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Investigation of the variability of bright Be stars using Hipparcos photometry*

A.M. Hubert and M. Floquet

URA 335 du CNRS, Dasgal, Observatoire de Paris-Meudon, F-92195 Meudon Principal Cedex, France

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Abstract. The high accuracy and the homogeneity of Hipparcos data for bright stars have allowed us to quantify the degree of variability of Be stars. This degree has been found to be highly dependent on the temperature of the star. Rapid variability is the main feature of the 86% of early Be and less than 20% of late Be stars taking into account the limit of detection considered. In addition to Be stars reported in the Hipparcos catalogue (ESA 1997) as short-period variables, we have been able to enlarge the number of detections as well as to confirm periods previously determined. Be stars that show larger amplitude rapid variations are proposed as candidates for a search of multiperiodicity i.e. as non-radial pulsators.

We have also searched for the presence of outbursts and fading events in the Hipparcos data. Outbursts have been frequently and preferentially detected in early Be stars with rather low to moderate v sini while fading events seem to be more conspicuous in stars with higher v sini. Mid-term and long-term variations have also been investigated. Several stars have shown some evidence of temporary quasi-periodic oscillations ranging between 10 and 200 days.

Finally information concerning long-term variations is reported. Cycles shorter than or equal to the Hipparcos mission have mainly been detected in stars earlier than B6. Long-term time scales of late Be stars are confirmed to be longer by far.

Key words: stars: emission-line, Be – oscillations – statistics– variables: other

1. Introduction

Rapid, mid-term and long-term variability has been investigated in bright Be stars using Hipparcos photometry. The astrometric satellite of the European Space Agency was operating from August 1989 to August 1993 (ESA 1997). In addition to astrometric measurements, it provided photometry with on average 110 observations for each observed star. The Hipparcos magnitude, designated as Hp, is defined by a broad pass-band which ranges from 340 to 850 nm (Turon et al. 1992). This broad-band system yields magnitudes close to the visual magnitude V. The advantage of Hipparcos photometry is the high accuracy of homogeneous measurements of the Hp magnitude of bright stars ($V \leq 7.5$), the number of measurements per star, and the duration of the monitoring. It has given an excellent opportunity to investigate the degree of variability of Be stars as a function of spectral type, to detect discrete events such as sudden brightness and fading episodes probably connected with discrete mass ejection at the surfaces of Be stars, to estimate rising time of outbursts and of their subsequent fading phases and to determine different time scales of variations. Such information will be very useful for a better understanding of Be phenomena and for constraining envelope models. This paper is devoted to a study of rapid variability with an investigation of short periods, occurrence of outbursts and fading events, and to determinations of other time scales of light variations. The aim of this paper is to give typical trends of a large sample of Be stars; other subsequent analysis will be published elsewhere.

1.1. The sample

Selected Be stars with spectral types ranging from O9.5 to A0 were taken from the list established by Jaschek & Egret (1982). Stars with a flag in the Hipparcos catalogue indicating a high probability of disturbed Hp magnitudes were excluded. The number of transits for each object is roughly 110, varying approximately from 50 to 280, depending on the star's ecliptic latitude. The accuracy of each individual transit depends on the magnitude of the star and is about 0.003, 0.005 and 0.008 mag for a 3, 5 and 7 magnitude star respectively. We considered Hp magnitude only for individual transits with a high quality flag and with a good accuracy of measurement regarding the magnitude of the star.

In a first step a sample of 289 Be stars was considered. Since Hipparcos photometry is photon noise limited, the detection threshold for varibility is strongly dependent on the magnitude. In the Hipparcos catalogue, the minimum peak-to-peak amplitude for stars to be confirmed as variables is 0.010 for Hp=4.5 and 0.015 for Hp=6.5. In our sample 23 stars were given as pe-

Send offprint requests to: A.M. Hubert

* Tables 1 and 2 are only available in electronic form at CDS via ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Correspondence to: Anne-Marie.Hubert@obspm.fr

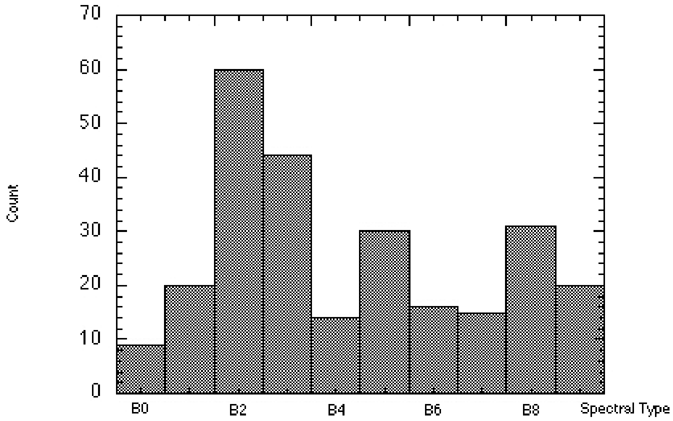

Fig. 1. Distribution of the Be stars of our sample as a function of their spectral types

