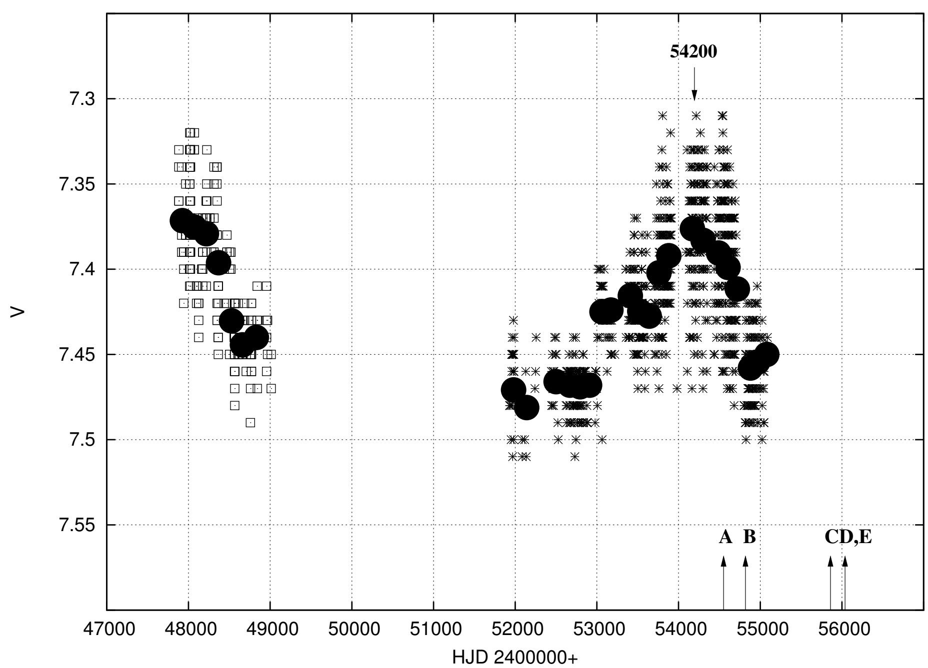

Figure 4. Light curve of HD 112999. Boxes and asterisks correspond to Hipparcos and ASAS data, respectively. Filled circles depict the average magnitude in about 114 days. The capital letters (see Table 1) show the almost temporal coincidence between the photometric and spectroscopic data explained in section 3.2.

The collected photometric data were analysed together and the resulting light curve is shown in Fig. 4. HD 112999 presents two kinds of variabilities: short-term one (1.302 days; Hubert & Floquet, 1998) and long-term one ($\sim$ years). The formerone with an amplitude smaller than 0.1 mag, is included in the Hipparcos data (see Fig. 5), and it is the reason why this star has been included in the General Catalogue of Variable Stars (Samus et al., 2009) and classified as BE[4].

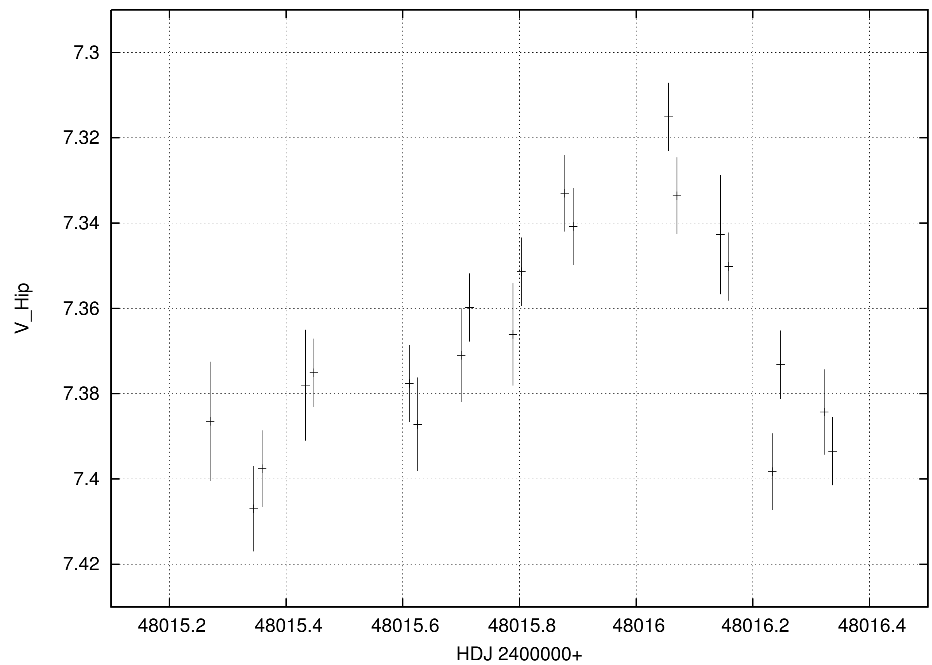

Figure 5. Hipparcos data showing variability smaller than 0.1 mag with a period ~ 1 day.

The long-term variation can be better observed in the ASAS data. To enhance and show it more clearly, we represent unweighted averages (calculated within intervals of ~114 days) with filled circles. In Fig. 4 we identified the light maximum reached around HJD 2 454 200 (ASAS data).

4 Discussion

The collected spectra show important variations, especially noticeable in the Balmer lines, i.e. their emission profiles decrease in intensity from May 2008 to June 2012 (A to E). Similar variability was already detected in other Be stars like MG 31 and MG 119 in NGC 3766 (McSwain et al., 2008); Pleione and κ Dra (Hubert & Floquet, 1998) and 66 Ophiuchi (Floquet et al., 2002).

The relation between the photometric and spectroscopic data is shown in Fig. 4. The capital letters are the same defined in Table 1. The light curve and the spectra obtained in A and B runs, are well correlated in the sense that as the star fades, the Balmer emissions decrease their intensities (Fig. 2). This behavior is related to disk dissipation. The lack of photometric data after 2009 August prevents us to determine if the star reached the minimum between B and C runs or it will be reached later.

The behavior observed in HD 112999 led us to search in the existing literature for more information about this star. Thus, we learned that the only Be spectrum of HD 112999 was obtained in the period 1967−1969 by Bidelman & MacConnell (1973)[5]. Unfortunately, they did not provide a precise date of observation. As already mentioned in Section 1, other authors have reported different spectral classifications for HD 112999. We adopted the B2−3 V spectral type for HD 112999, which was determined following the criteria of Walborn & Fitzpatrick (1990).

[4]Due to the type of variability, BE is used when a Be variable cannot be readily described as a Gamma Cassiopeiae variable (GCAS) star, (Samus et al. 2009)

[5]This observation was the reason to be included in the Catalogue of Be Stars (Jaschek & Egret, 1982)

5 Summary

The analysis of the spectroscopic and photometric data of HD 112999 allowed us to identify a long-term variability in its V light curve and the change of the Balmer line profiles from emission to absorption. The decline in V magnitudes between 2007 and 2009 is related to the disappearance of emission lines, very noticeable in some Balmer lines. We propose that the reported changes are induced by the loss of the disk. Photometric data were not sufficient to search for long-term periodicities; therefore, we encourage other researchers to monitor this star in the future. We classified our spectra as B2−3, the luminosity class should be clarified with further observations.

We used the observations obtained in different observing programs to measure some important parameters such as the projected rotational velocity and the distance modulus. Also, our last spectrum E, obtained in June 2012, was analysed with the BCD method, from which we noted that a circumstellar envelope is still present. Hence, further spectra should be obtained to determine if HD 112999 will reach a normal B-type.

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