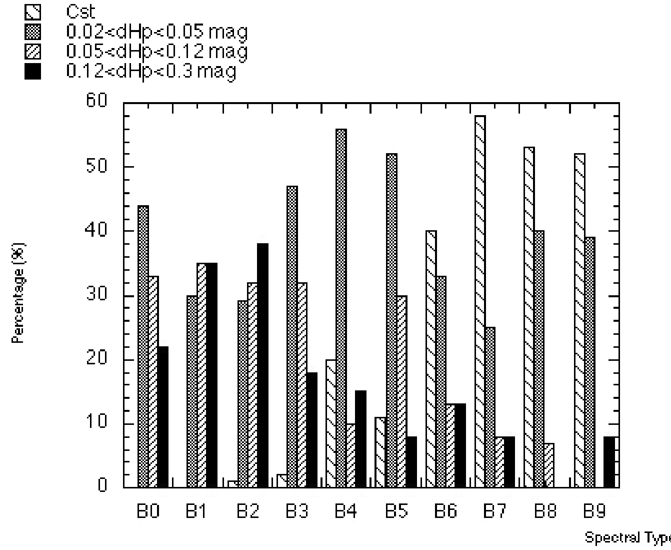

Fig. 2. Distribution of the degree of variability ΔHp (dHp on the graph) as a function of the spectral type

riodic variables (P), 157 as unsolved variables (U), 16 as micro-variables with amplitude below 0.03 mag (M), 39 as stars with probability >0.5 of being constant (C) and 54 without any indicator of variability; this latter case concerns stars either with insignificant amplitude of variations or with insufficient data for tests of variability or with probability of being constant between 0.5 and 10^{-4}.

Finally stars discovered by Hipparcos with a period P > 3.4d and well-known interacting binaries were excluded from the sample in the case of a statistical investigation. So in this more restrictive research our definitive sample contains 273 Be stars; the distribution of these stars is given in Fig. 1 as a function of their spectral sub-type. Therefore, in addition to spectral classification given in the input catalogue of Hipparcos (INCA) (Turon et al. 1992) , we also consider determinations made by Jaschek et al. (1980), Slettebak (1982) and Zorec & Briot (1991). As a general trend agreement was found between determinations by these authors in the limit of one spectral sub-type and one luminosity class difference.

2. Results

2.1. *Degree of variability*

Firstly, we investigated the degree of variability of each Be star during the Hipparcos mission, using the quantity ΔHp defined as the difference between the magnitude Hp at maximum (5th percentile) and at minimum (95th percentile), these extreme values being given in the Hipparcos catalogue; stars with ΔHp $\leq$ 0.02 mag have generally been considered as constant. Statistics on the degree of variability of Be stars as a function of the spectral sub-type are shown in Fig. 2. Almost all ($\geq$ 98%) early Be stars (B0 – B3e) to 45% of late (B7 – B9e) stars have shown light variability during the mission. Larger amplitudes of variability (0.12 $<$ Hp $<$ 0.30 mag) have been found in more than 33% of B0 – B2e stars compared with less than 10% of B7 – B9e stars. The majority of late Be stars, when found to be variable, have shown a lower amplitude of variability (0.02 $<$ Hp $<$ 0.05 mag). This general trend was also drawn by Pavlovski et al. (1997) from long-term photometric monitoring of 48 Be stars at Hvar Observatory. However the high accuracy and the homogeneity of Hipparcos data for bright stars have allowed us to quantify the degree of variability of Be stars.

2.2. *Types of variability*

It is well known that photometric variability in Be stars is rather complex; three time scales are often present and superimposed (i) short-term (hours, days) variability most often of low amplitude (several hundredths of magnitude); (ii) mid-term (days, weeks) variability, the amplitude goes up to 0.3 mag; (iii) long-term (years, decades) variability, the amplitude goes up to 0.8 or 1 mag in earliest Be stars as shown in the past for γ Cas (HD 5394) and X Per (HD 24534). The observational window of the Hipparcos mission was very suitable for studying the presence of short and mid-term variability in stars.

2.2.1. Short-term periodic variability

It has been found that short-term variability ($\leq$ 3.5d) is present in almost all early Be stars (86%), in 40% of intermediate sub-spectral types (B4 – B5e) and in only 18% of late Be stars (see Fig. 3). Short periods given in the Hipparcos catalogue in the case of 14 Be stars of our sample are related to stars whose light curves are ruled by short-term variations. In addition, in a first step, for many Be stars having shown both short-term and long-term variability, we have been able to obtain a determination or an estimation of short periods after subtracting long-term variations. Fourier transform and CLEAN algorithm were applied to long-term corrected data. Some Be stars having a short periodicity given by the Hipparcos catalogue were also reconsidered with our approach.

A list of newly short-term periodic Be stars has been established in this way; for some stars already discovered we have been able to confirm or reject periods previously reported in

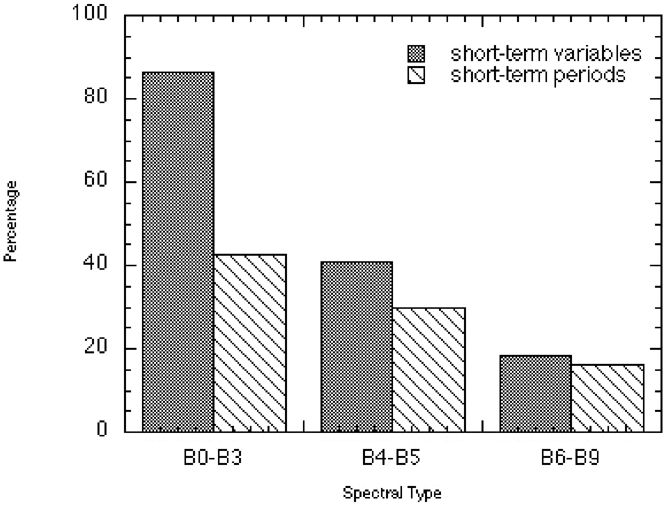

Fig. 3. Distribution of short-term variability as a function of spectral type for stars of our sample

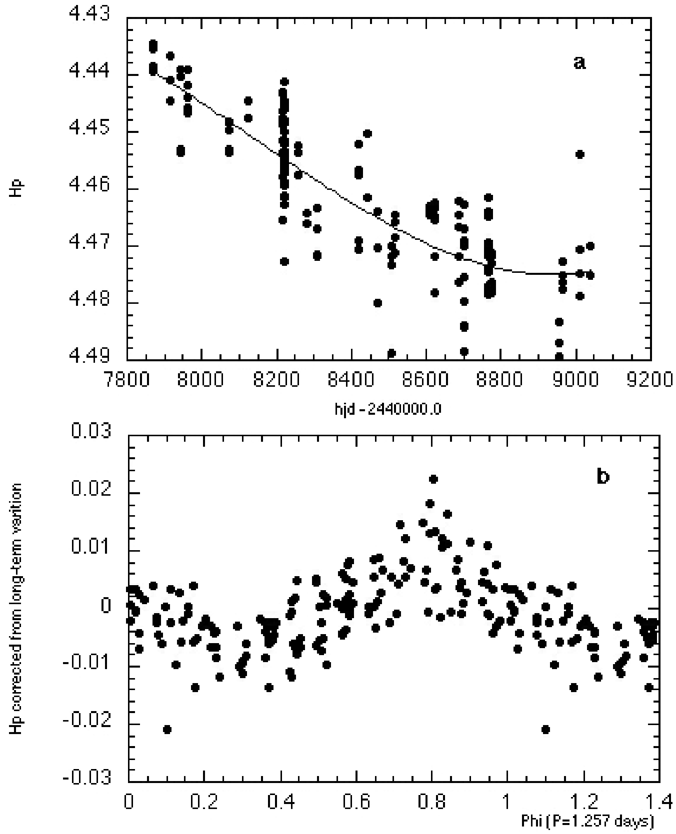

Fig. 4a and b. *o* Cas; **a** long-term variation, the full line represents the 3rd degree polynomial fitting; **b** short-term variability obtained after subtracting long-term variation; the period has been found by using TF + CLEAN algorithm

the literature (Balona 1995, and references therein). Very preliminary results were presented in Hubert et al. (1997); a more exhaustive list is contained in Table 1. We also added in Table 2 the list of Be stars belonging to our sample and given as short-period variables in the Hipparcos catalogue. For a few stars showing a double wave light curve with both minima nearly equivalent, we found, half the Hipparcos period and a single wave light curve. An illustration of superposition of short-term and long-term variations is given in Fig. 4a for *o* Cas. Short-term periodicity in this star, shown in Fig. 4b, was obtained after subtracting long-term variations by a 3rd degree polynomial fitting.

Moreover larger amplitudes (up to 0.1 mag) of short-term variations are conspicuous in about twenty Be stars. Some are known to be multiperiodic variables, for example KY And (HD 218674, Pavlovski & Ružić 1988), EW Lac (HD 217050, Pavlovski et al. 1993), *o* And (HD 217675, Sareyan et al. 1998). In the case of this latter star, the 0.79d period is present in the 1990 data (Fig. 5a) as the 1.57d period is dominant in 1992 with a highly non-sinusoidal signal (Fig. 5b). In this object there is a switch between both 0.79d and 1.57d periods which are in the ratio 2 in their values. For EW Lac (HD 217050) the most dominant period is 0.443 day in 1990–91, and 0.623 day from 1992 to 1993 in Hipparcos data.

Other stars of our sample having shown large amplitude in short-term variations are considered to be good candidates for detecting multiperiodic light variability; among them, we may cite HD 35439, HD 44458, HD 88661, HD 50013, HD 113120, HD 127972, HD 152478, HD 165921, HD 191610 and possibly HD 45725, HD 105435, HD 168797, HD 200310. High amplitude rapid variability with suspected numerous outbursts has been observed in HD 91465 and HD 105521.

The case of γ Cas (HD 5394) is puzzling; no well-established periodicity has been found with our method in spite of high accuracy on individual data (σ(Hp) ~ 0.002mag) and evidence of rapid fluctuations (ΔHp ~ 0.04mag).

When the observational window was suitable we found some stars with a variable amplitude in their short-term variations, as is clearly shown in β^1 Mon (HD 45725) (Fig. 6). It is crucial to know if the period value has remained constant with varying amplitude or if it has changed as occurs when several oscillations are superimposed. It would in fact be possible to discover whether there is light modulation linked with stellar activity or a beat period due to the presence of non-radial pulsations. However Hipparcos data are insufficient in number for drawing conclusions in many cases and only intensive monitoring of light variations in these interesting objects will provide more useful information.

2.2.2. Outbursts

Outbursts have been more frequently observed in early Be stars. These phenomena seem to occur randomly, varying in strength and lifetime in each star. They have been preferentially detected with a higher level (ΔHp $\leq$ 0.3 mag) in early Be stars with a low to moderate v sini (Fig. 7). According to their different characteristics we have distinguished several types or occurrences of outbursts. In the past, ground-based intensive photometric campaigns on several targets (μ Cen, Hanuschik et al. 1993; κ CMa, Balona 1991) and long-time photometric surveys such

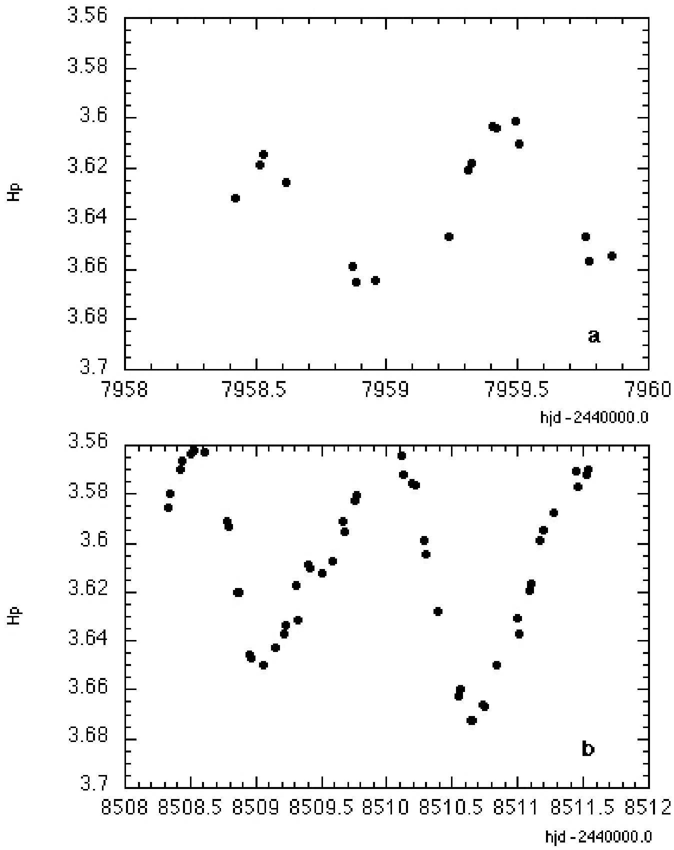

Fig. 5a and b. Short-term variability of o And displayed by continuous series of observations; **a** for HJD 2447958–2447960; **b** for HJD 2448508–2448512 (Note the difference in time scales)

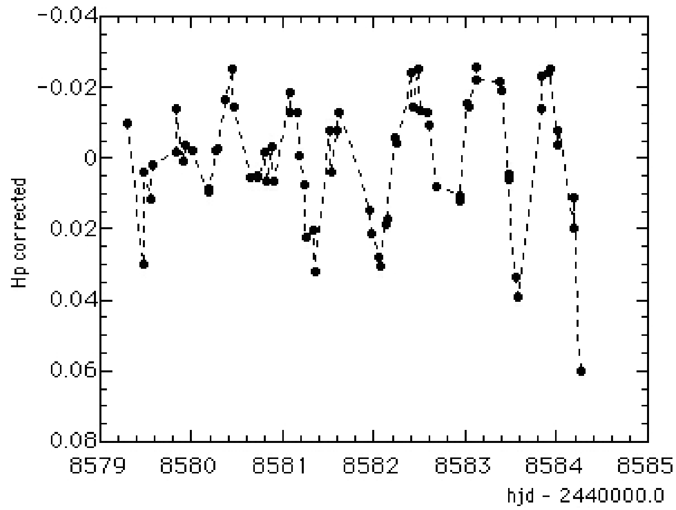

Fig. 6. Variation in the amplitude of the short-term variability of β^1 Mon after subtraction of a linear fitting of the data, in this interval. Note a 2.3d modulation although not detected by FT+CLEAN, superimposed to the 0.676d oscillation.

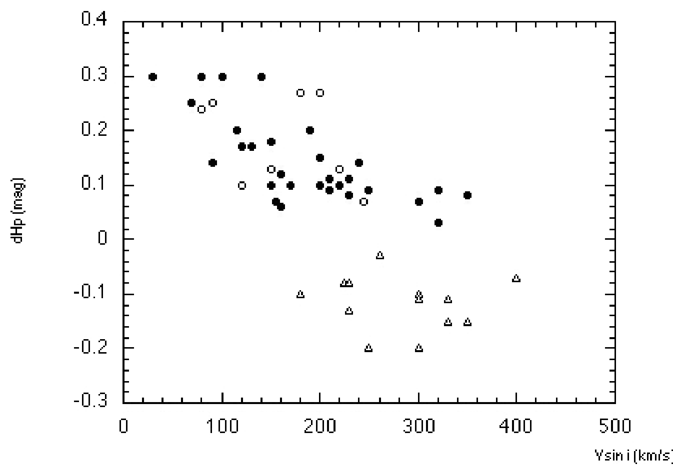

Fig. 7. Correlation between ΔHp (dHp on the graph) of outbursts and fadings (noted as negative quantities) and the v sini values taken from Slettebak (1982) and Halbedel (1996). $\bullet$: short-lived outbursts; $\circ$: long-lived outbursts; $\triangle$: short-lived fadings

as ESO surveys (Mennickent et al. 1994; Sterken et al. 1996) have already made possible such kinds of distinction. The great advantage of Hipparcos data has been to allow the extension of outburst detection to a very large number of stars, some of them having been poorly observed in photometry and/or in spectroscopy up to now. We distinguish (i) recurrent short-lived outbursts; (ii) outbursts followed by a slow decrease, both observed in Be stars with strong emission line features and (iii) outbursts closely linked to a temporary Be phase or strong emission line variation.

Stronger outbursts are long-lived (about 100 days), weaker outbursts are always short-lived (days or tens of hours).

i - recurrent short-lived outbursts

The number of isolated outbursts reveals the "pathological" state of the Be star. In a few cases, these cannot be distinguished from quasi-periodic oscillations (QPO) (see subsection 2.2.4) though they can be an observational window effect.

Minor and major outbursts are typically observed in B1 – B4e stars; in ω CMa (Fig. 8), minor outbursts with ΔHp $\leq$ 0.1 mag preceded a major outburst (ΔHp = 0.3 mag) which reached its maximum over 100 days. The same kind of behaviour occurred in 6 Cep. Many short-lived outbursts are also seen in HD 67888 and μ Cen. In some stars such as HD 11606, HD 193009 and HD 194335, 6 or 7 outbursts with ΔHp $\leq$ 0.1 mag have occurred over the time span of the Hipparcos mission. Short-lived outbursts have not been generally detected in Be stars with intermediate and late spectral sub-types (only one, maybe two detections). In Table 3, an estimation of time span between observed recurrent short-lived outbursts is given and the maximum outburst intensity associated with them. These data should be considered only as higher limits because of our sparse data span. Therefore it can be seen that stars mentioned in Table 3 and having presented recurrent outbursts are Be stars earlier than B4.

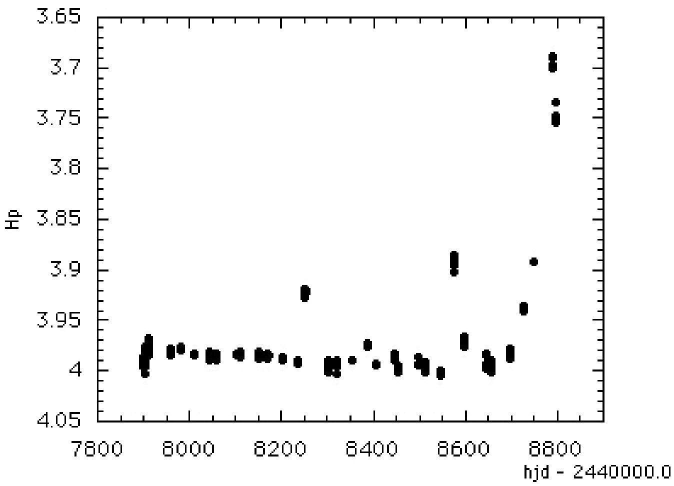

Fig. 8. Hipparcos photometry of ω CMa showing short-lived outbursts

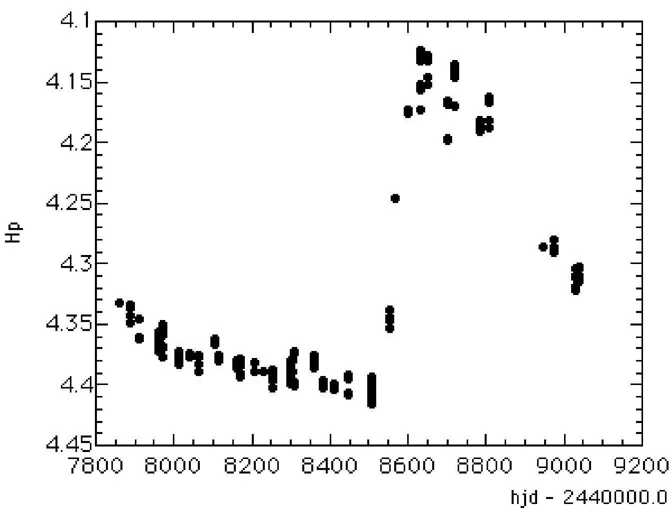

Fig. 9. Strong long-lived outburst in υ Cyg

ii - long-lived outbursts

The best example is provided by υ Cyg which exhibited a strong increase (ΔHp = 0.25 mag) of brightness over 100 days (Fig. 9) followed by a slow gradual decrease ($>$ 400d). Other examples are given in Table 4.

Note that short-term periodic variations seem to be always present in Be stars with short-lived and long-lived outbursts. In the case of υ Cyg, the amplitude of short-term variations has increased from 0.03 mag before the outburst to 0.05 mag after it.

2.2.3. iii - associated outbursts and Hα emission variations

Temporary Hα emission phases have sometimes been found associated with major outbursts, as for λ Eri (Fig. 10) according to CCD data (Peters 1990, 1992).

Recurrent outbursts in ω Ori have occurred every 8–10 months and this time scale is consistent with Guinan's report as mentioned by Peters (1996); though our data are insufficient

Table 3. Recurrent short-lived outbursts

HD	Name	Sp. Type	Time span (d)	ΔHp
11606		B1 V	50-100	0.15
33328	λ Eri	B2 IV	400-500	0.08
37490	ω Ori	B3 III	250-300	0.06
37657		B3 V	200-300	0.15
56139	ω CMa	B2 IV-V	200/330	0.30
67888		B3 V	100-200	0.20
105521		B3 IV	50-100	0.17
120324	μ Cen	B2 IV-V	20-30	0.06
120991		B2 III	250-330 ?	0.25
164284	66 Oph	B2 V	400-500	0.15
187811		B2.5 V	100-200	0.11
193009		B1 V	100-300	0.18-0.20
194335		B2 V	150 ?	0.10
194883		B2 V	100-200	0.20

Table 4. Long-lived outbursts

HD	Name	Sp. Type	Increase (d)	decrease (d)	ΔHp (mag)
36012		B5 V	$<$ 200	$>$ 800	≥ 0.18
49131	HP CMa	B2 III	100	400	0.35
53367		B0 IV	$\sim$ 400		0.25
54309		B2 V	$<$ 200	$>$ 600	~ 0.30
92938	V518 Car	B3 V	200	500	0.15
178175		B2 V	$\geq$ 300		≥ 0.12
202904	υ Cyg	B2 V	100	$>$ 400	0.20
203467	6 Cep	B3 IV	$<$ 200		≥ 0.20

to definitively confirm the reality of the 337d period proposed by McDavid et al. (1996) there is a slight tendency supporting it.

Large fluctuations of the strong Hα emission line with F/Fc varying between 5.2 and 12.7 were reported by Peters (1989, 1992, 1994), Ghosh et al. (1993) and Hanuschik et al. (1995, 1996) for 66 Oph when Hipparcos showed 3 outbursts with ΔHp ≥ 0.1 mag.

The search for a link between spectroscopic and photometric variations, crucial for testing dynamic models of circumstellar matter, strongly suffers from the lack of spectroscopic data available for the last decades on Be stars.

2.2.4. Fadings

Isolated short-lived fadings (several hours or days) are mostly observed in Be stars with a rather high v sini (Fig. 7), generally shell stars, such as 48 Lib (HD 142983), EW Lac (HD 217050, see Fig. 11), ϵ Cap (HD 205637) and HD183656 (V923 Aql); previous detections were also reported on these stars by Stagg et al. (1988) and Mennickent et al. (1994). These fadings are the negative image of short-lived outbursts preferentially seen in rather low to moderate v sini Be stars. Both phenomena probably have the same origin and can be explained by discrete high

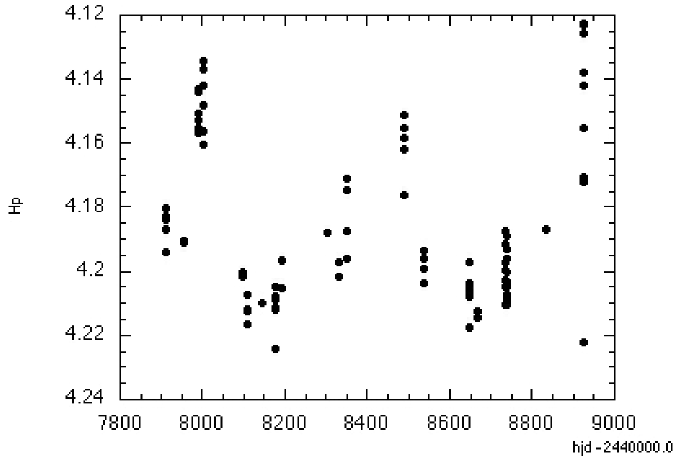

Fig. 10. Outbursts in λ Eri. Hα outbursts have been observed at HJD 2447900-8000 and 2448400-8500 (Peters 1990, 1992)

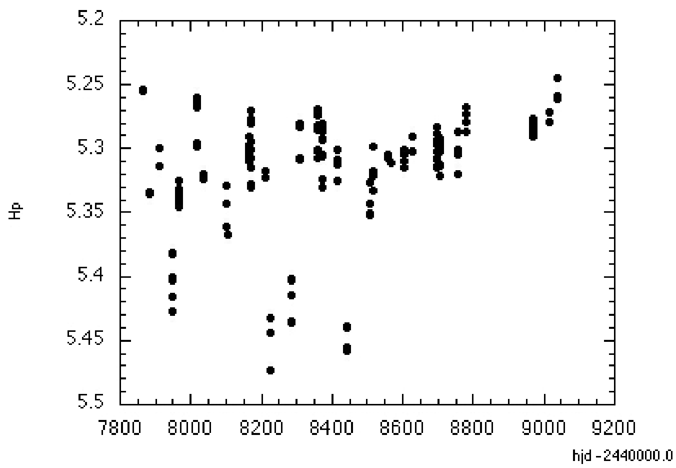

Fig. 11. Fadings superimposed to long-term variation in EW Lac

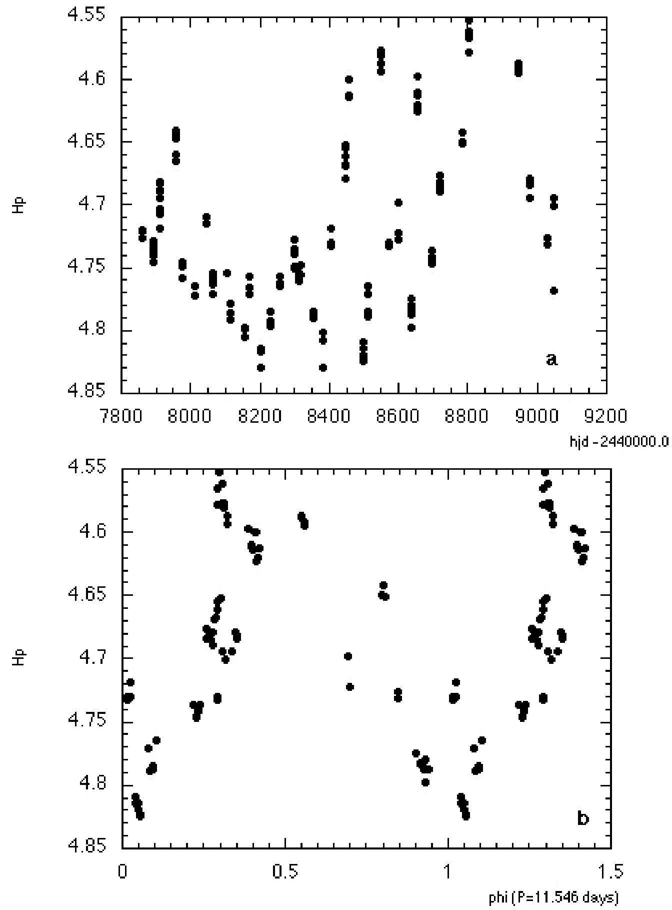

Fig. 12. Hipparcos photometry of MX Pup showing QPO superimposed on long-term variation (a) and curve obtained with QPO period of P=11.546 days for HJD $>$ 2448400.0 (b)

density emitting plasma events seen under various inclination angles above or inside an anisotropic envelope.

Fadings over several tens of days or more are sometimes seen before large fluctuations of light, so-called quasi periodic oscillations (QPO) by Mennickent et al. (1994).

2.2.5. QPO

Quasi periodic oscillations of light (several days, tens of days or several months) have been detected in several early Be stars; they are generally not always observed throughout the Hipparcos mission and they are often superimposed to long-term variations, see for example HD 68980 (MX Pup, P = 11.55d), Fig. 12 a and b. Obviously, detection in FY CMa made by Mennickent et al. (1994) has been confirmed, though our estimation of P = 107.6 days is slightly different from theirs. On the contrary Hipparcos data did not confirm the 87.9d period found by the same authors for HD 48917. Moreover a 137.99d period is given in the Hipparcos catalogue (ESA 1997) for HD 78164. Other candidates for QPO are HD 58011 with P $\sim$ 200d, HD 58343 with P $\sim$ 40–60d, HD 120991 with large variations over 20–30 days, though data are insufficient for a clear conclusion, and HD 58050 for which data are too scarce to be able to distinguish recurrent outbursts from QPO.

2.2.6. Long-term variations

Estimation of long-time scale variations is strongly limited by the duration of the Hipparcos mission. However, these variations are obviously seen in the great majority of Be stars. Cycle duration could be estimated in a few Be stars, see Table 5; those cycles with P $\leq$ 1200 days only concern Be stars earlier than B6 in our sample. In the case of late Be stars, their light curve varies smoothly, not disturbed by short-lived outbursts. Large long-term light variations are sometimes observed as in 4 Her (B7 V) for which a decline of brightness of 0.18 mag in Hp occurred over 700 days as a new Be phase started, giving evidence of a cooler pseudo-photosphere (Koubsky et al. 1997). A similar decline of brightness of 0.25 mag over 800 days was seen in o Aqr (B7 III).

Slow, very weak gradual increase/decrease of brightness could be linked to enhancement/faintness of the Hα emission line. A brightening of 0.04 mag over 110 days occurred in

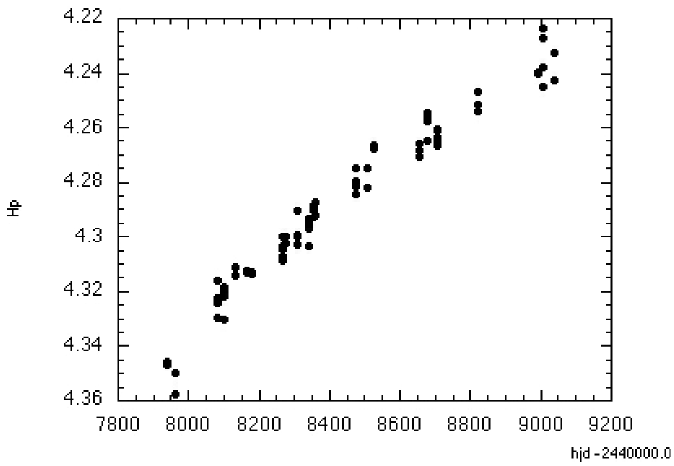

Fig. 13. Long-term variation of ψ Per

Table 5. Quasi-cyclical variations

HD	Name	Sp. Type	Time span (d)	ΔHp
698		B5 II	850	0.04
7636		B2 III	500	0.08
19243		B1 V	270/350	0.07
32991	105 Tau	B2 V	700	0.09
37202	ζ Tau	B2 IV	800	0.09
48917		B2 III	$\geq$ 1000	
58978		B0 IV	900-1200	0.06
62753		B3 V	$\geq$ 800	0.06
83953		B5 V	$>$ 1200	
91188		B3 III	$>$ 900	0.10
129954		B2 V	$\sim$ 900	0.10
131492	θ Cir	B4 V	1000	0.20
137387	κ^1 Aps	B1	$>$ 1200	
142983	48 Lib	B4 III	$\geq$ 1200	

Table 6. Monotonic long-term variation

HD	Name	Spectral Type	Time span (d)	ΔHp
4180	o Cas	B5 III	1200	0.045
22192	ψ Per	B5 III	1100	0.115
23862	Pleione	B8	900	0.03
42054		B4-B5	2000	0.025
49336		B3 V	1200	0.08
56014		B3 II	900	0.07
86612		B5 V	900	0.05
104015		B5 V	900	0.06
109387	κ Dra	B5 III	800	0.03
162732	88 Her	B8	900	0.035
187567		B2.5 V	750 ??	0.055
193182		B8	1200	0.06
208886		B5 III	1200	0.12

Pleione (B8 V) during an enhancement of Hα, and a decline of 0.03 mag over 1200 days in κ Dra (B5 III) when Hα became fainter (from Dodaira Hα photometric data, Hirata 1995). Furthermore 10 of 12 stars in our sample (Table 6) having shown only a significantly ($\geq$ 0.03 mag) monotonic increase or decrease in their light curve with generally superimposed rapid periodic oscillations such as ψ Per, Fig. 13, have a spectral type later than B4. These results merely tend to confirm the proposition previously made by Hubert-Delplace et al. (1982) and Hirata & Hubert-Delplace (1981) from data of An Atlas of Be Stars (Hubert-Delplace & Hubert 1979) that B – Be – Be shell cycles are statistically longer as spectral types of Be stars are later.

3. Conclusions

This paper gives a first glance at the main information provided by an investigation of numerous photometric data on a large sample of Be stars provided by the Hipparcos mission. It has been established as a general trend that the degree of variability is highly dependent on the temperature of the star. Recurrent short-lived outbursts are generally not detected in late (B6 – B9) Be stars, furthermore they are mainly detected in early Be stars with rather low to moderate v sini. Temporary fading events are preferentially seen in Be stars with large v sini. The high accuracy of individual measurements of the Hp magnitude has allowed us to widen the number of detections of rapidly periodic variables among Be stars as well as to confirm the existence over a long time duration of short periodicities previously determined from intensive monitoring only on runs of several days. A list of Be stars having rapid variations of large amplitude (ΔHp $\sim$ 0.1 mag) are proposed as candidates for a search for multiperiodicity i.e. as non-radial pulsators. Some Be stars have shown quasi periodic oscillations ($\leq$200 days) analogous to QPO discovered by Mennickent et al. (1994). Finally estimations of cycles of long term variations ($\geq$ 1 year) could be made for Be stars which have early spectral types. Light increases or decreases associated with transition phases from a quasi normal B phase to a Be or Be shell phase are timely depending on the temperature of the star.

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